

Radiation Protection at CERN

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esipap...

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in Particle & Astroparticle Physics

ESIPAP
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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)

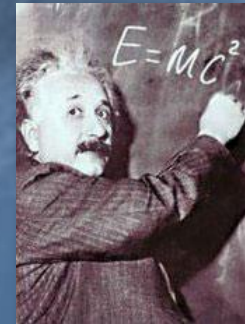
La Suisse du 30 octobre 1953



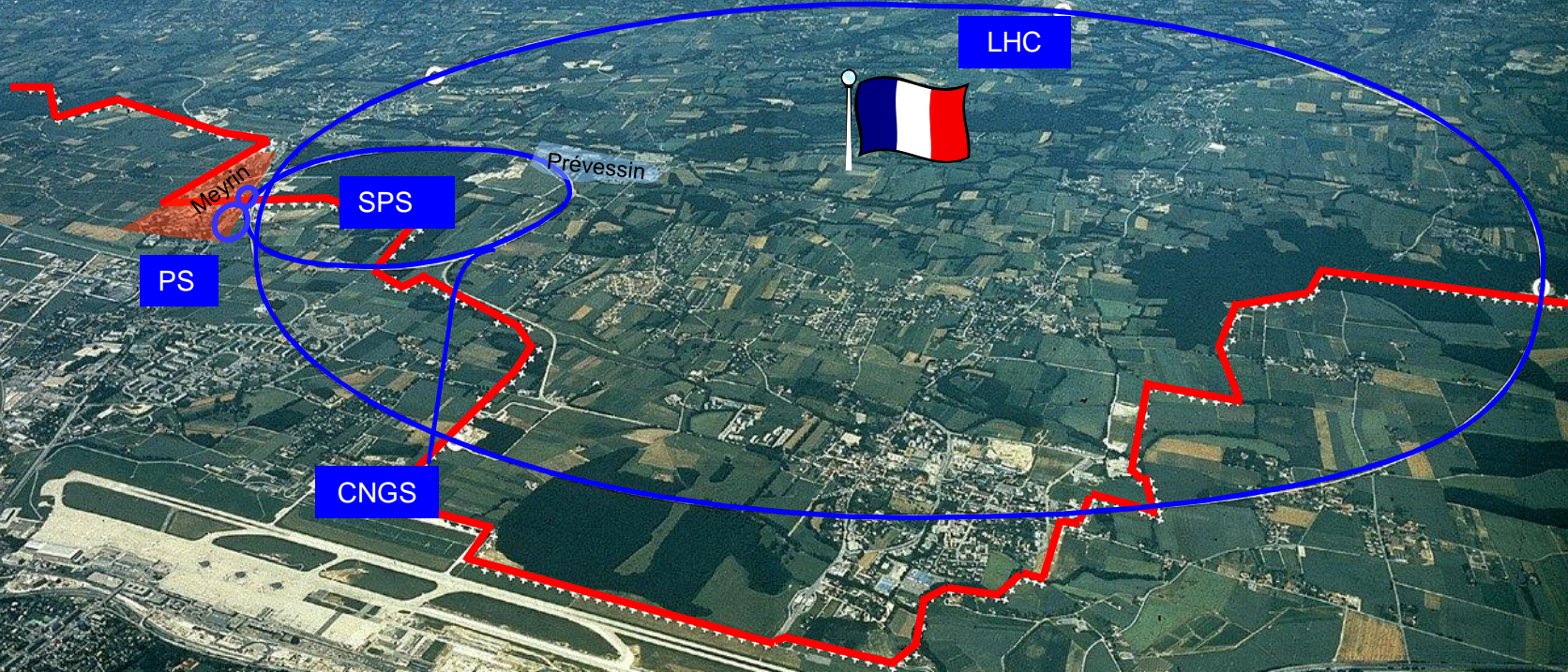
1954:

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

Today: Particle Physics



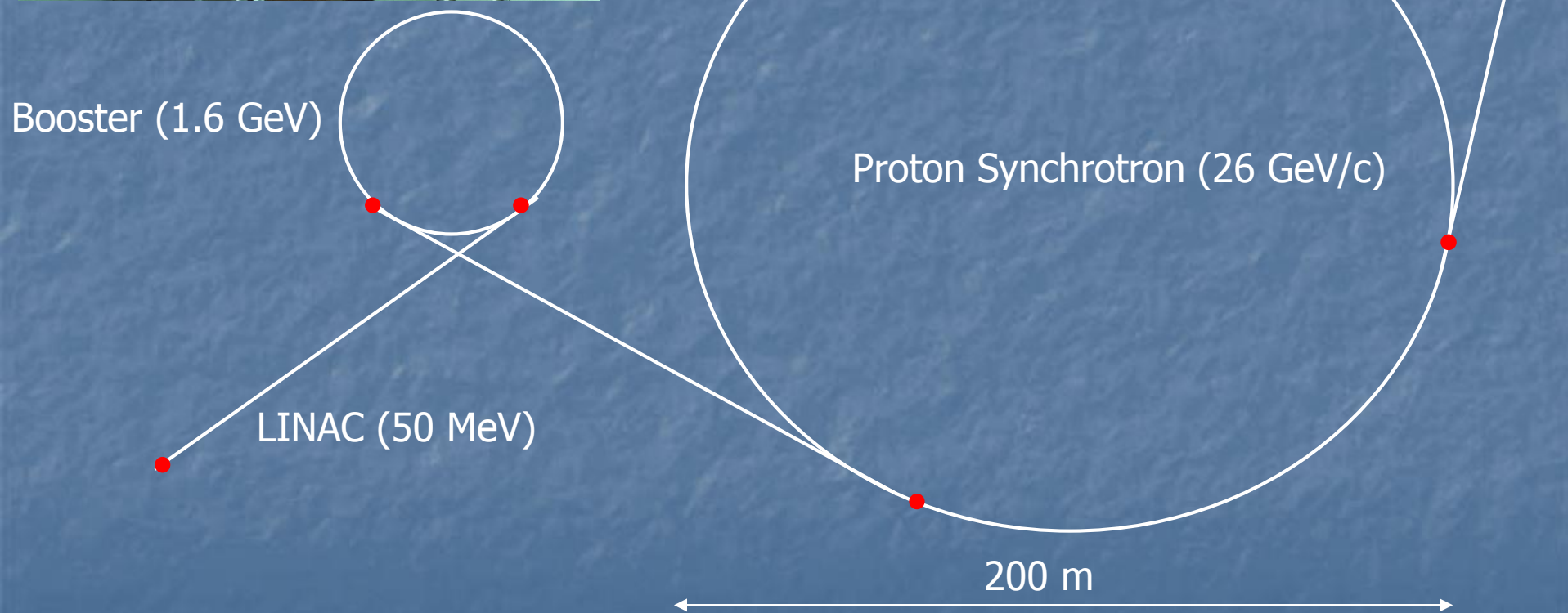
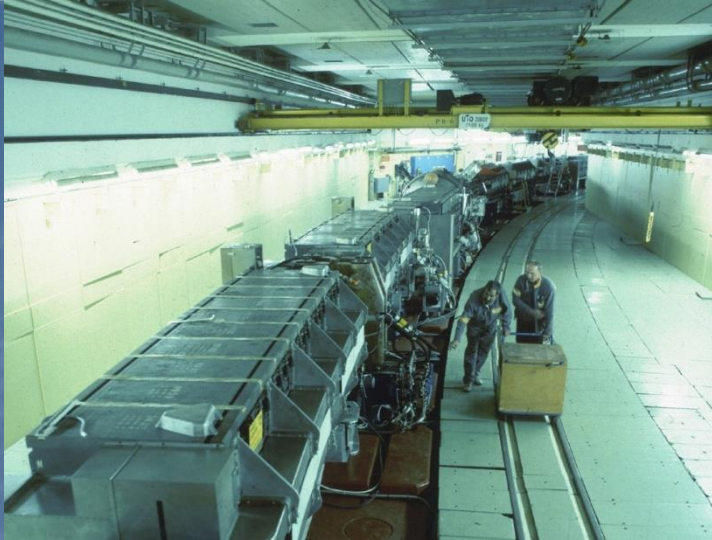
~ 2400 staff
~ 800 other paid personnel
> 11000 registered users from ~ 100 countries
~ 3500 registered contractors



- **21 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.
- **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

Accelerator chain at CERN (low-energy part)



Accelerators at CERN

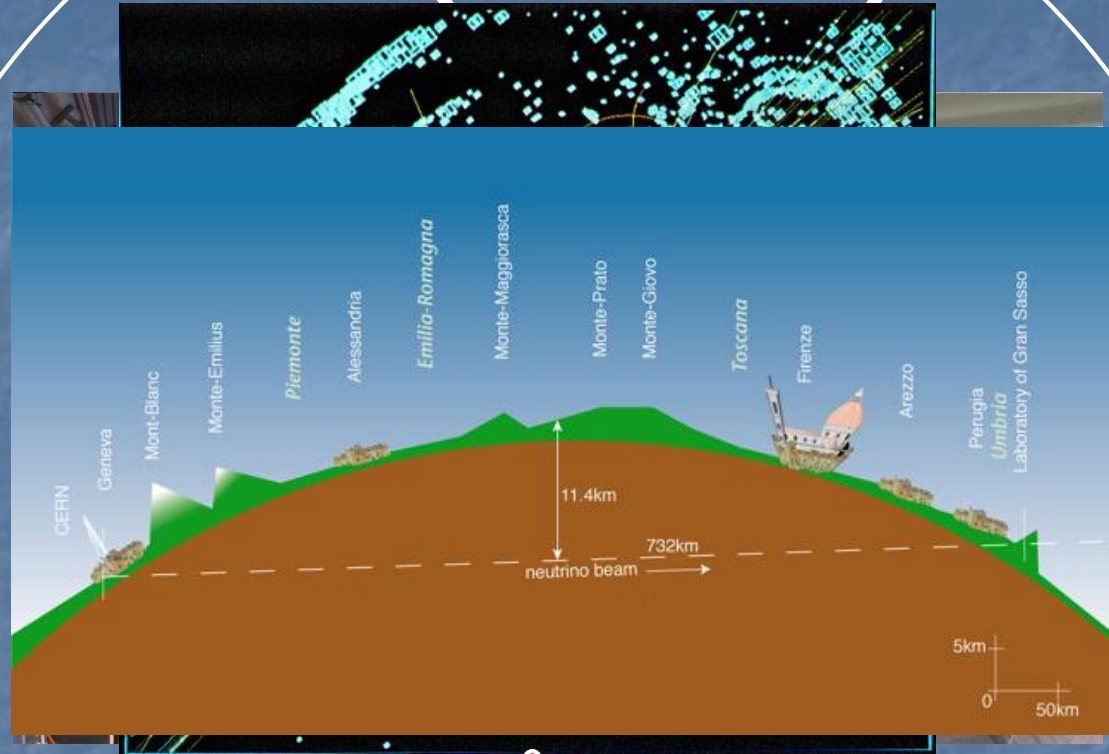
(high-energy part)

LHC (2 x 7 TeV)

SPS

Circumference: 7 km

Intensity per filling of the ring: $6E13$ protons



SPS beam

Fixed target experiments

LHC

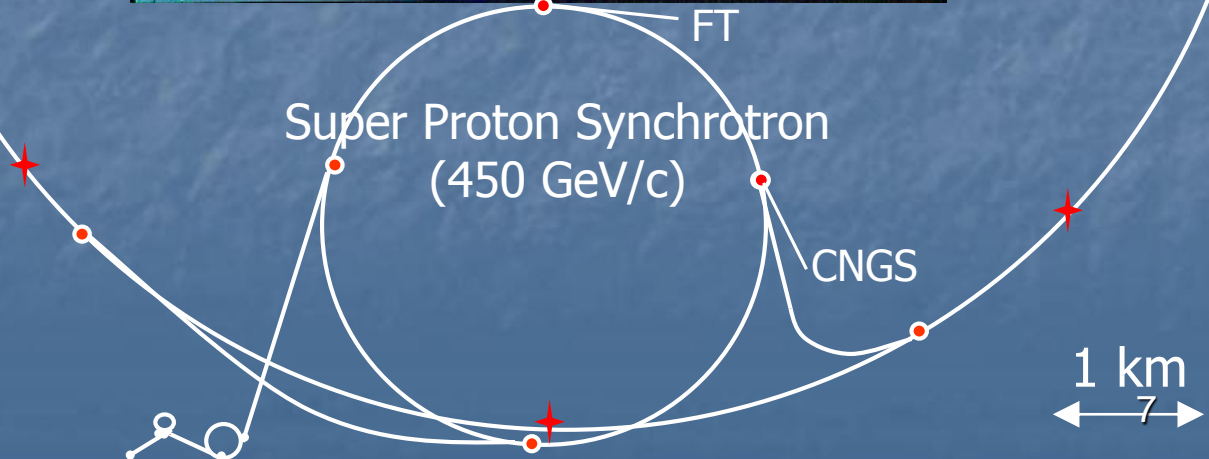
CNGS
now
AWAKE

Super Proton Synchrotron
(450 GeV/c)

FT

CNGS

1 km
7



Large Hadron Collider (LHC)

Particle type:
Protons

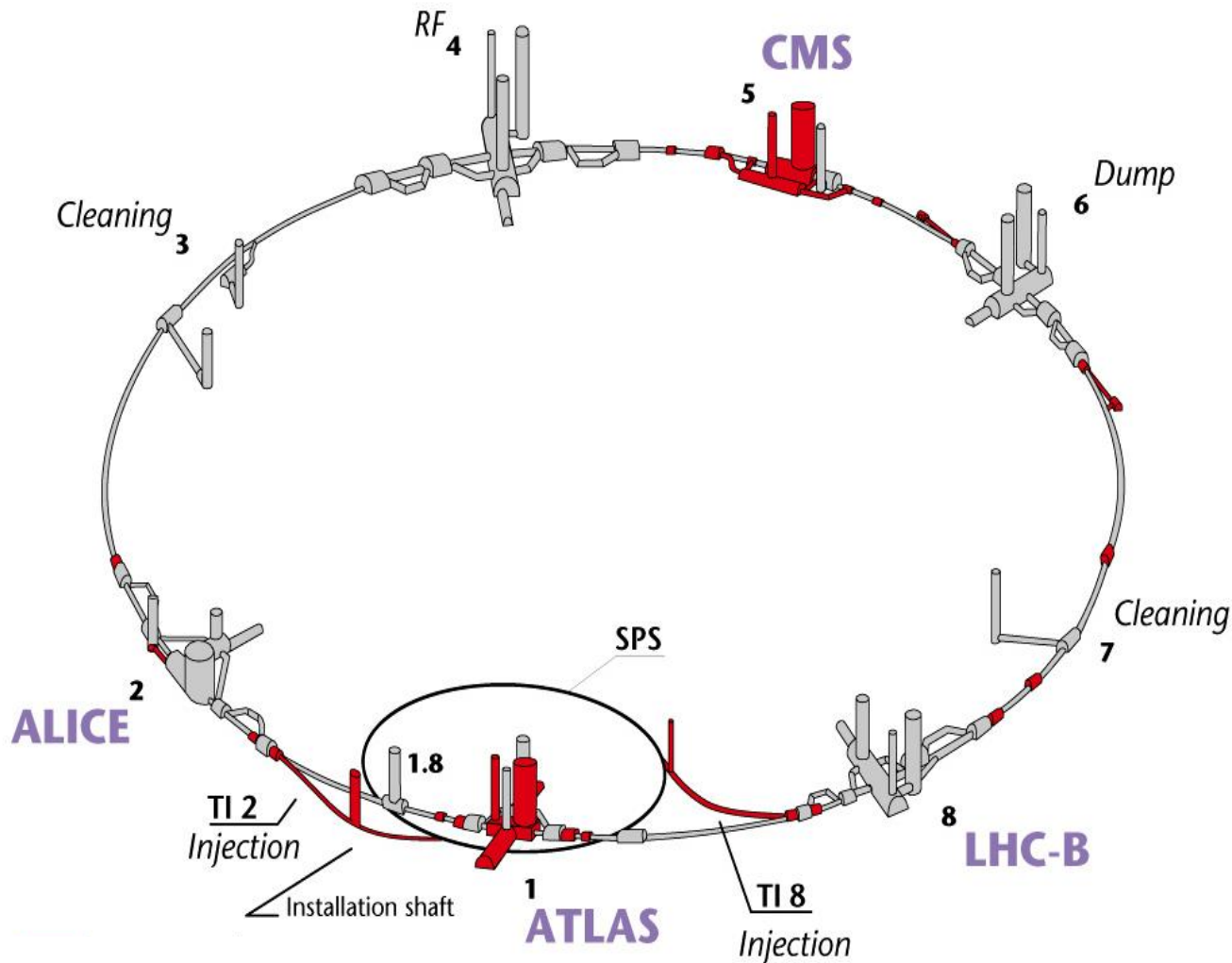
Beam energy:
7 TeV

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: ~ 10 μ g



CERN AC - HF267 - 04-07-1997

The same amount of energy as in one LHC beam is stored in:
An F16 airplane at supersonic speed (mach 1)



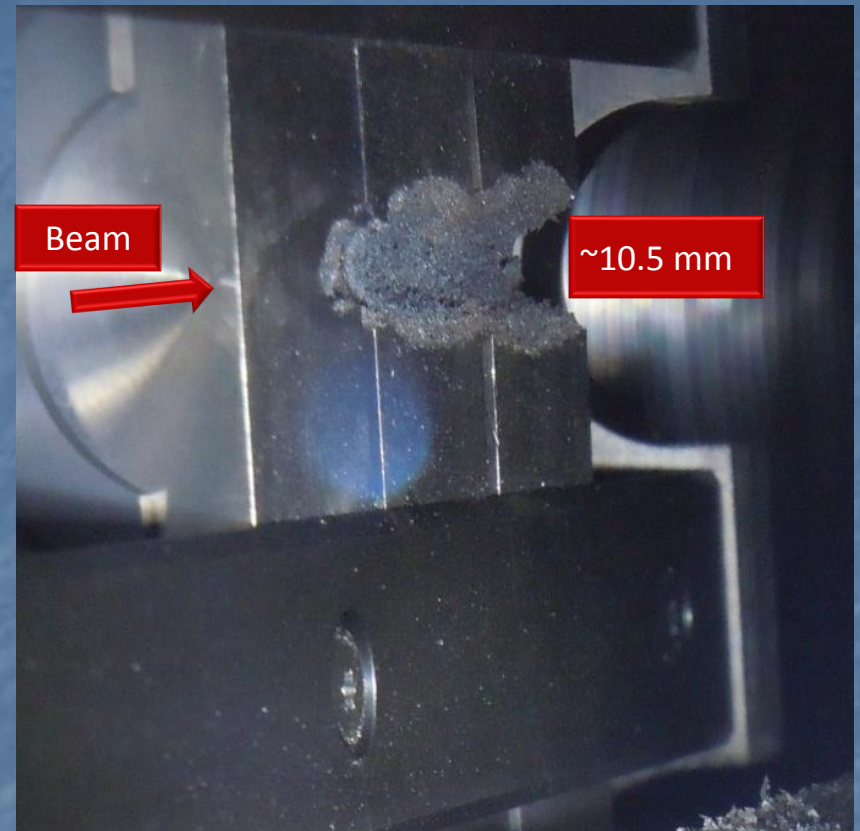
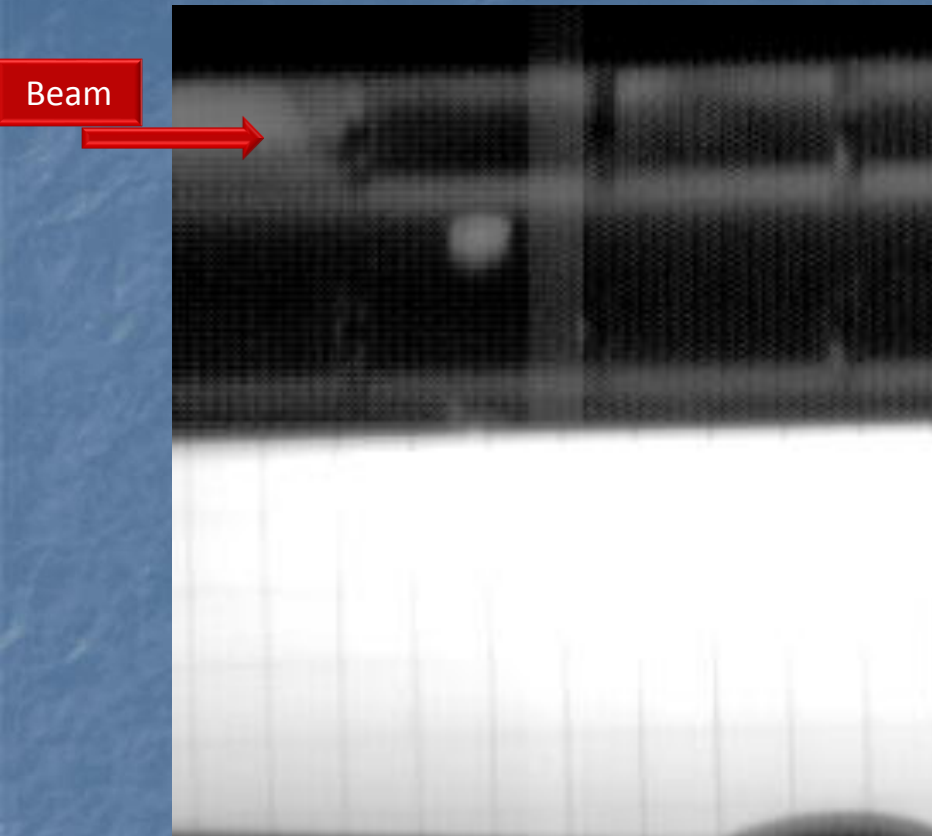
In an aircraft carrier at a speed of 12 km/h

CERN operates powerfull (and dangerous) beams: full impact of a typical high-energy beam on tungsten ($\sim 0.16\%$ 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?**



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.

$$D = \frac{dE_{dep}}{dm}$$

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

$$H_T = \sum_R w_R D_{T,R} \quad \text{Unit: Sievert (Sv)}$$

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

ICRP publication 103

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

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

$$E = \sum_T w_T H_T = \sum_T w_T \sum_R w_R D_{T,R} \quad \text{Unit: Sievert (Sv)}$$

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		

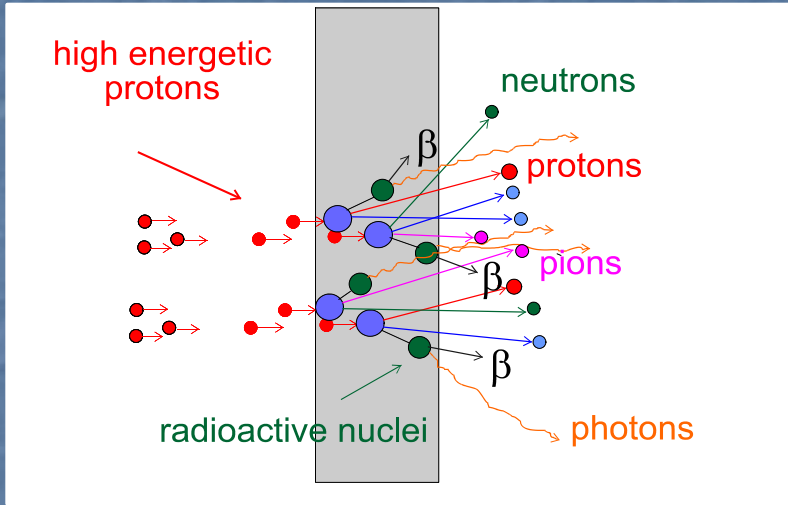
Radiation Fields around High Energy Accelerators

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

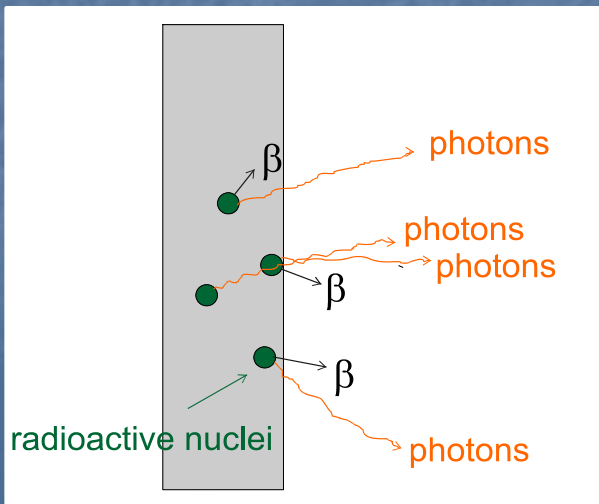


High pressure ionization chamber

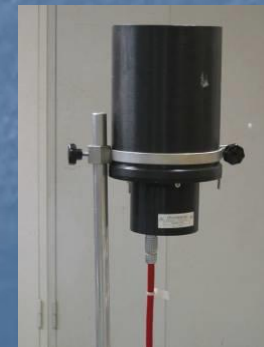


REM counter

- Ionizing Radiation due to induced radioactivity – beam off



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

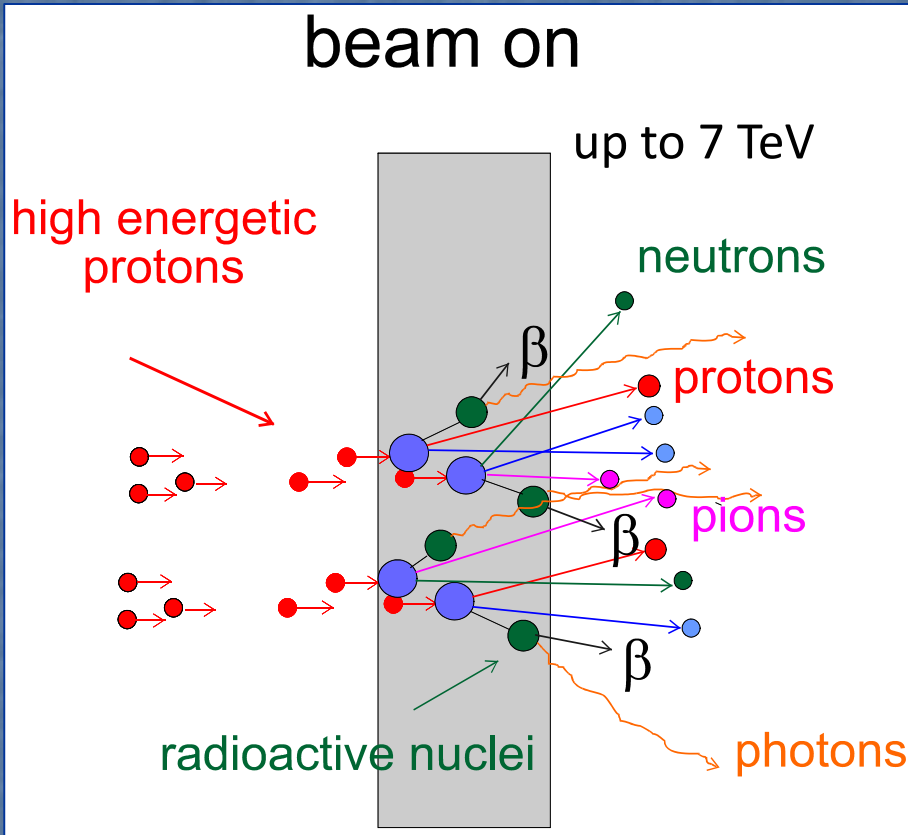


Air filled ionization chamber

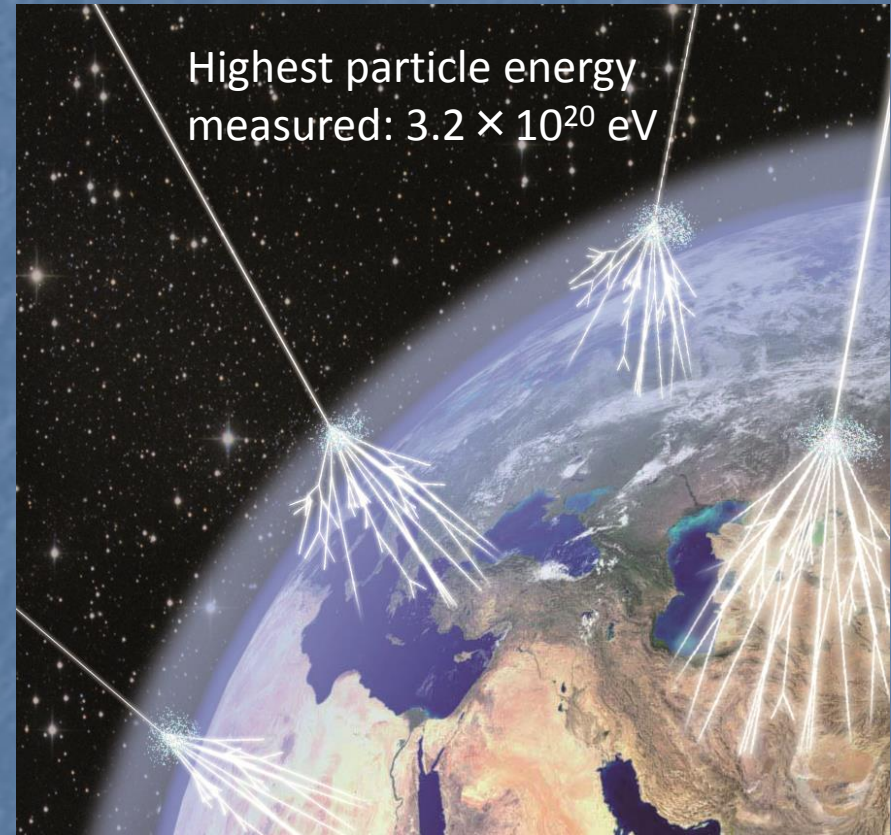


Handheld devices

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

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

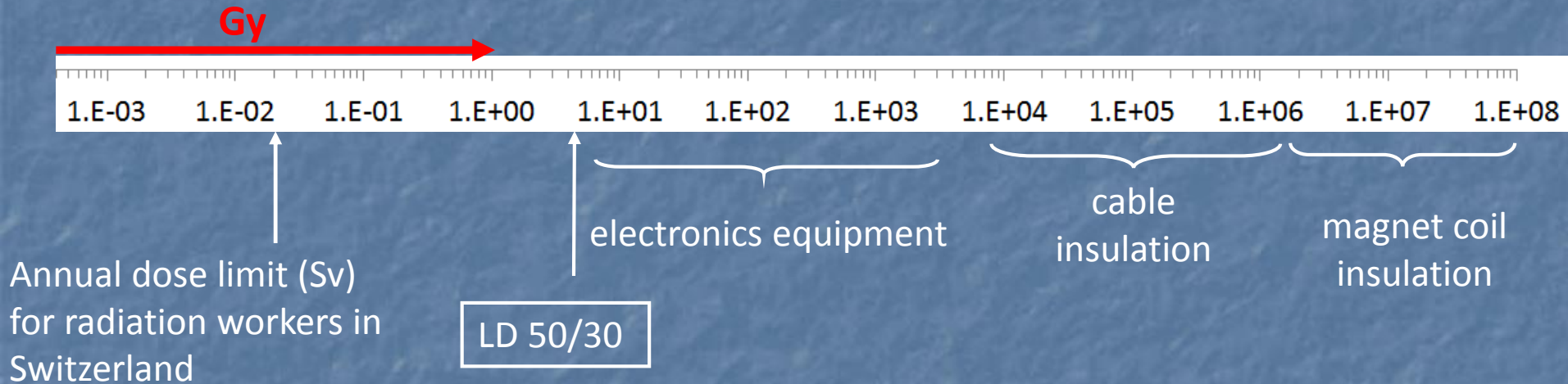
Radiation triggered failure of electronics

Aging of organic materials like insulations

Activation of material

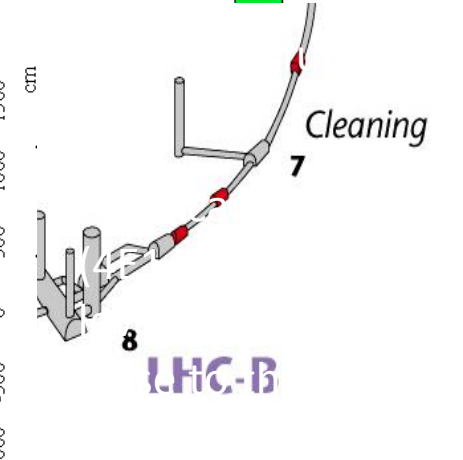
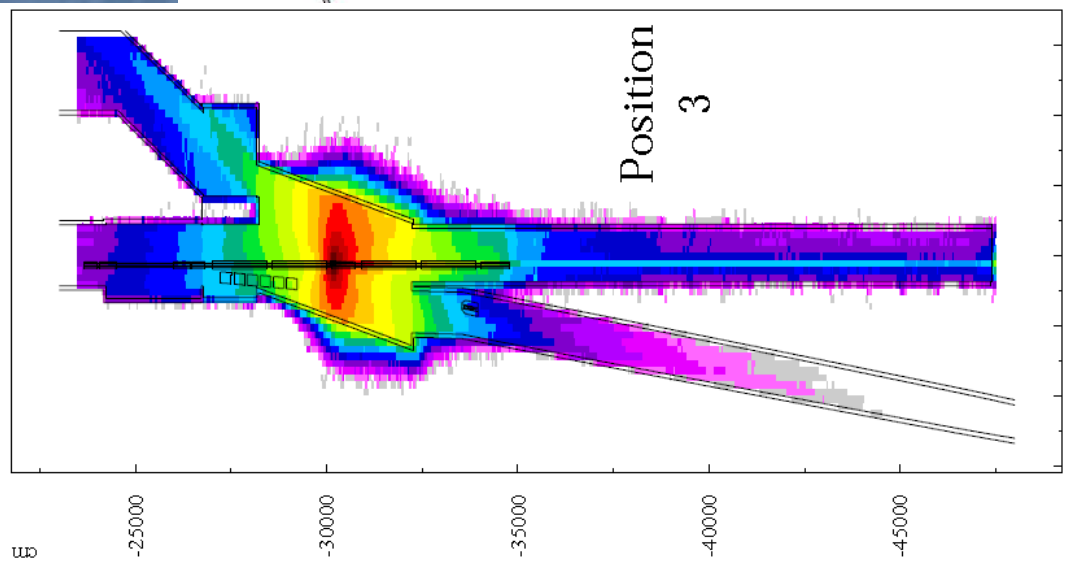
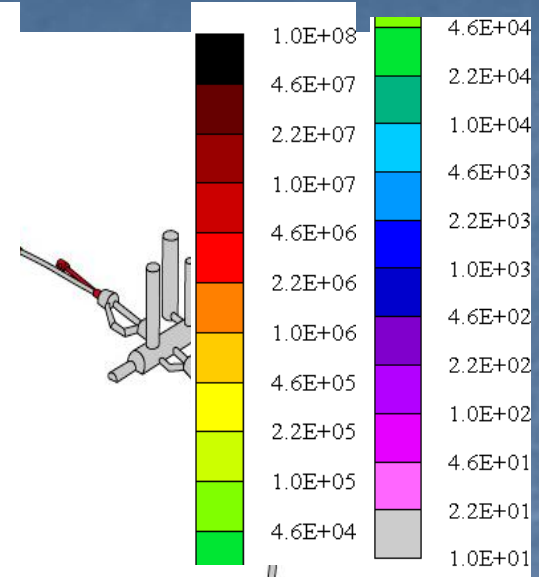
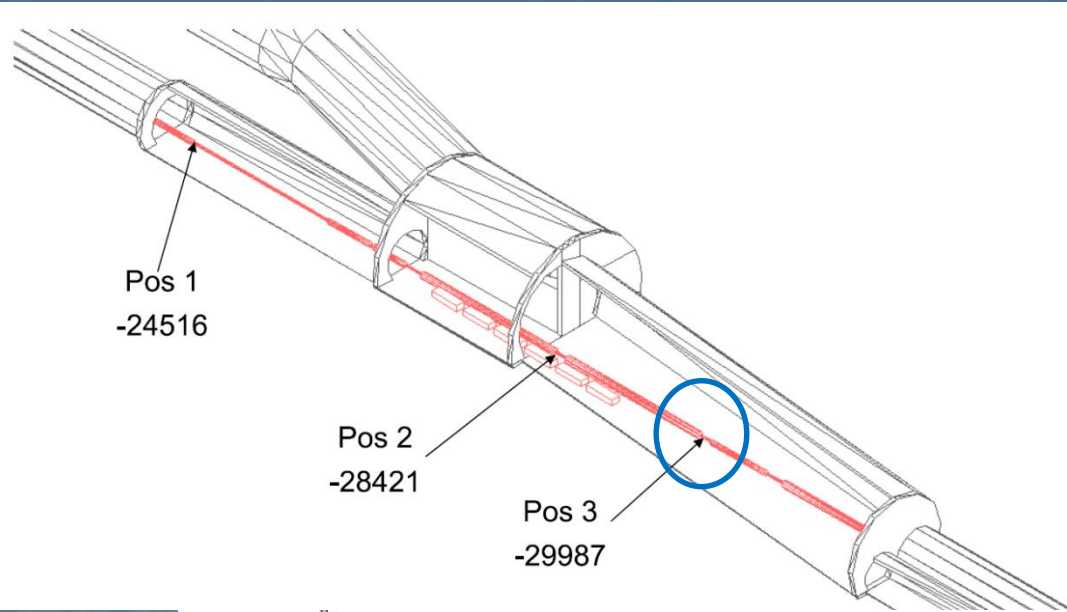
Radiation impact

- Relation between absorbed dose and damage caused by radiation



Dose to people

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




loss

beam loss (7 TeV) reaches thousands of Sv.

→ strong shielding required to significantly reduce dose

Main aspects of radiation field attenuation in accelerator environments

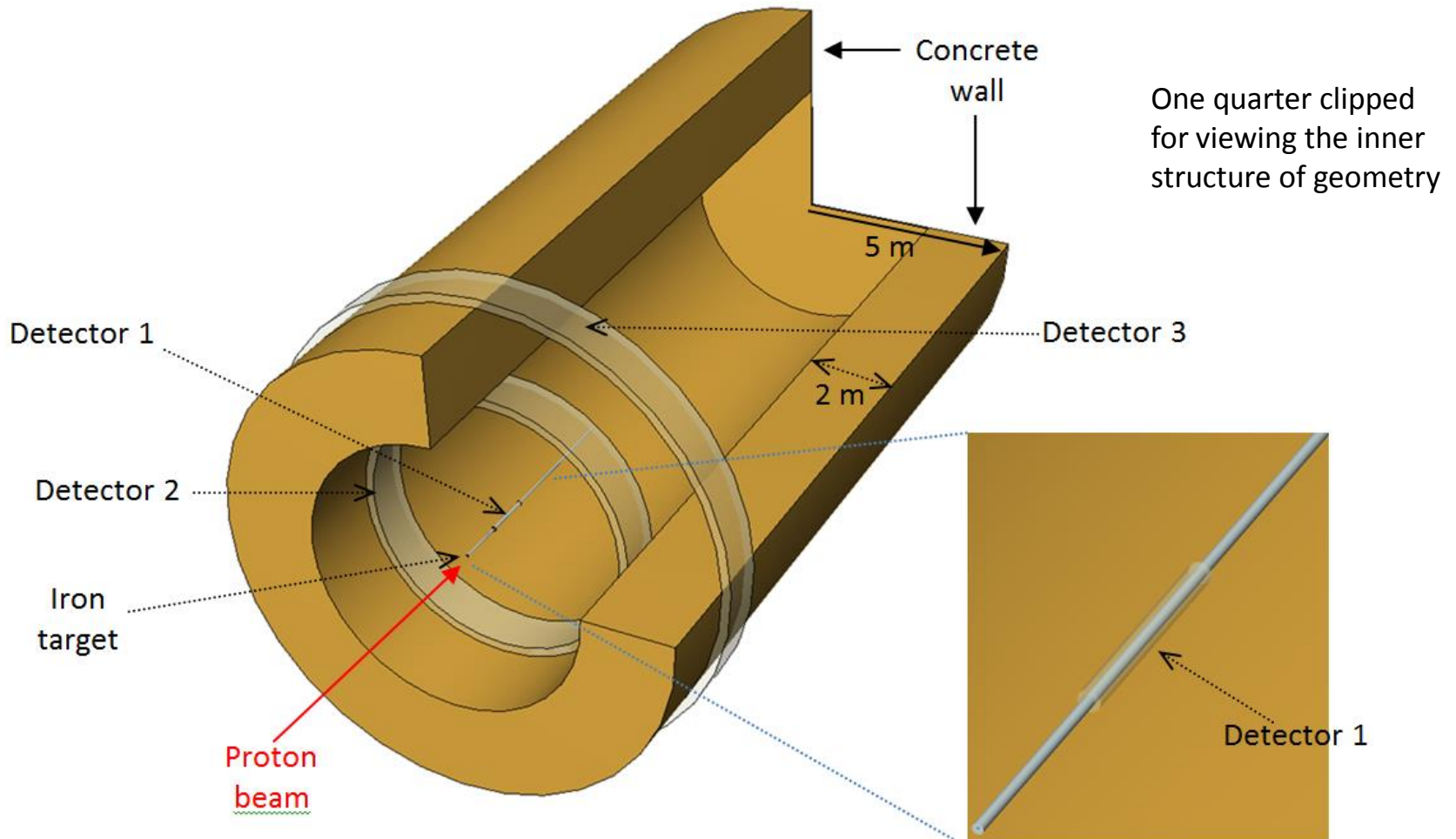


Lateral to beam impact
point

Downstream to beam impact
point

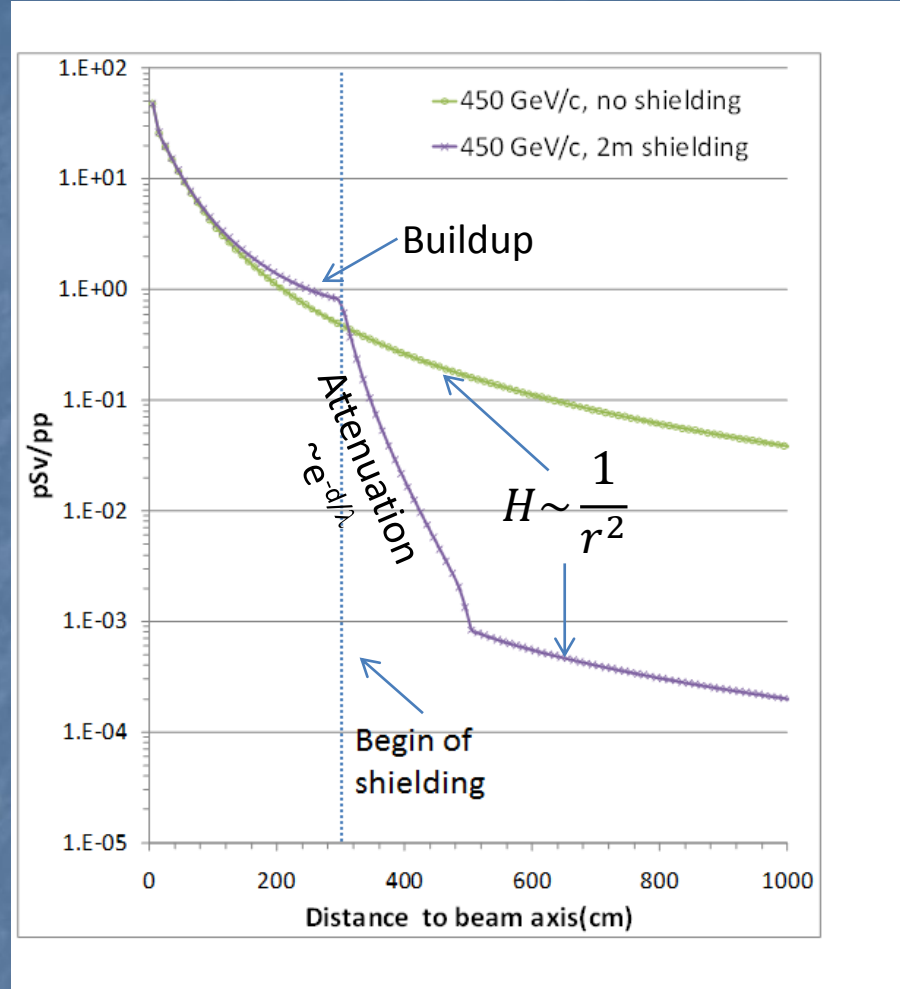
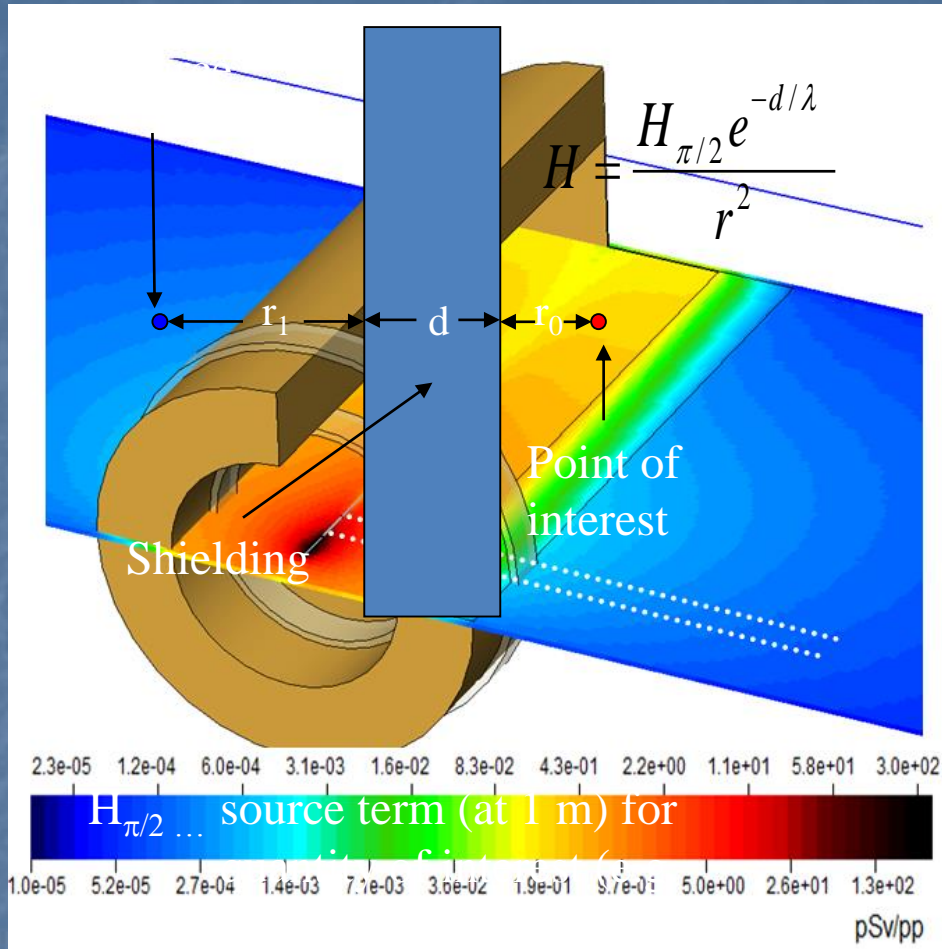
Radiation lateral to the beam impact point

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

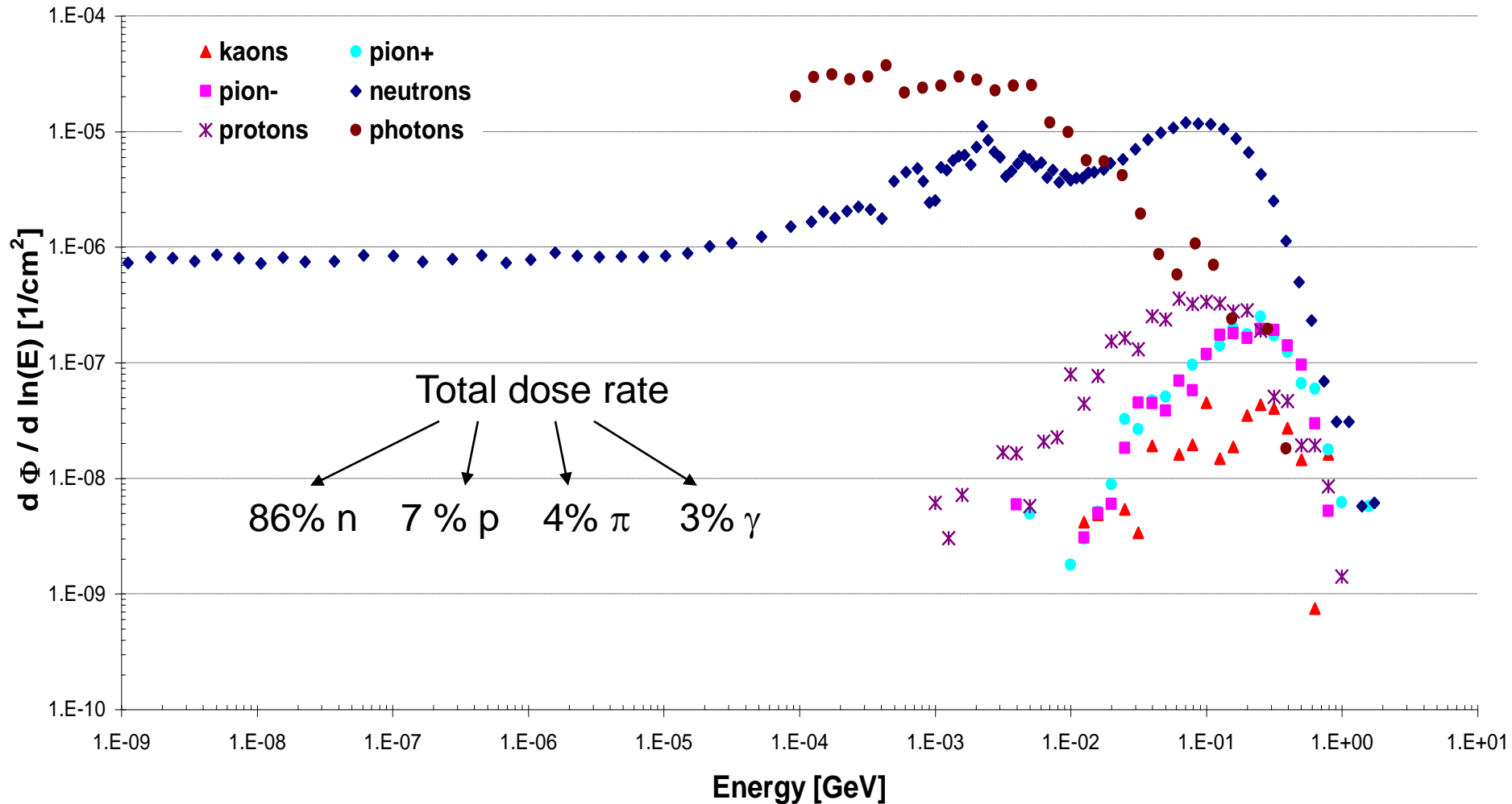
Point source/line of sight model



$$r = r_0 + d + r_1 \quad \text{in m}$$

$\lambda \dots$ hadronic interaction length

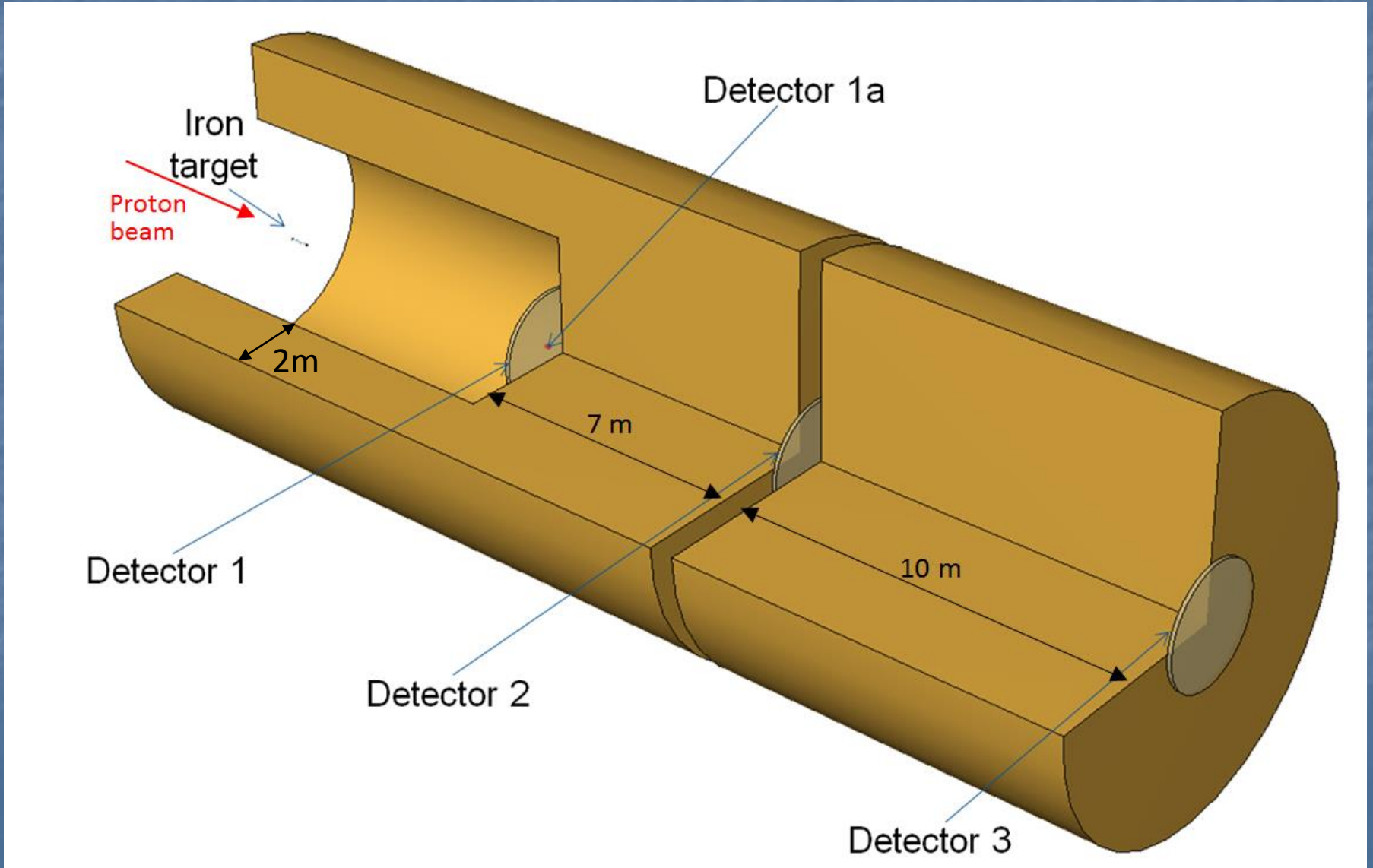
Typical particle fluence spectra at areas located behind lateral thick concrete shielding



Radiation downstream to the beam impact point

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

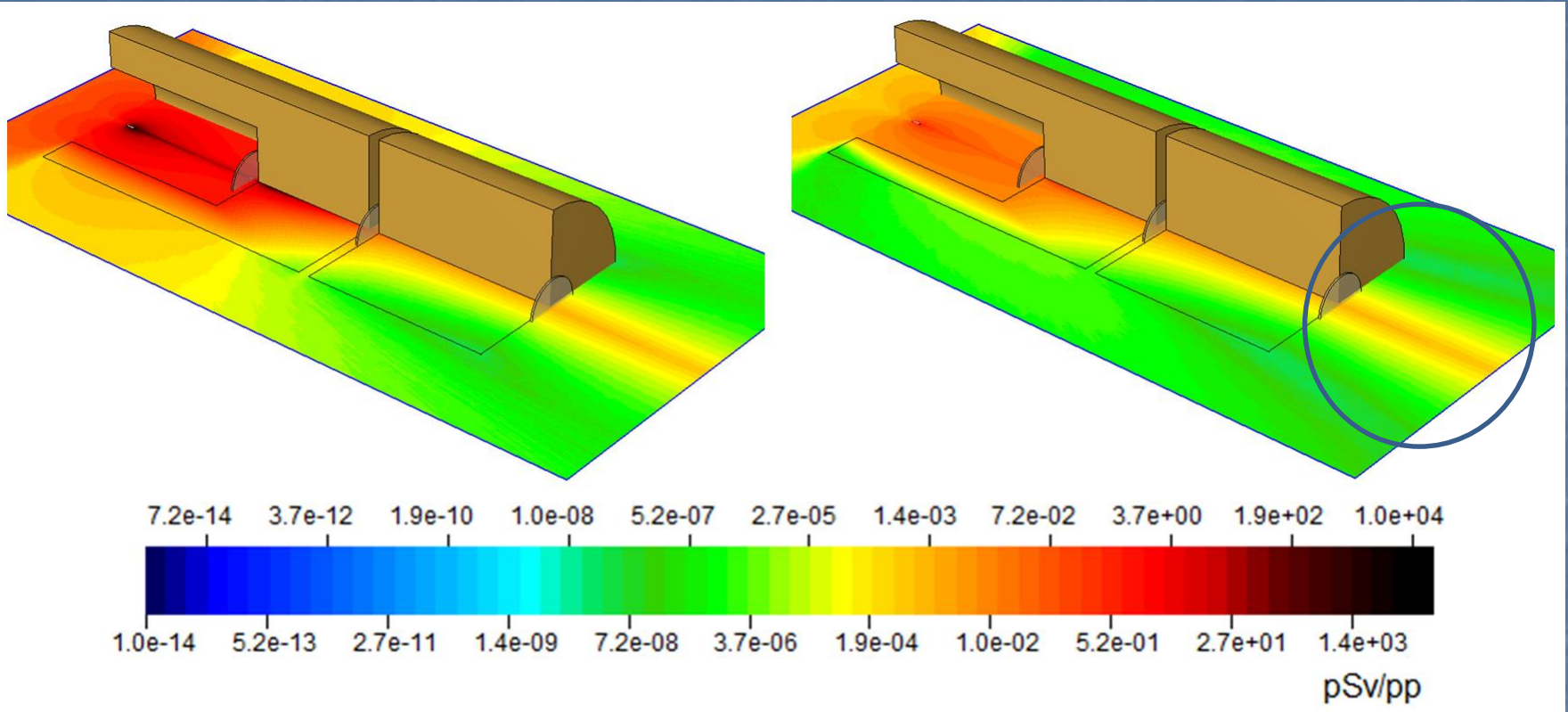
450 GeV proton beam on 50 cm long copper target



Dose simulation results

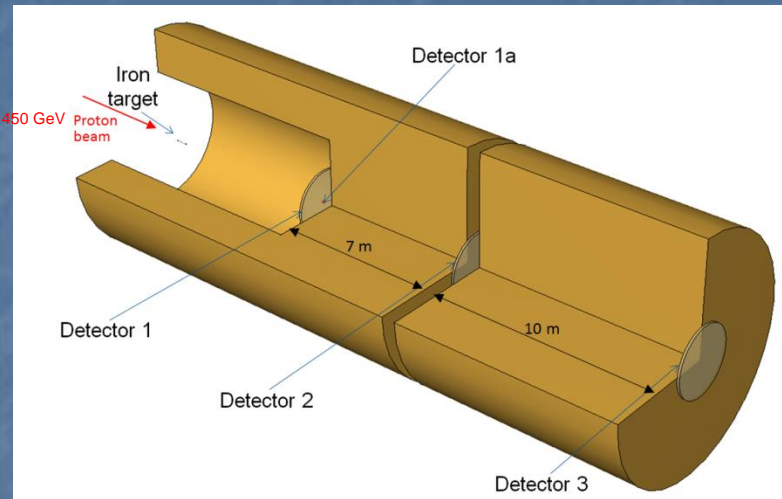
Dose of all particles

Dose by muons only



Muons strongly dominate the dose seen downstream the heavy shielding

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

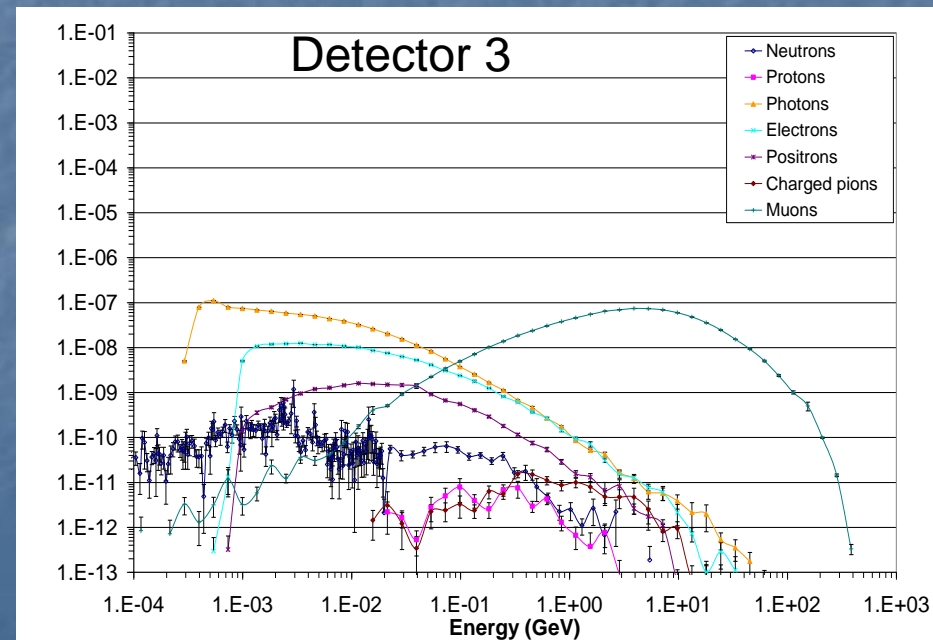
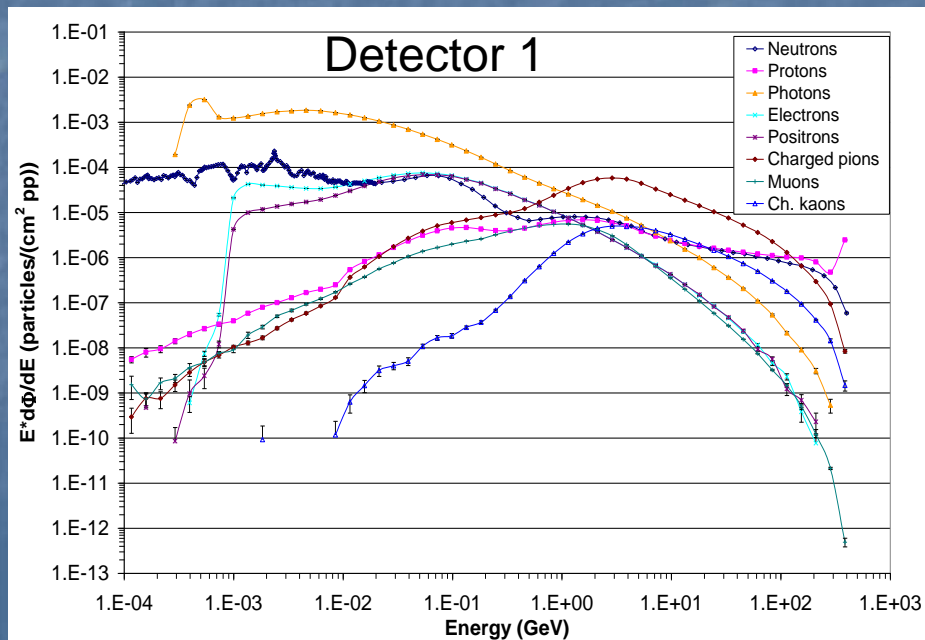


Strong domination of muons downstream the shielding

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

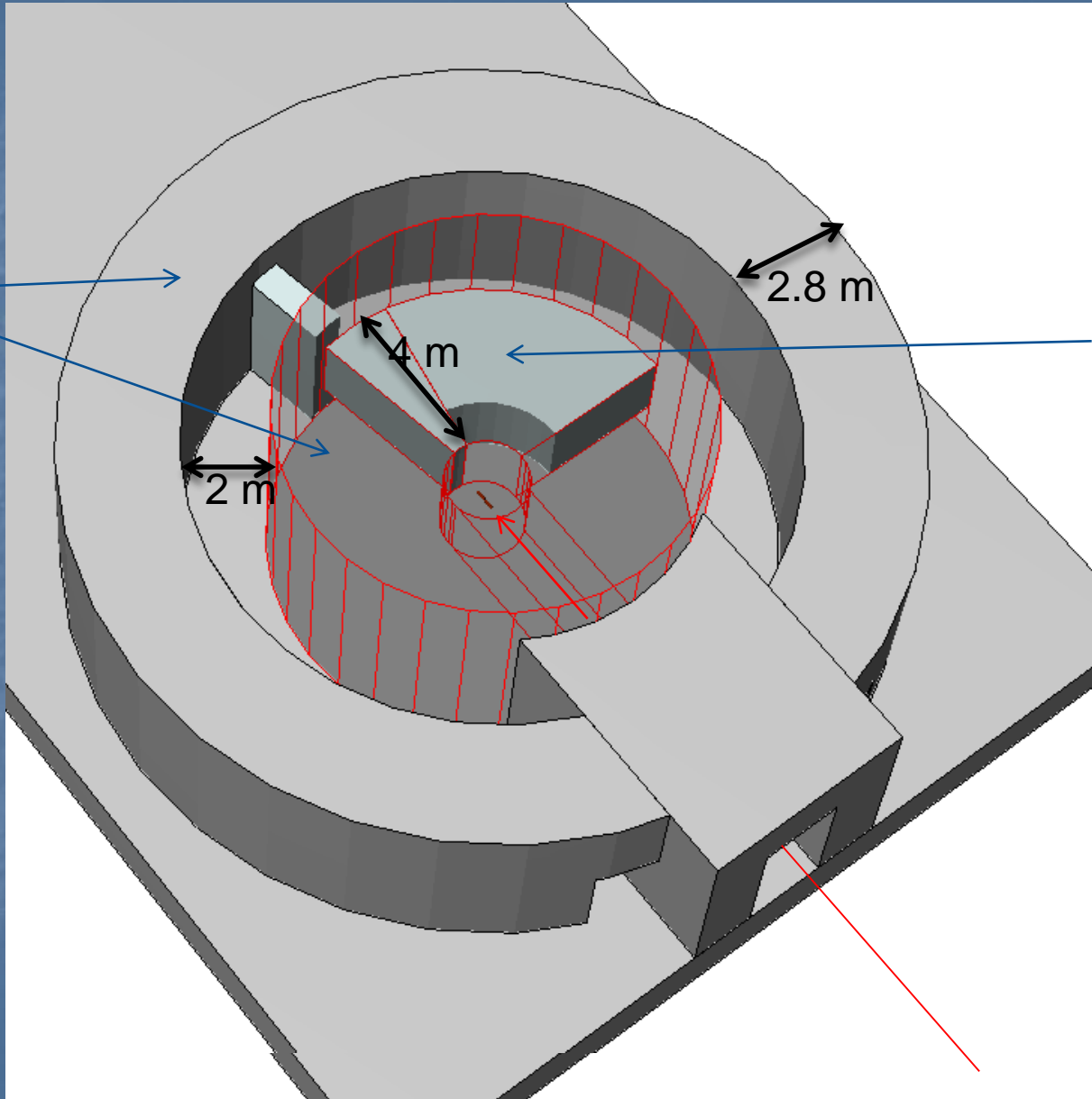
High-energy muons lose ~ 1 GeV when traveling through 1.8 m of concrete or 70 cm of iron.

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



Conceptual design of an irradiation facility

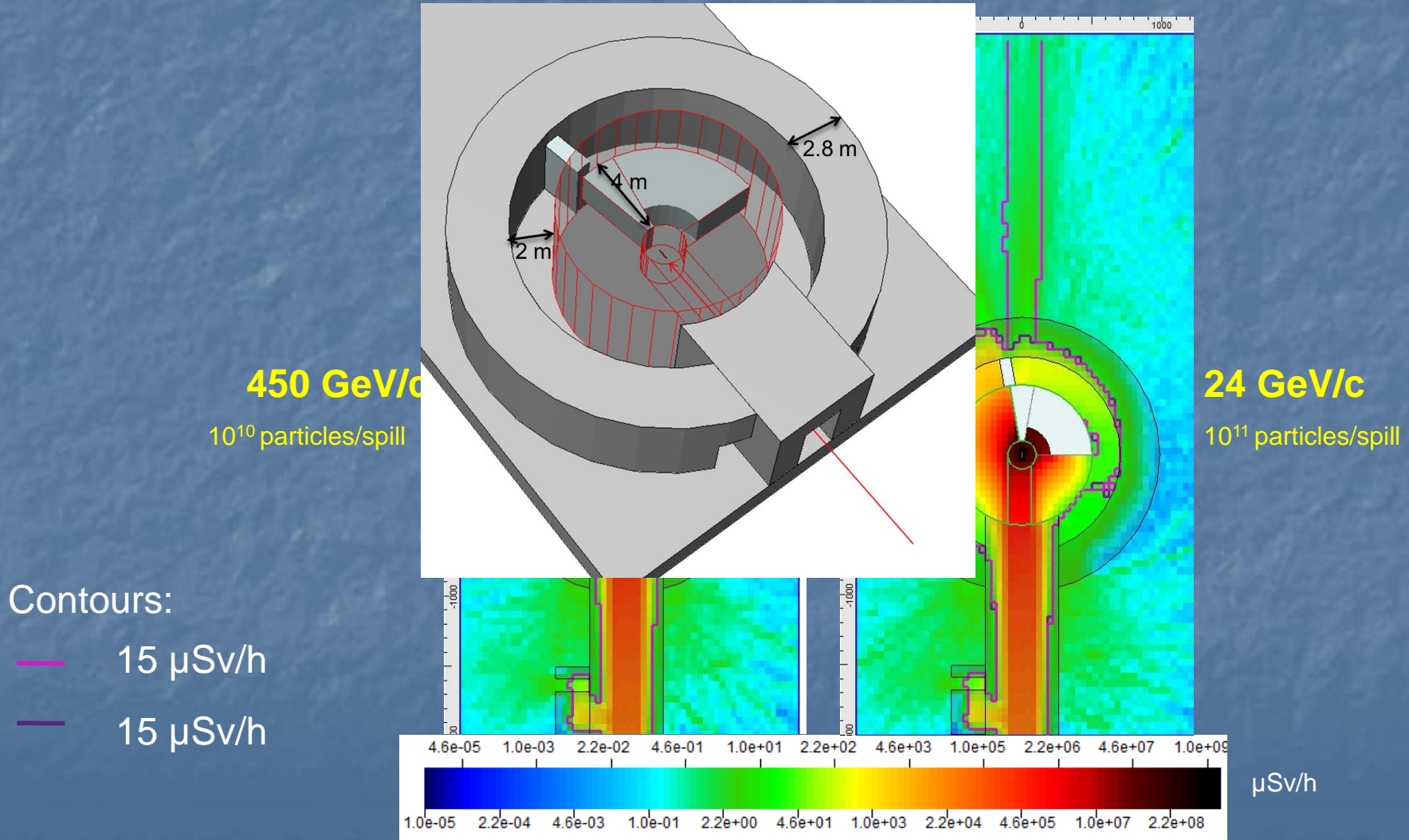
Concrete shielding



Iron shielding and dump

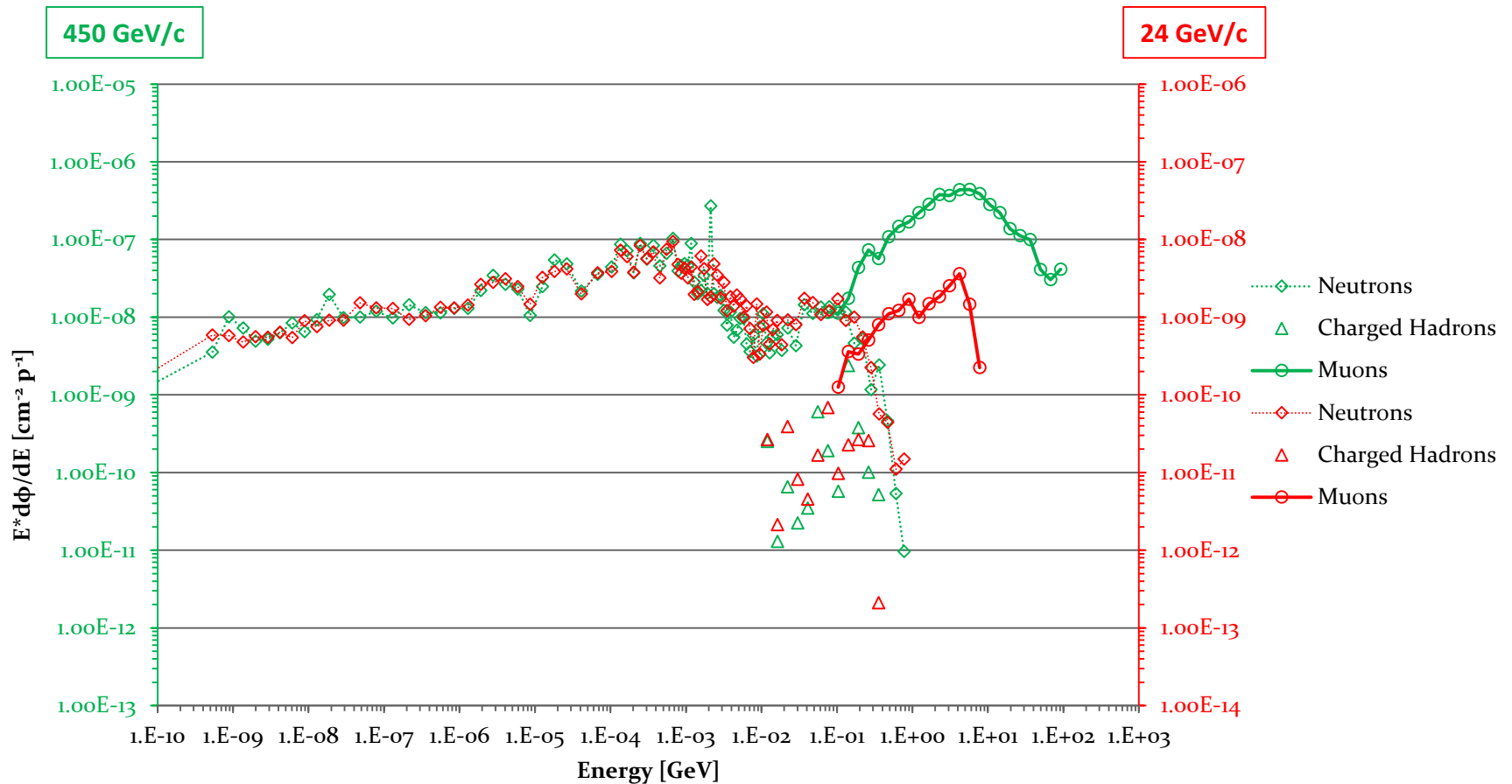
Dose rate mapping at beam height Comparison: 450 GeV/c vs 24 GeV/c

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



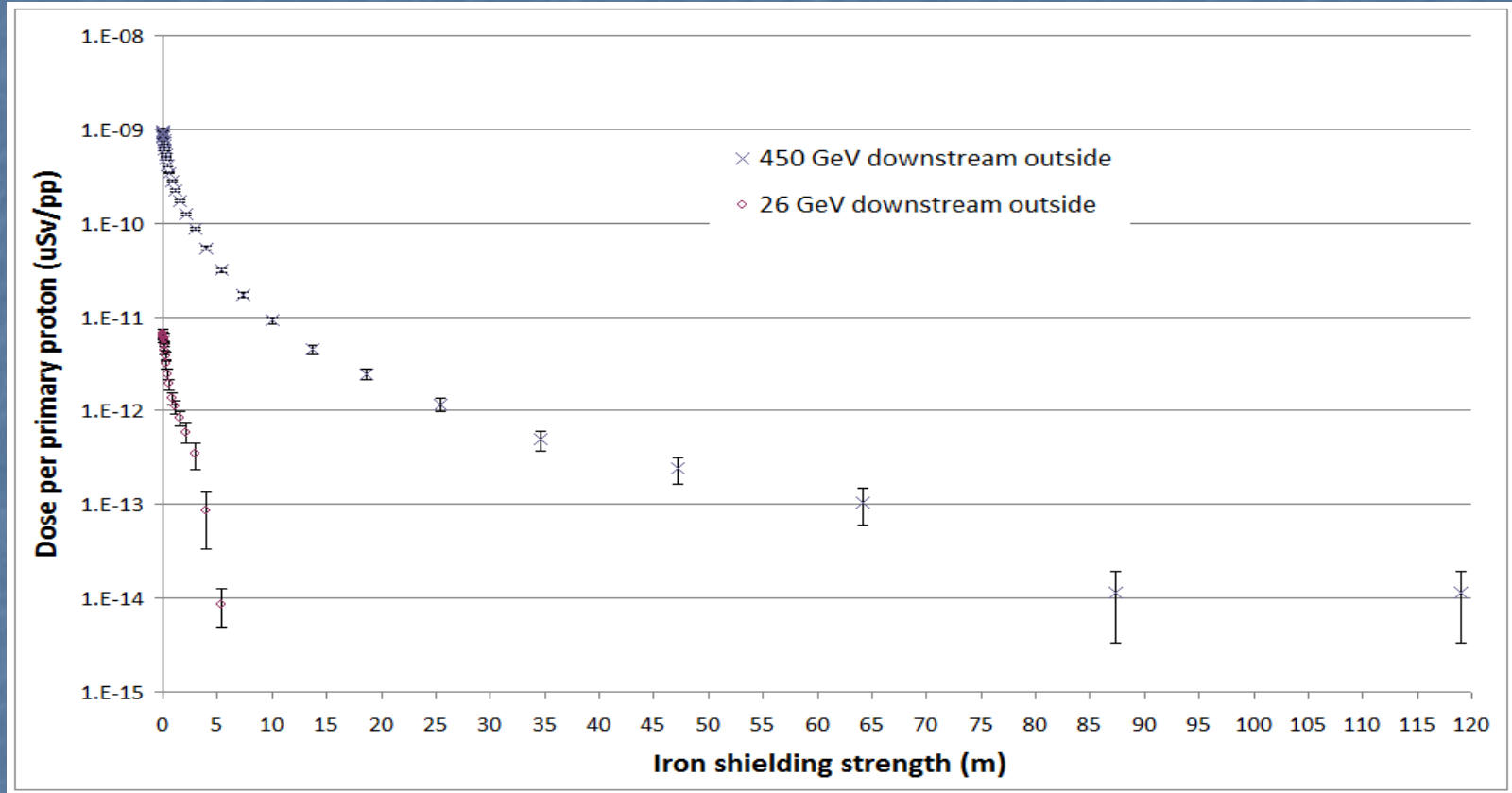
Courtesy of E. Feldbaumer

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



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

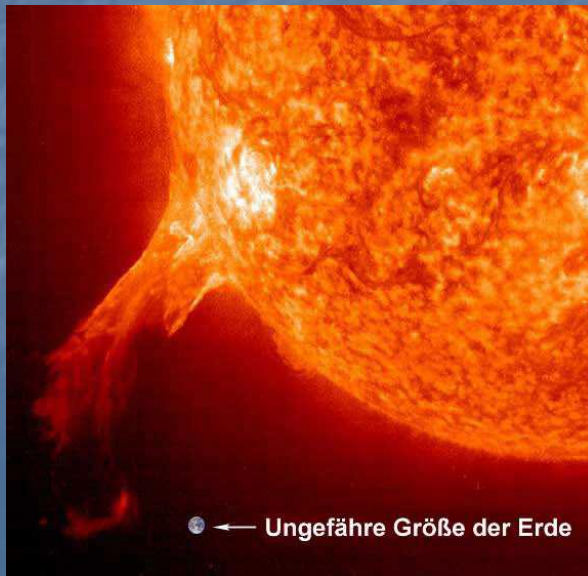
Contents:

- 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:

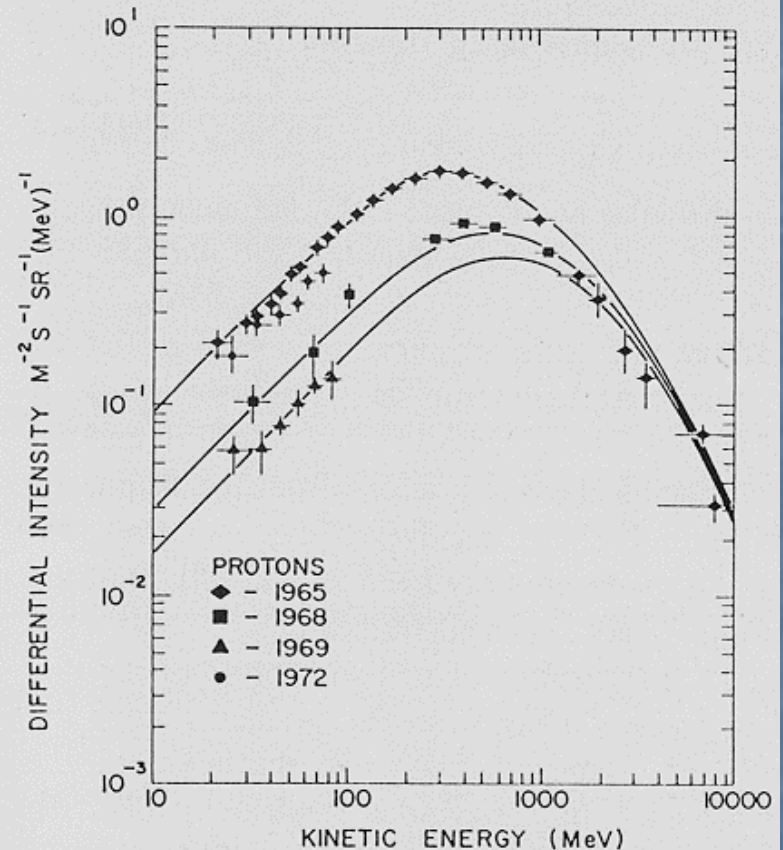
87% protons 12 % α -particles 1% heavy nuclei

Almost no anti-matter detected

Spectrum:

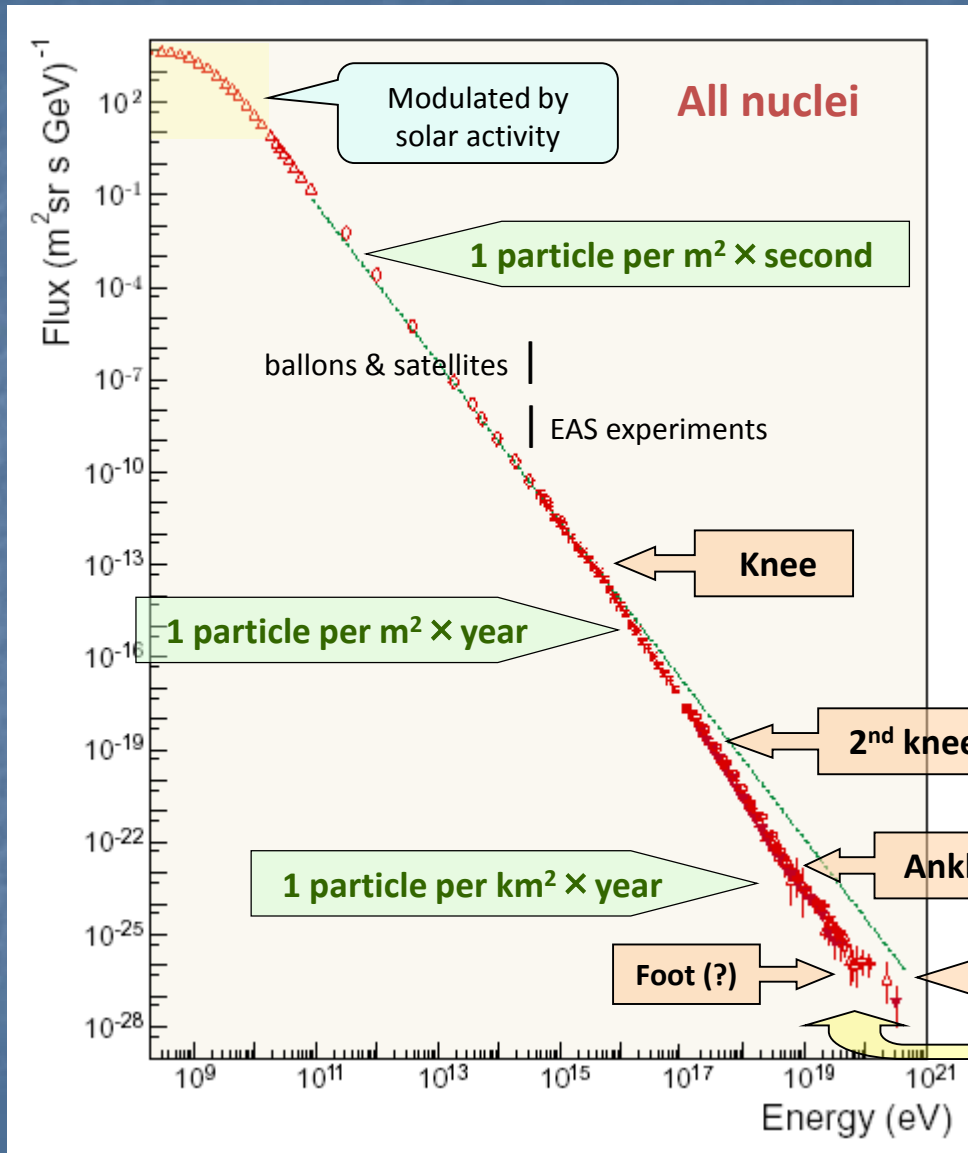
- Main part of the GCR particles have an energy below 10 GeV
- Interaction with solar magnetic field modulate the particle's energy
- → GCR fluence up to 10 GeV shows a dependence on the solar activity
- There is a high-energy component of the GCR spectrum, reaching energies higher than 10^{20} eV.

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

$$\alpha = 2.7 \text{ for } E < 3 \times 10^{15} \text{ eV}$$

and

$$\alpha = 3 \text{ for } E > 3 \times 10^{15} \text{ eV}$$

Highest energy measured:

$$3.2 \times 10^{20} \text{ eV (Fly's Eye detector)}$$

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

Energy of particle : $3.2 \times 10^{20} \text{ eV} = 51 \text{ J}$




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

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

we calculate
Lorentz factor γ :

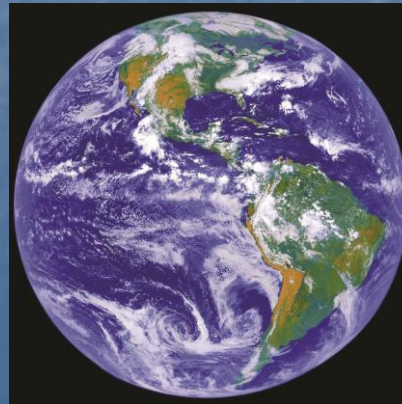
$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}}$$

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



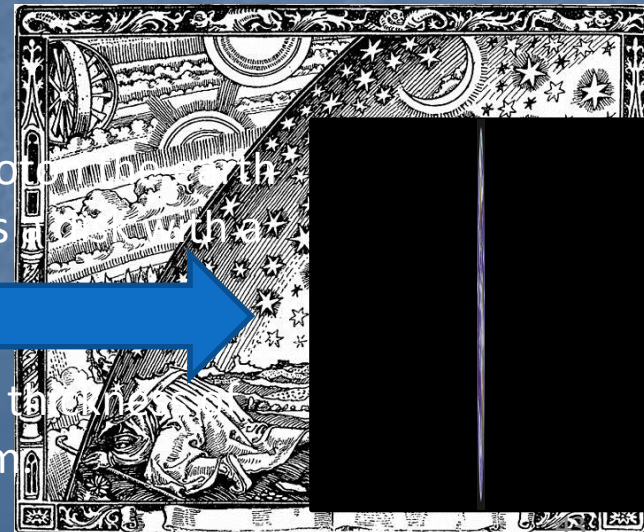
Length contraction:

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



For the proton the Earth
appears as

maximum thickness
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:

$$f = f_0 \sqrt{\frac{1 + \beta}{1 - \beta}} \quad \text{With: } \beta = v/c \dots (\beta (3.2 \times 10^{20} \text{ eV}) = (1 - 4.8 \times 10^{-24}))$$

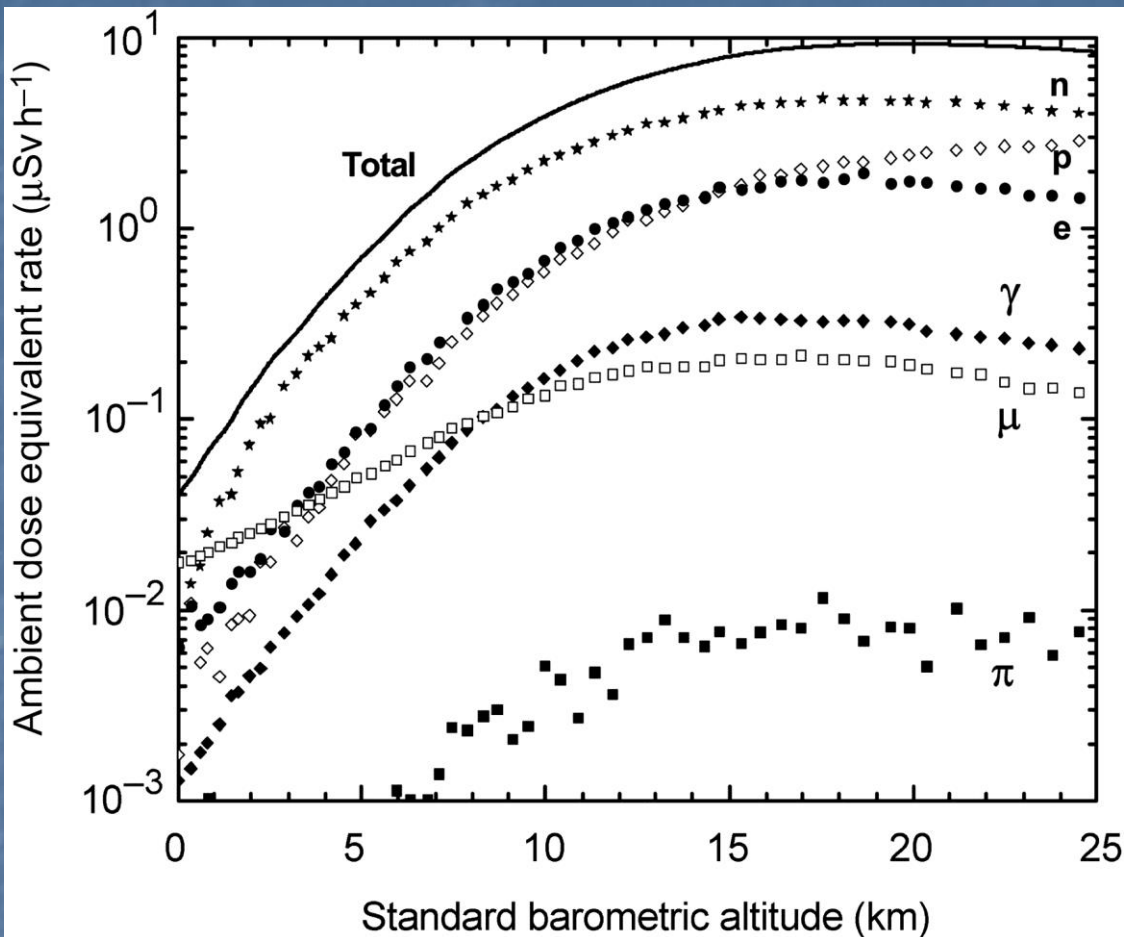
Typical energy of microwave photon: $1.1 \times 10^{-3} \text{ eV}$.

$$E = E_0 \sqrt{\frac{1 + \beta}{1 - \beta}} = 1.1 \times 10^{-3} \times 6.4 \times 10^{11} = 7.04 \times 10^8 \text{ eV} \rightarrow \text{Proton should interact with microwave photons producing pions.}$$

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**.

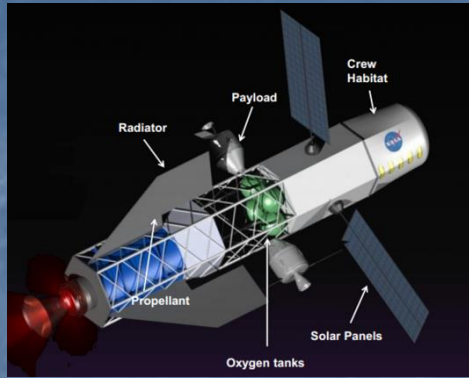
Dose to space- and aircraft crews



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

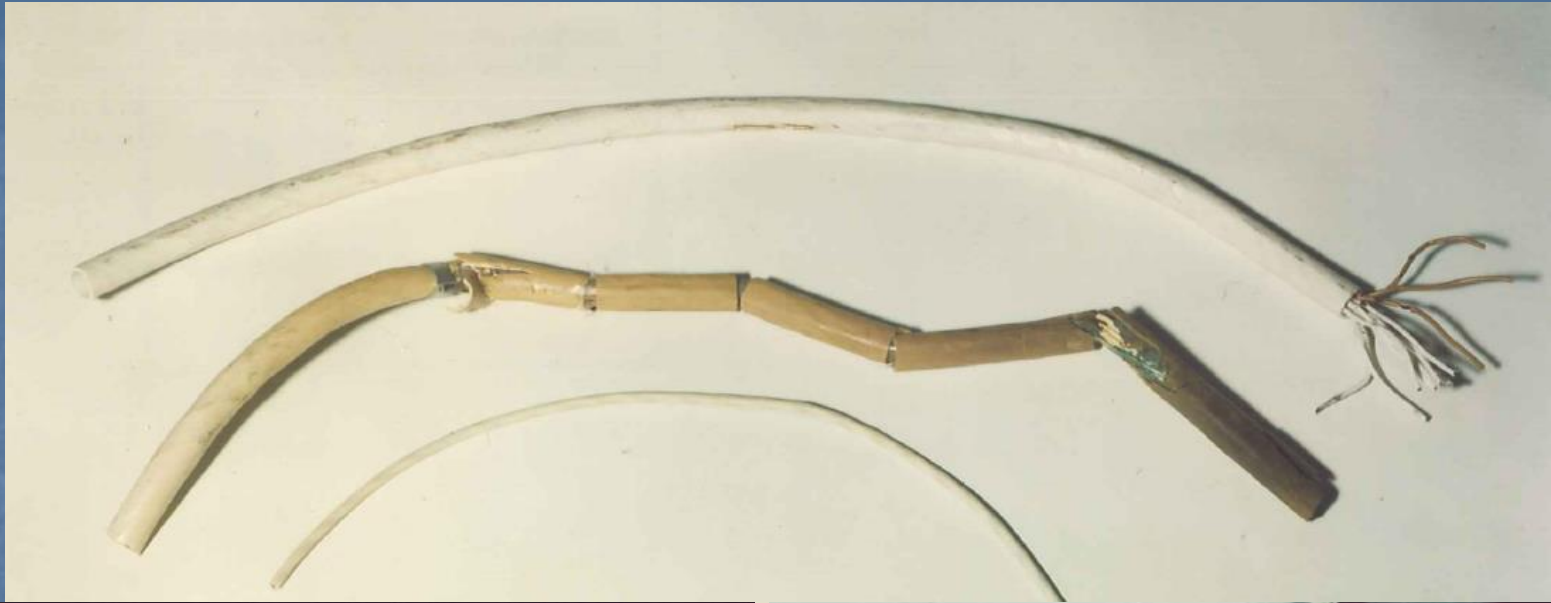
Examples for radiation damage

Resin used for magnet coil insulation

0 5×10^6 10^7 2.5×10^7 5×10^7 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.

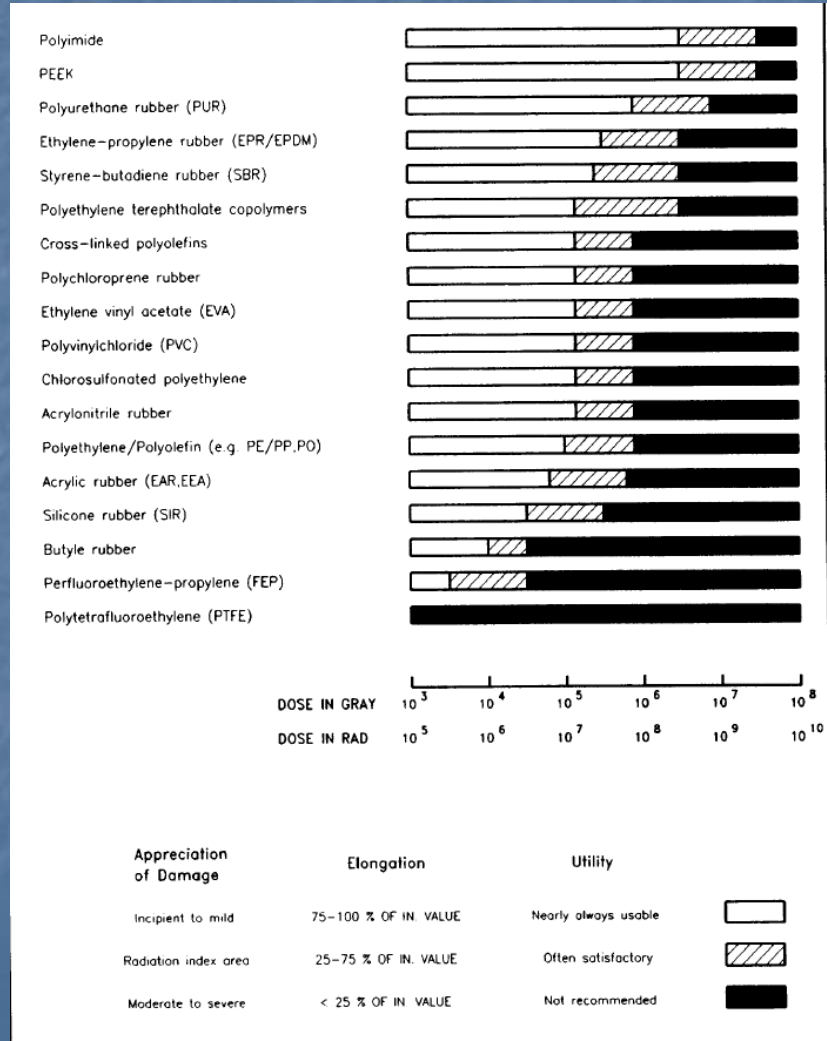


In the last millennium many radiation hardness tests were carried out and documented at CERN.



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

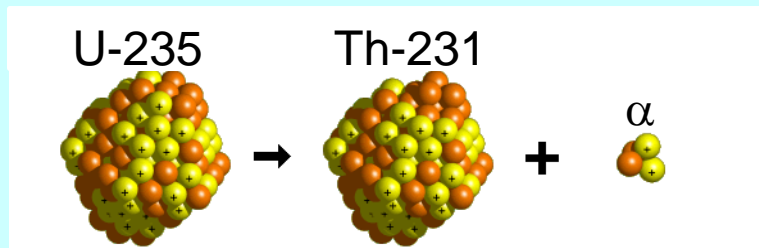
What is radioactivity?

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

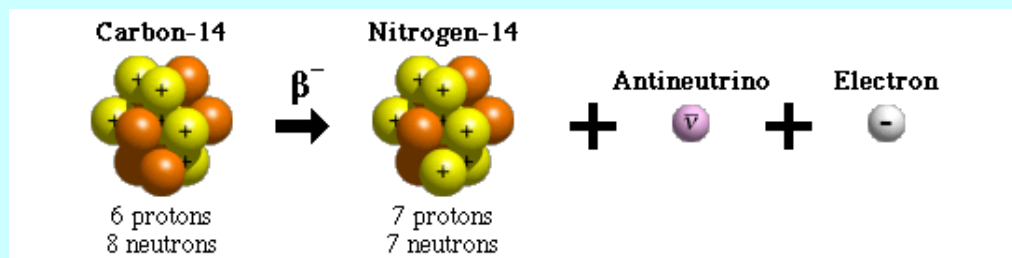
α -decay: Emission of an alpha particle, a part of the nucleus consisting of 2 protons and 2 neutrons. $\rightarrow A_{\text{new}} = A_{\text{old}} - 4$ and $Z_{\text{new}} = Z_{\text{old}} - 2$

Example:



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

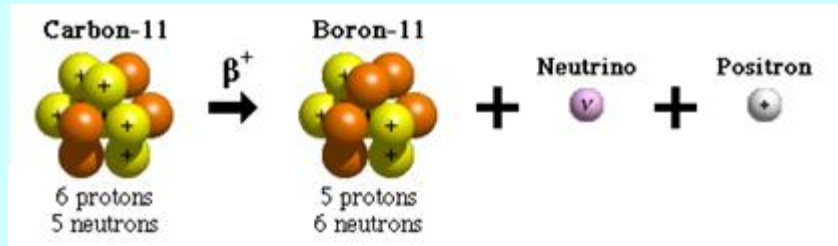
Example:



Modes of radioactive decay

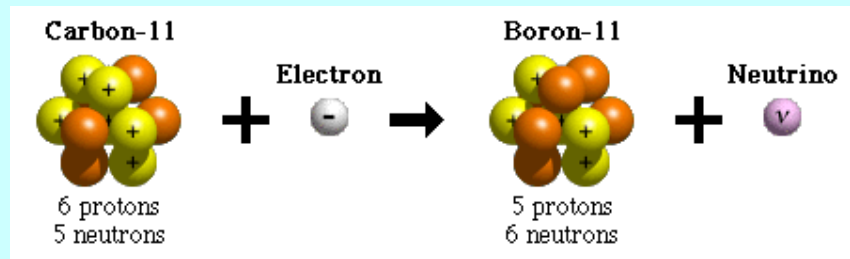
β^+ -decay: A proton in the nucleus is transformed into a neutron via the emission of a positron and an electron-neutrino $\rightarrow A_{\text{new}}=A_{\text{old}}$ and $Z_{\text{new}}=Z_{\text{old}}-1$

Example:



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

Example:



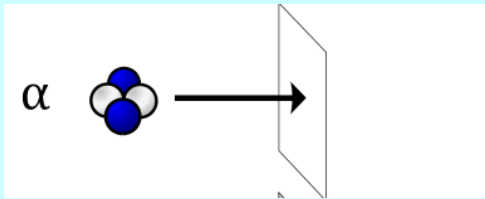
Alternative decay of C-11

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.

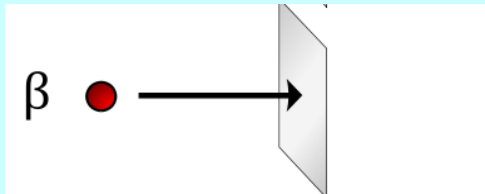
Radiation types emitted by radioactivity

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

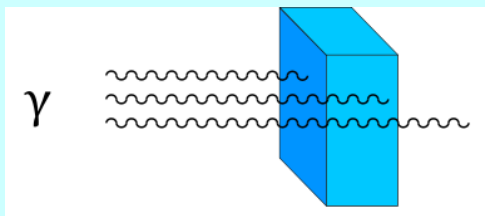
How can we shield these particles?



Sheet of paper



Several mm of aluminium



Heavy shielding

How dangerous 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:

$$A = -\frac{dN}{dt} \sim N$$

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

$$\Rightarrow A = -\frac{dN}{dt} = \lambda \cdot N$$

N... Number of radioactive isotopes

A ... Activity, decay per time unit

λ ... Decay constant, defining the speed of decay

$$\Rightarrow \frac{dN}{N} = -\lambda \cdot dt$$

With $N(t=0) = N_0$

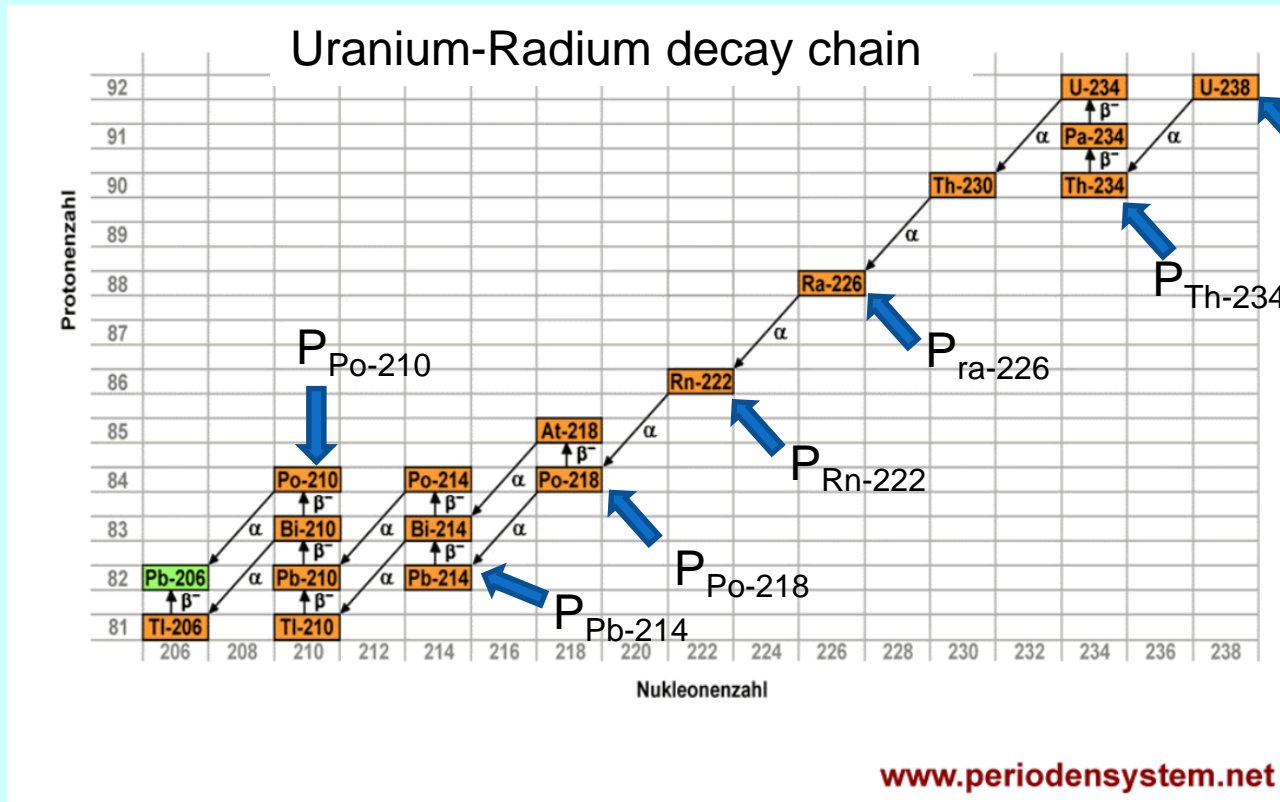
$$\Rightarrow N(t) = N_0 \cdot e^{-\lambda \cdot t} \quad | \quad \lambda$$

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

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

$$\frac{dN_1}{dt} = P_1 - \lambda_1 \cdot N_1$$

$$\frac{dN_2}{dt} = P_2 + (b_{1,2} \cdot \lambda_1 \cdot N_1) - \lambda_2 \cdot N_2$$

\vdots \vdots

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

\vdots \vdots

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

\vdots \vdots

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

$N_n \dots$	Number of isotope n
$P_n \dots$	Production rate of isotope n
$\lambda_n \dots$	Decay constant of isotope n
$b_n \dots$	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 \rightarrow 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 .


$$\begin{aligned}
 s \cdot F_1(s) - N_1(t=0) &= \frac{P_1}{s} - \lambda_1 \cdot F_1(s) \\
 \vdots & \\
 s \cdot F_n(s) - N_n(t=0) &= \frac{P_n}{s} + b_{n-1,n} \cdot \lambda_{n-1} \cdot F_{n-1}(s) - \lambda_n \cdot F_n(s) \\
 \vdots & \\
 s \cdot F_m(s) - N_m(t=0) &= \frac{P_m}{s} + b_{m-1,m} \cdot \lambda_{m-1} \cdot F_{m-1}(s) - \lambda_m \cdot F_m(s)
 \end{aligned}$$

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 $F_n(s)$ $\mathcal{L}^{-1}(F_n(s)) \longrightarrow N_n(t)$

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

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

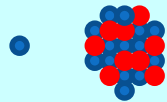
Which production mechanisms of activation occur at high-energy accelerators?

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,α) , ..



- Particle capture (mainly neutrons)

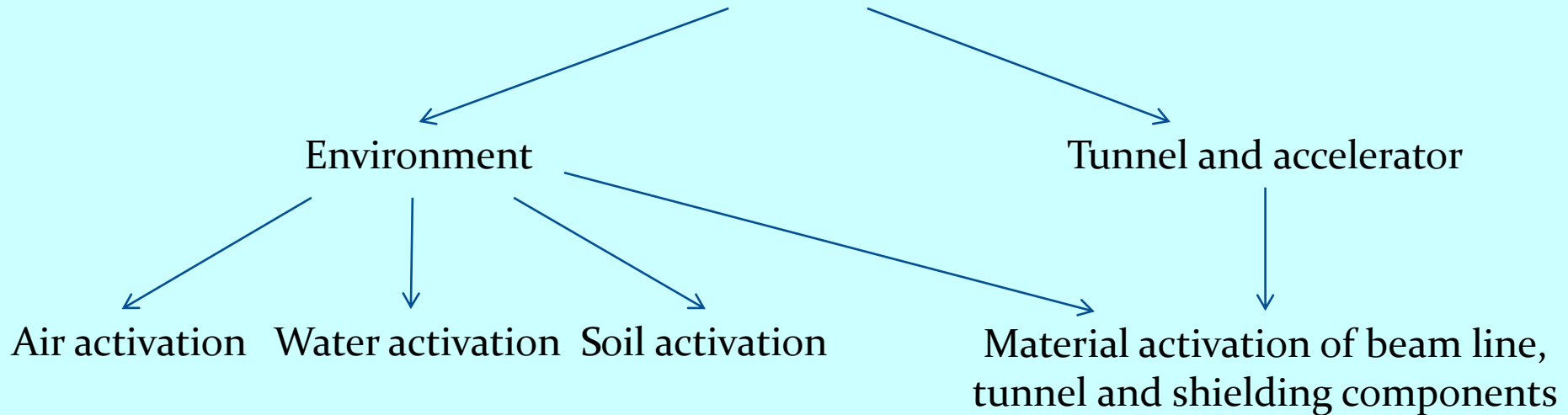


- (γ,n) -reactions (important for electron accelerators)



Questions about activation III/III

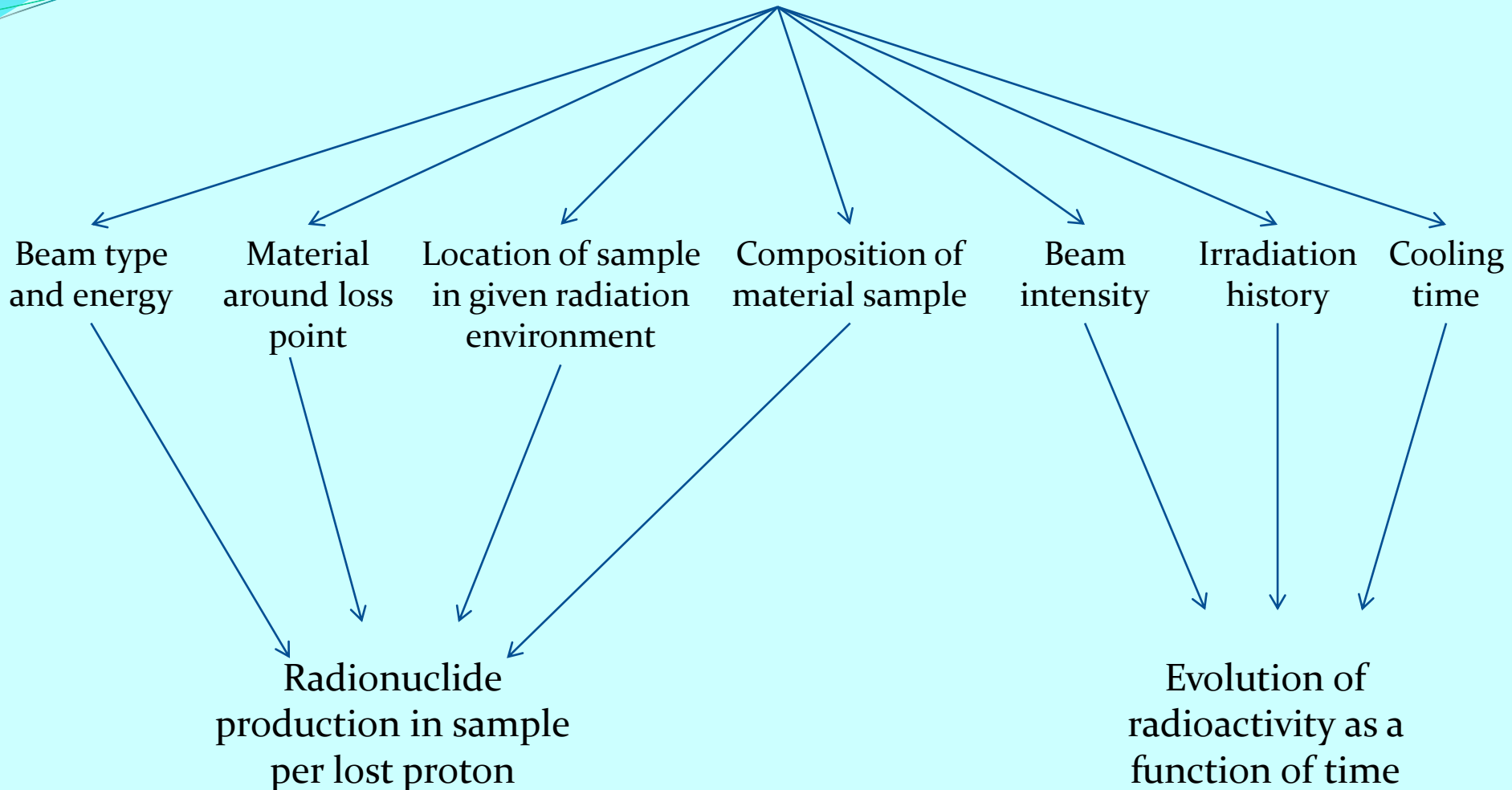
Why is activation important for high-energy accelerators?



Required information to classify activation:




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

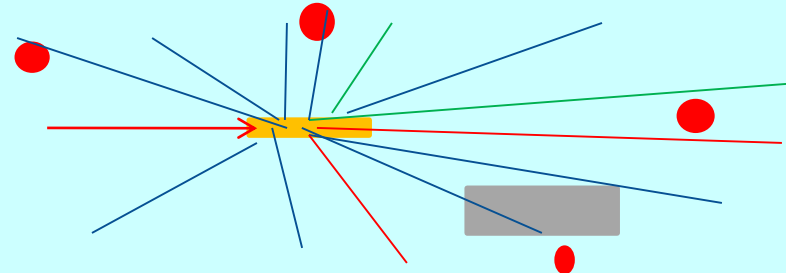
Parameters responsible for production of radioactivity in a given material sample at high-energy accelerators



Physics principles of radio nuclide production per lost proton

Beam on target situation:

-  Target
-  Sample positions
-  Shielding



Total production rate of radio-nuclide i → $P_i =$

↑
Atomic density of isotope j in given volume

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

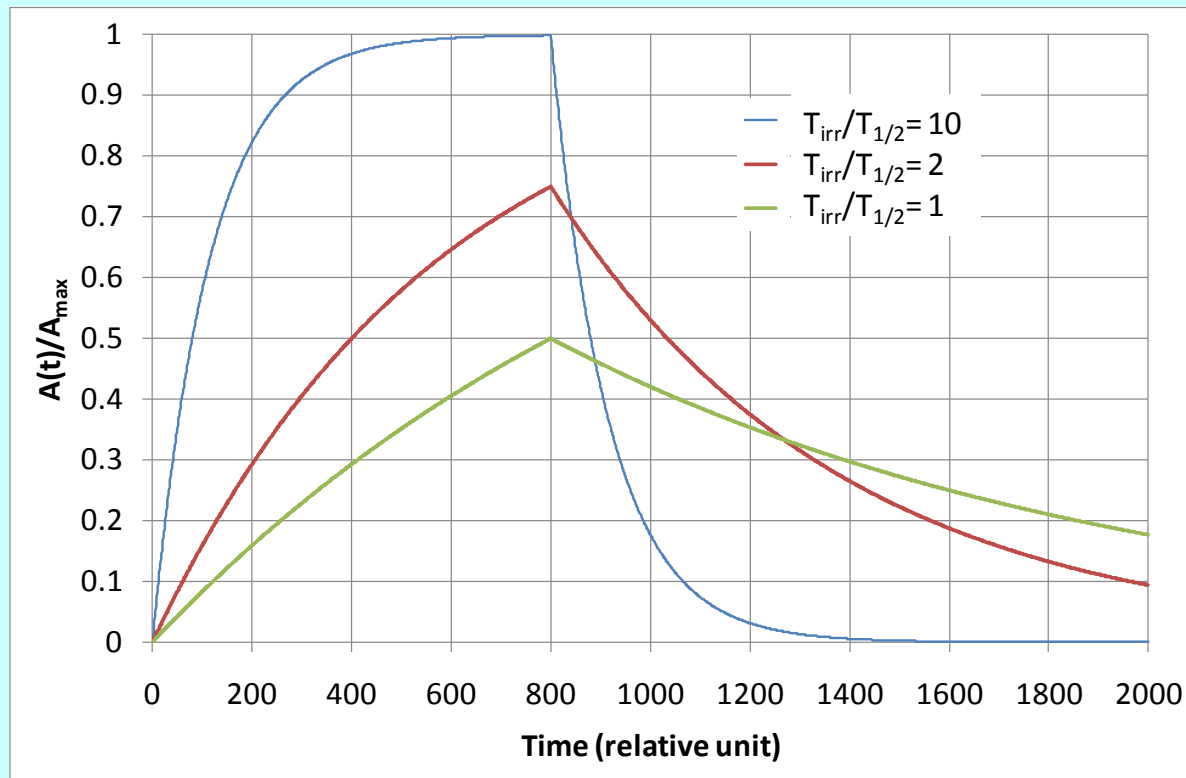
← Total track length of particle type k through volume of interest as a function of energy (E)

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

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

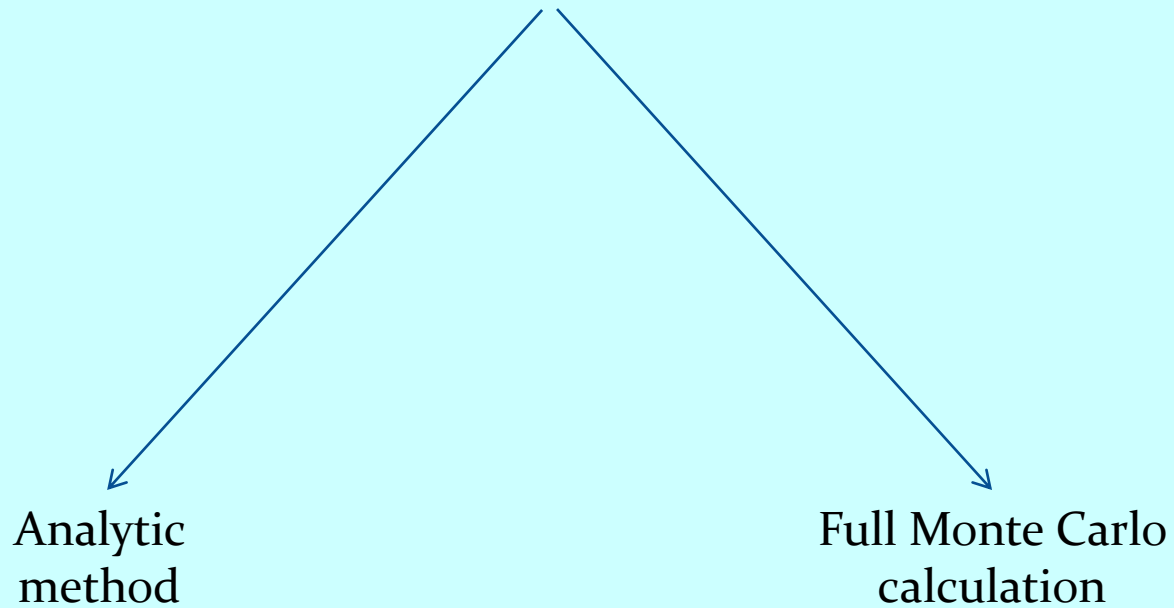
90% of $A_{i,max}$ are obtained after $\sim 3.32 \cdot t_{1/2}$

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



Video demonstration of radioactivity
production, build-up and decay

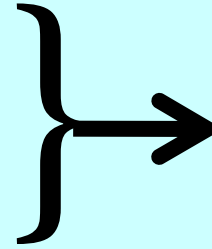
Calculation procedures to forecast activation and dose rates in high-energy accelerators



Analytic 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

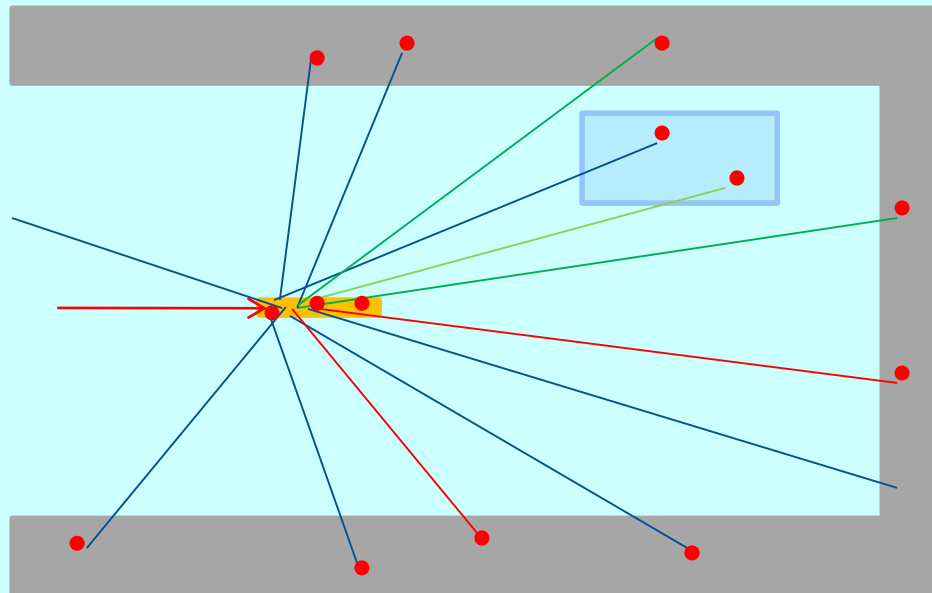
Full Monte Carlo calculation of activation

Input required:

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

Procedure inside code:

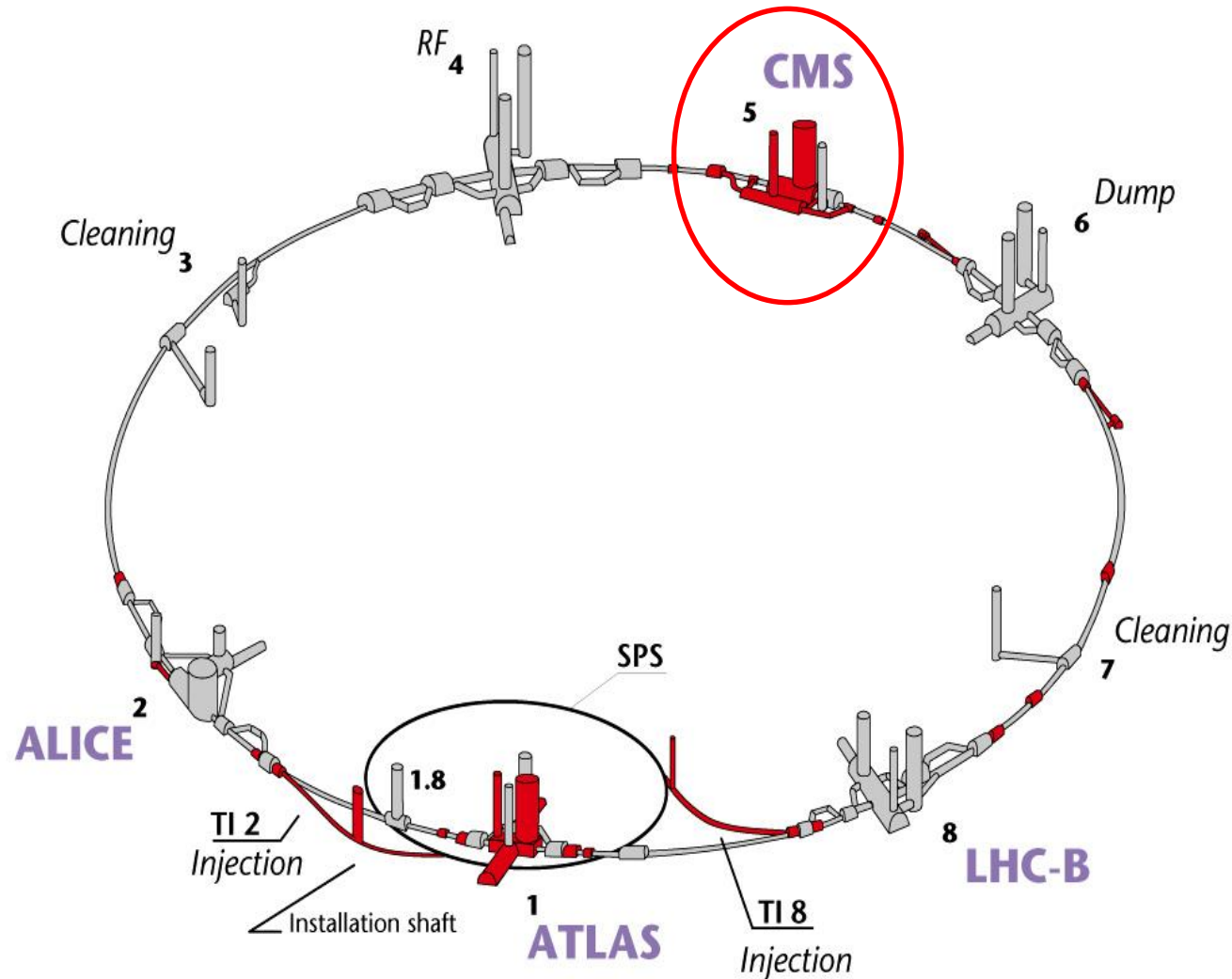
- 1) Simulation of particle cascade and isotope production around beam impact point
- 2) Radiation emerging from radio-isotopes are further transported to calculate dose rate in the surroundings of activated material



Applications for FLUKA activation simulations

Applications at the Large Hadron Collider (LHC)

Layout of the LEP tunnel including future LHC infrastructures.



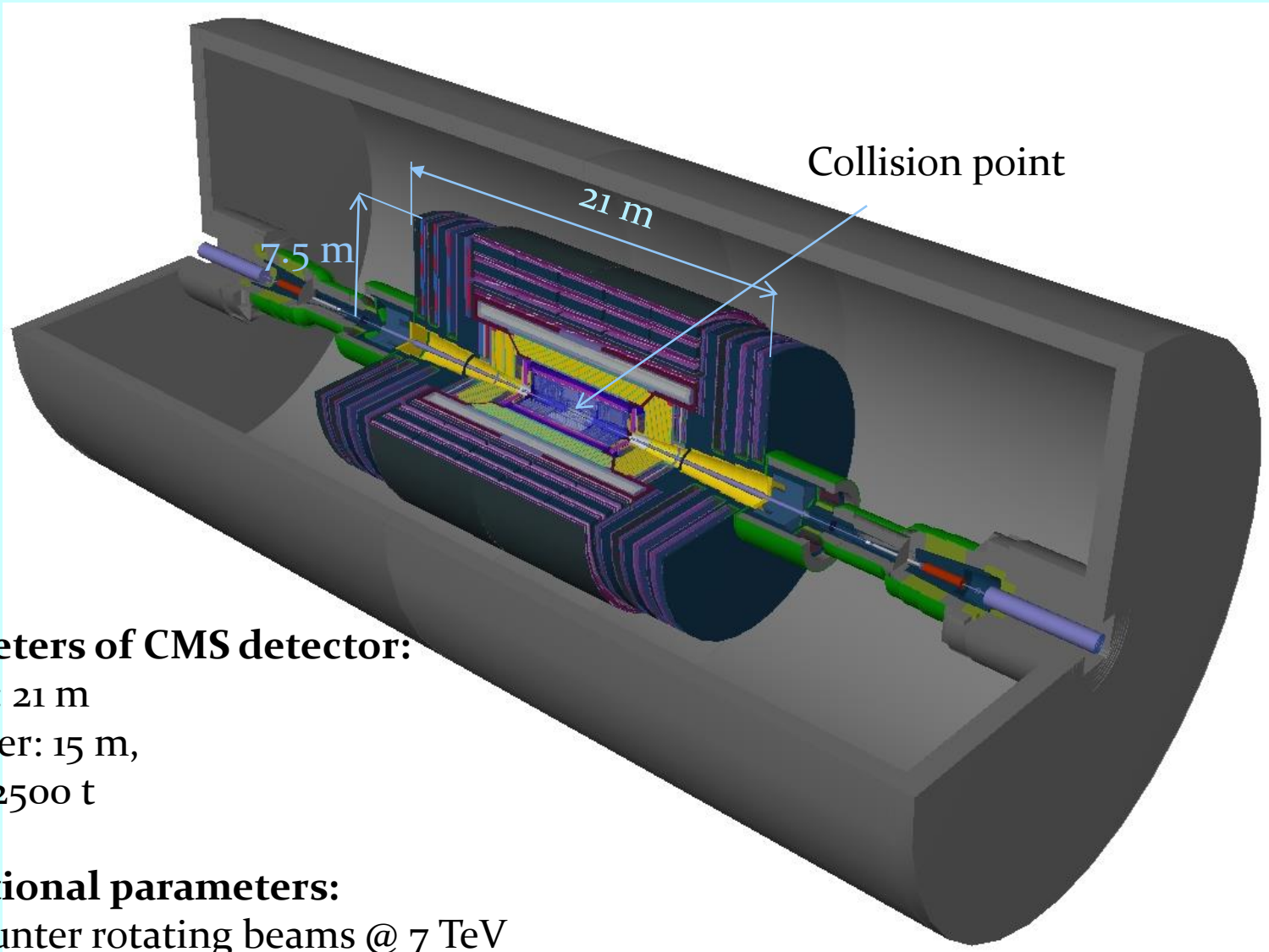
CERN AC - HF267 - 04-07-1997

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

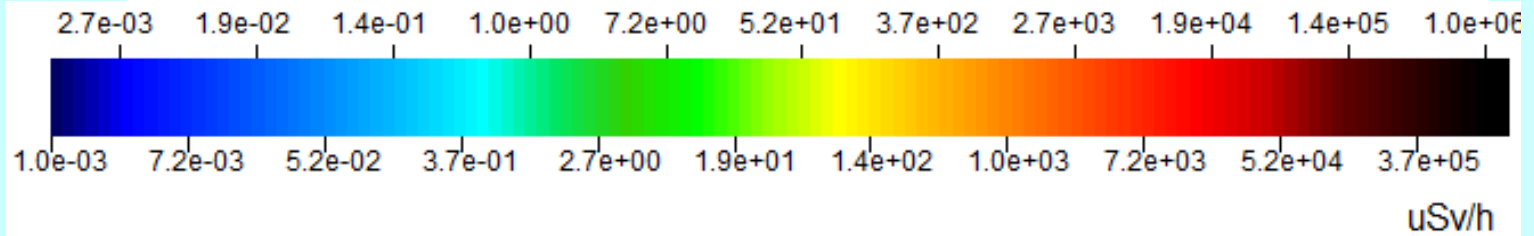
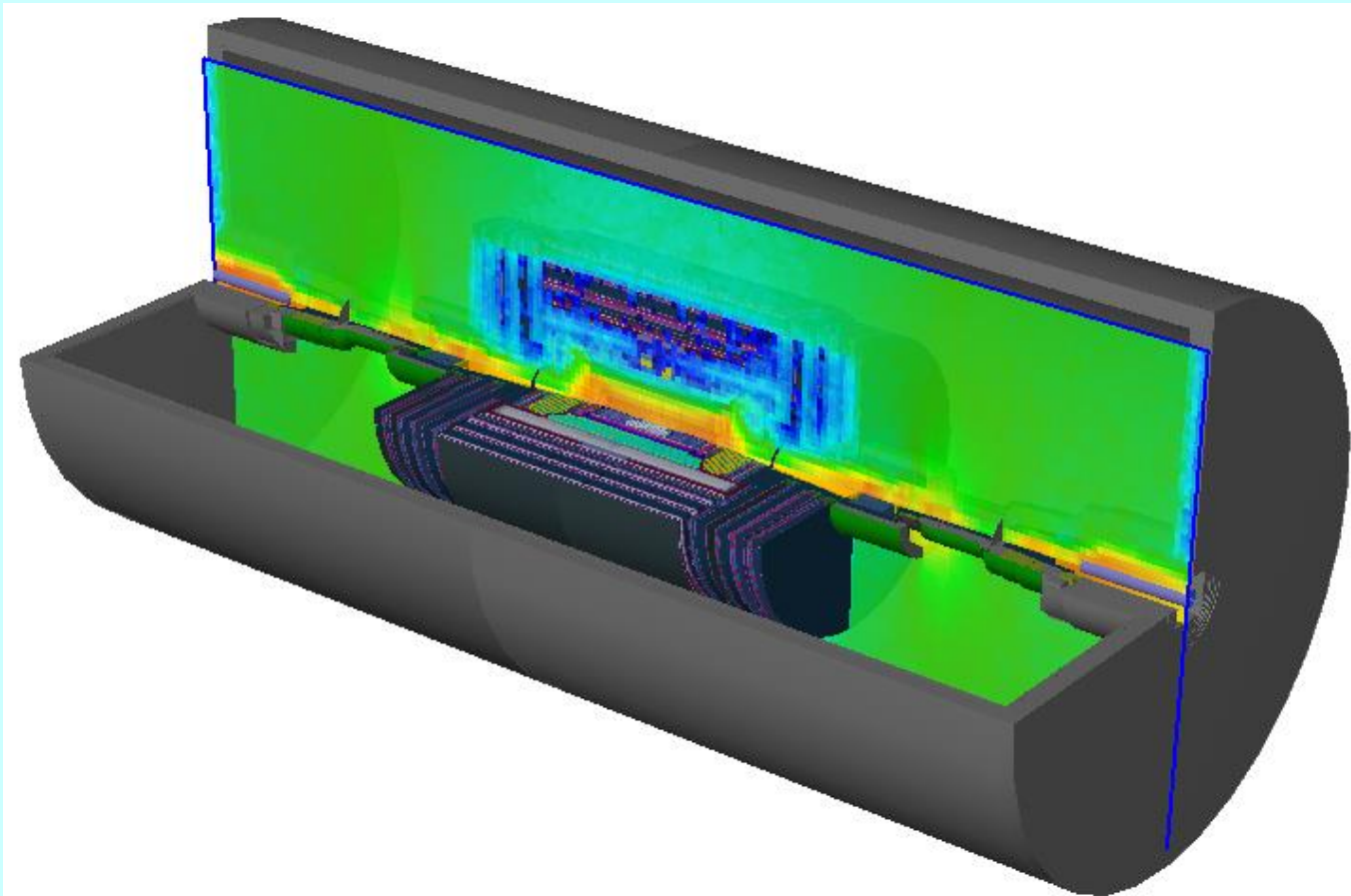
Luminosity: $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

→ 10^9 proton-proton collisions/s

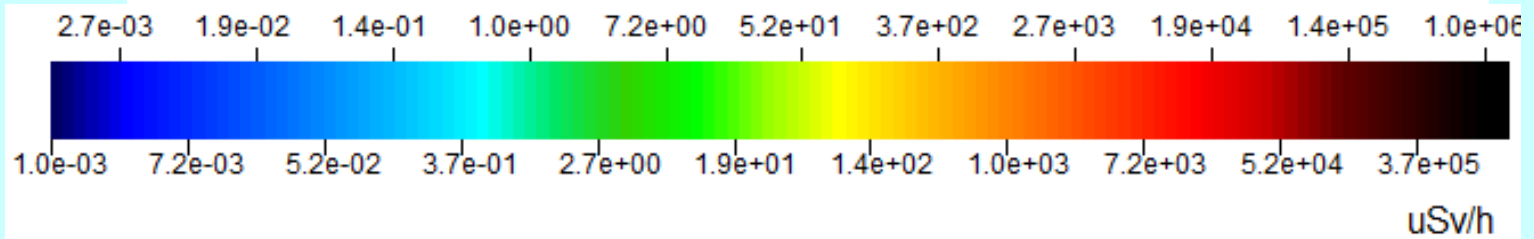
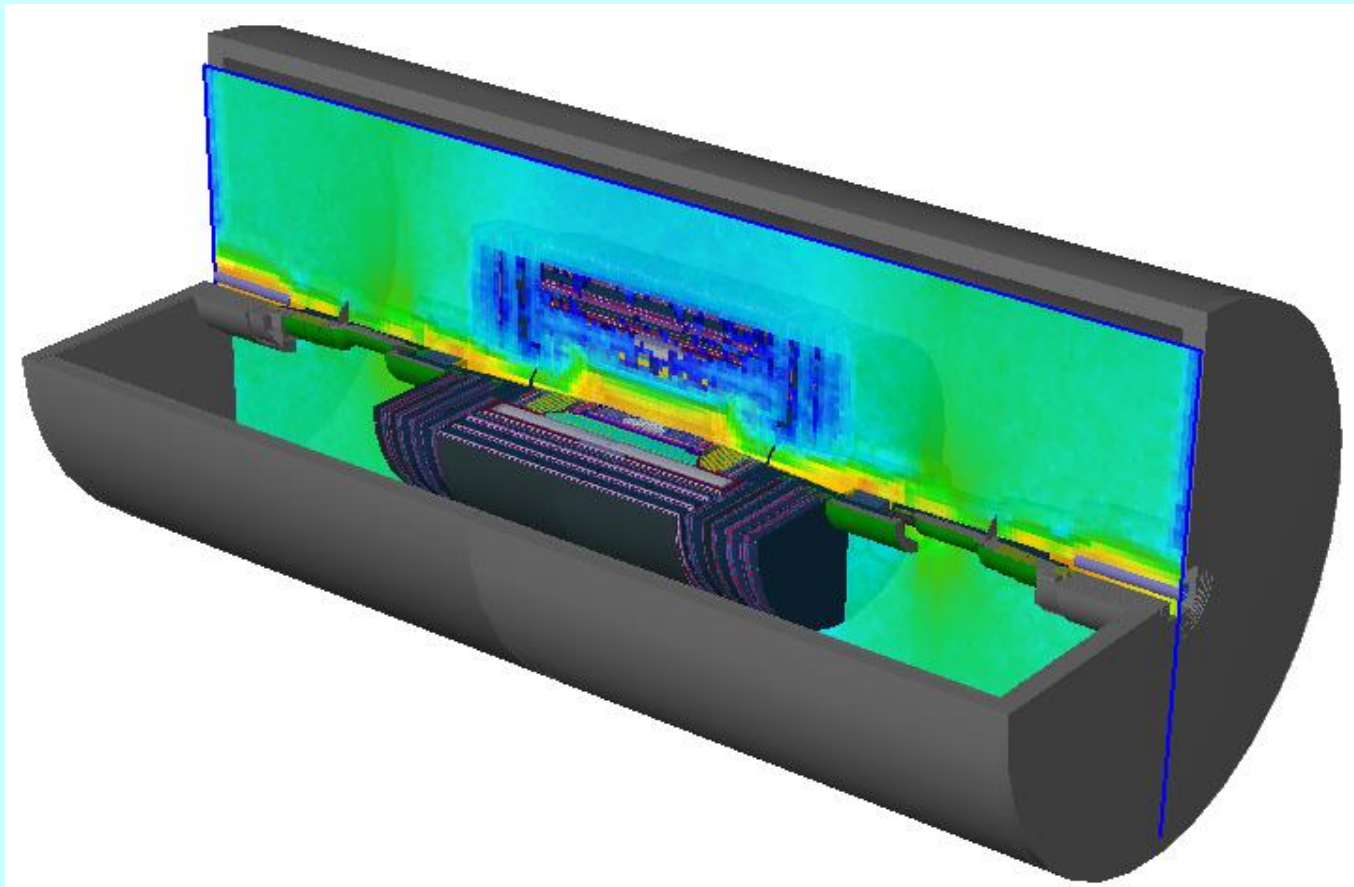
Residual dose rates to be expected after beam operation

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

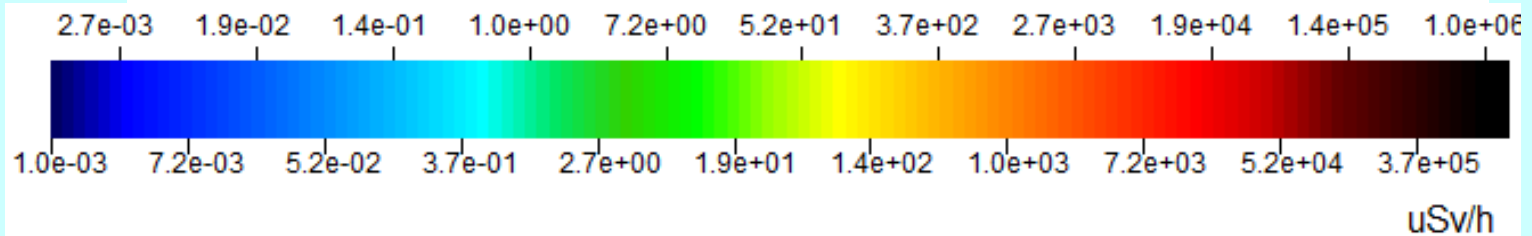
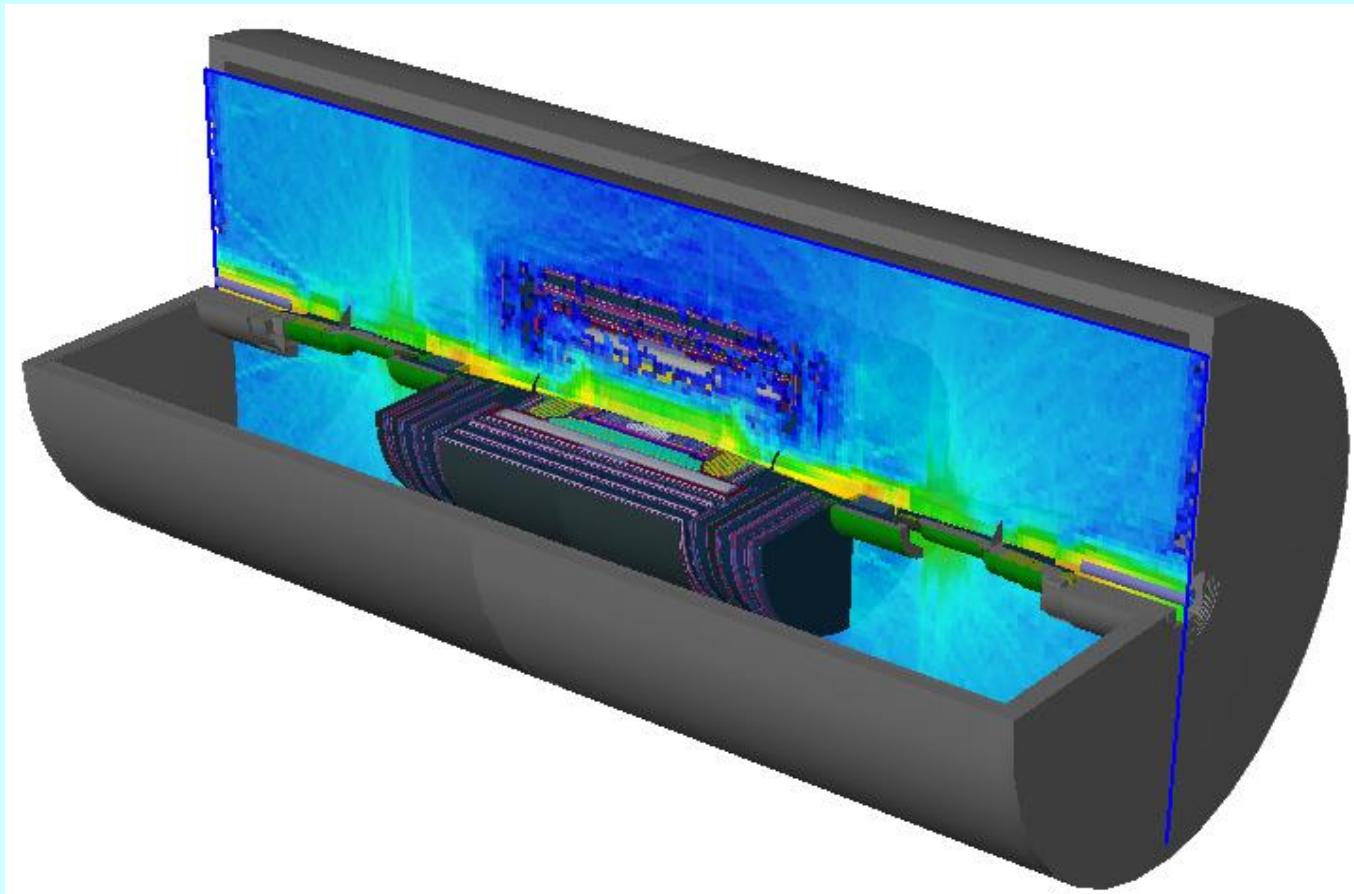
180 days of irradiation, 10^9 pp/s, 1h of cooling



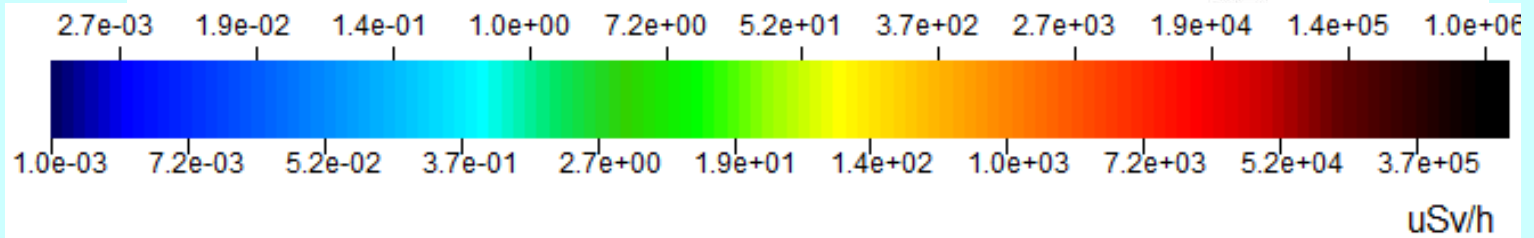
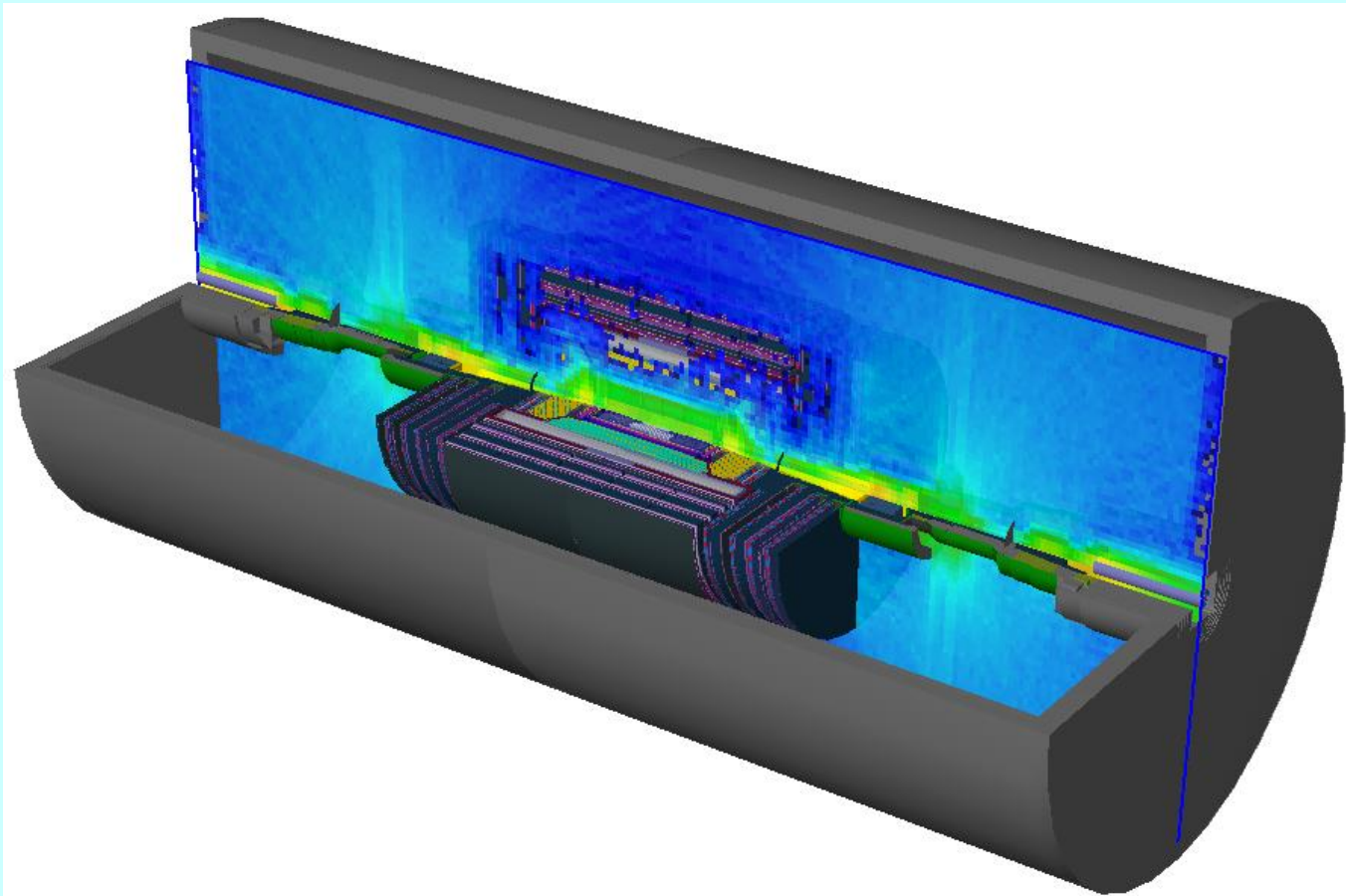
180 days of irradiation, 10^9 pp/s, 1d of cooling



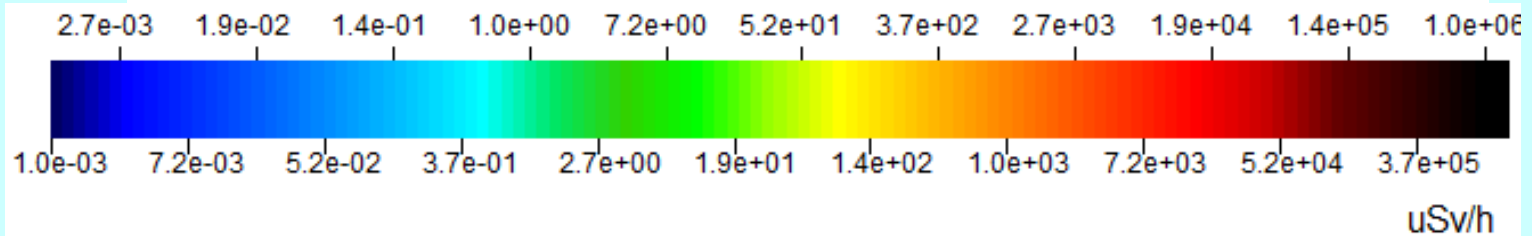
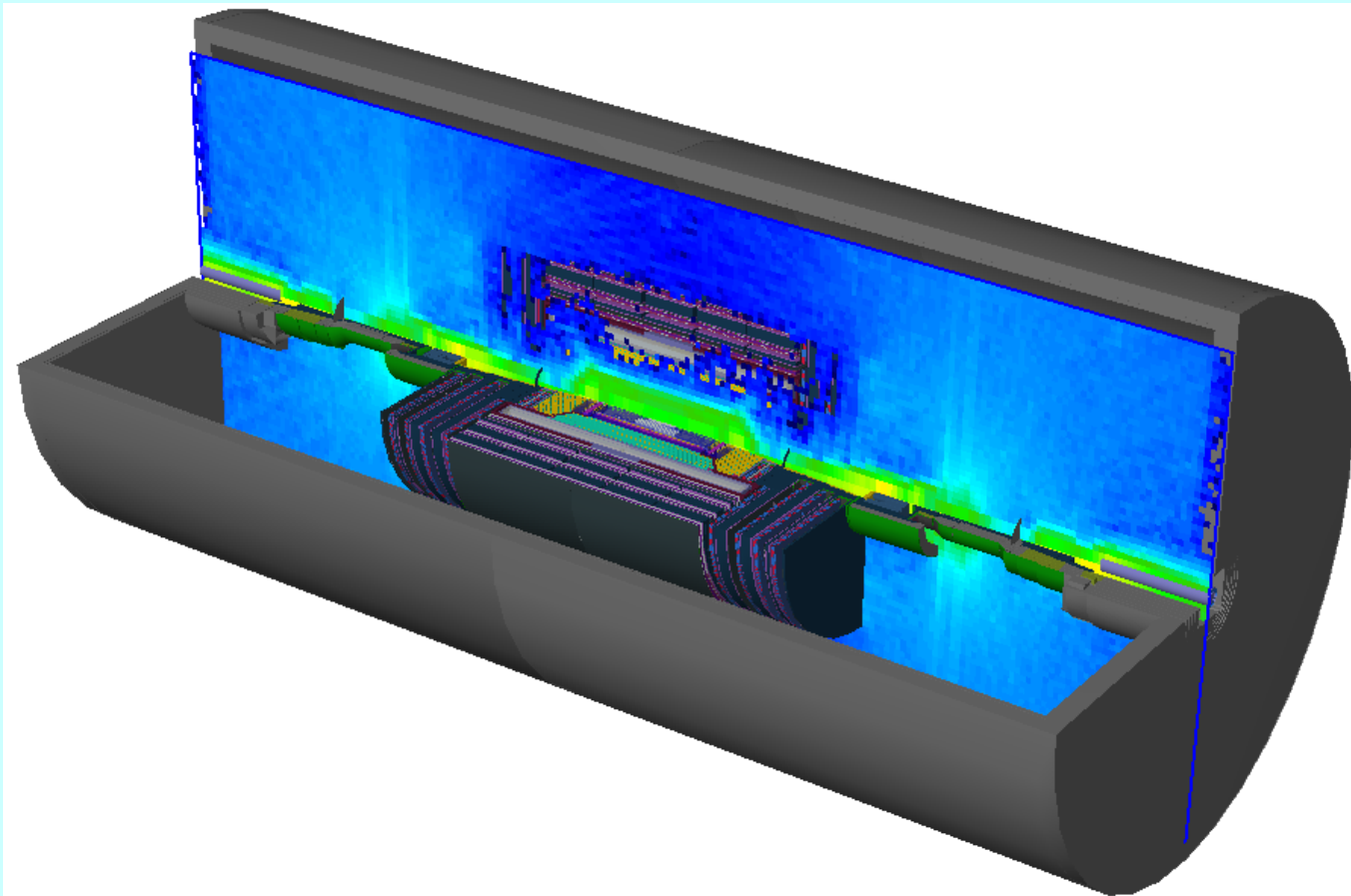
180 days of irradiation, 10^9 pp/s, 1W of cooling



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



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

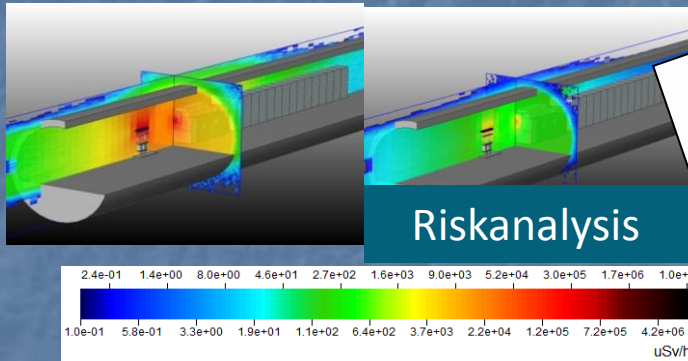


Radiation Protection at CERN

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



MEMORANDUM

TO: B. BISHARA, G. BISHARA
 R. BAGLEY, AB, M. BISHA, SC, P. COLLIER, AB, M. FERRO, LUDZPPE
 M. LAGOSTINI, AB, S. SEVERI, AB, R. TRANTIC

FROM: D. FORSEK, RW/RS/SC, H. MINDLER, SC

SUBJECT: SPS LHC SYNCHRONIZATION TEST on 1st - 3rd SEPTEMBER 2008

DATE: 1st SEPTEMBER 2008

EDSAS 002774

AB departments will conduct another SPS LHC Synchronization test week from Friday 5th September 2008 in the evening until Monday 8th September 2008 in the early morning. SC-SP agrees that you carry out the synchronization test as you plan, based on the information received by AB during the preparatory phase (Synchronization Test Meetings, class Mike Lawson).

Information received via you since EDSAS 002444

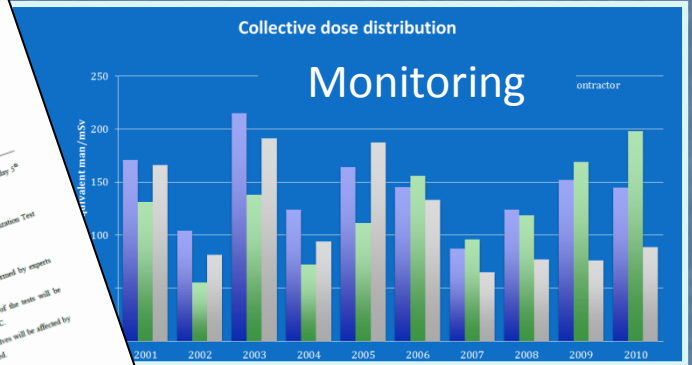
- Information received via you since EDSAS 002444
- Results of the corresponding radiation protection studies performed by experts from SC-SP

SC-SP has verified that the area affected by radiological consequences of the test will be limited to the areas already classified as radiation areas plus sector 6 of LHC.

Notwithstanding the filling of the CMS vacuum chamber, the closed valves will be affected by the beam. Radiological consequences for these two areas can be excluded.

The SP will ensure that radiation protection aspects only.

Authorization



Legislation

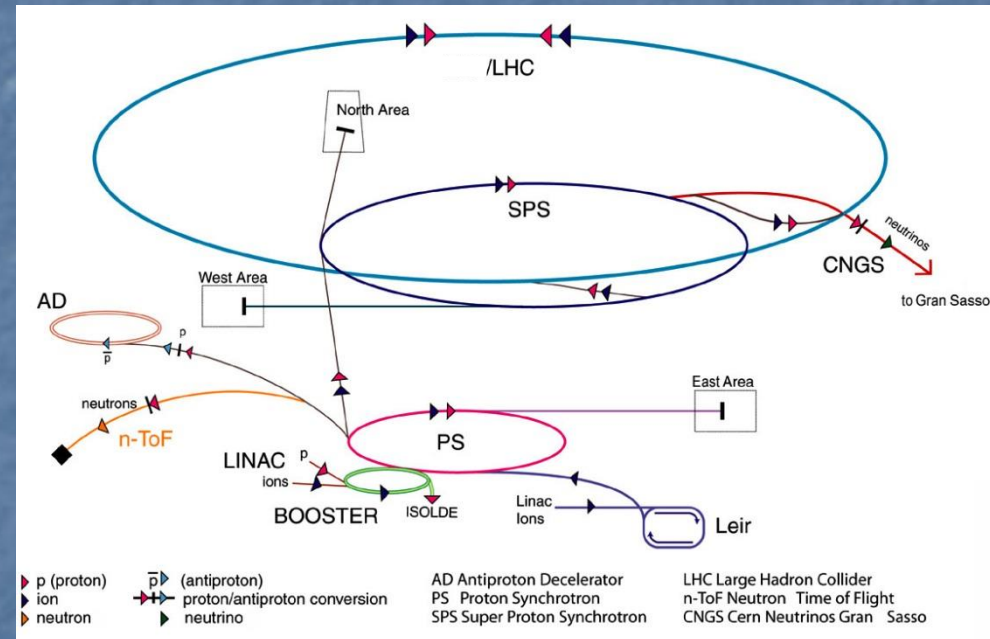
Safety Code F



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

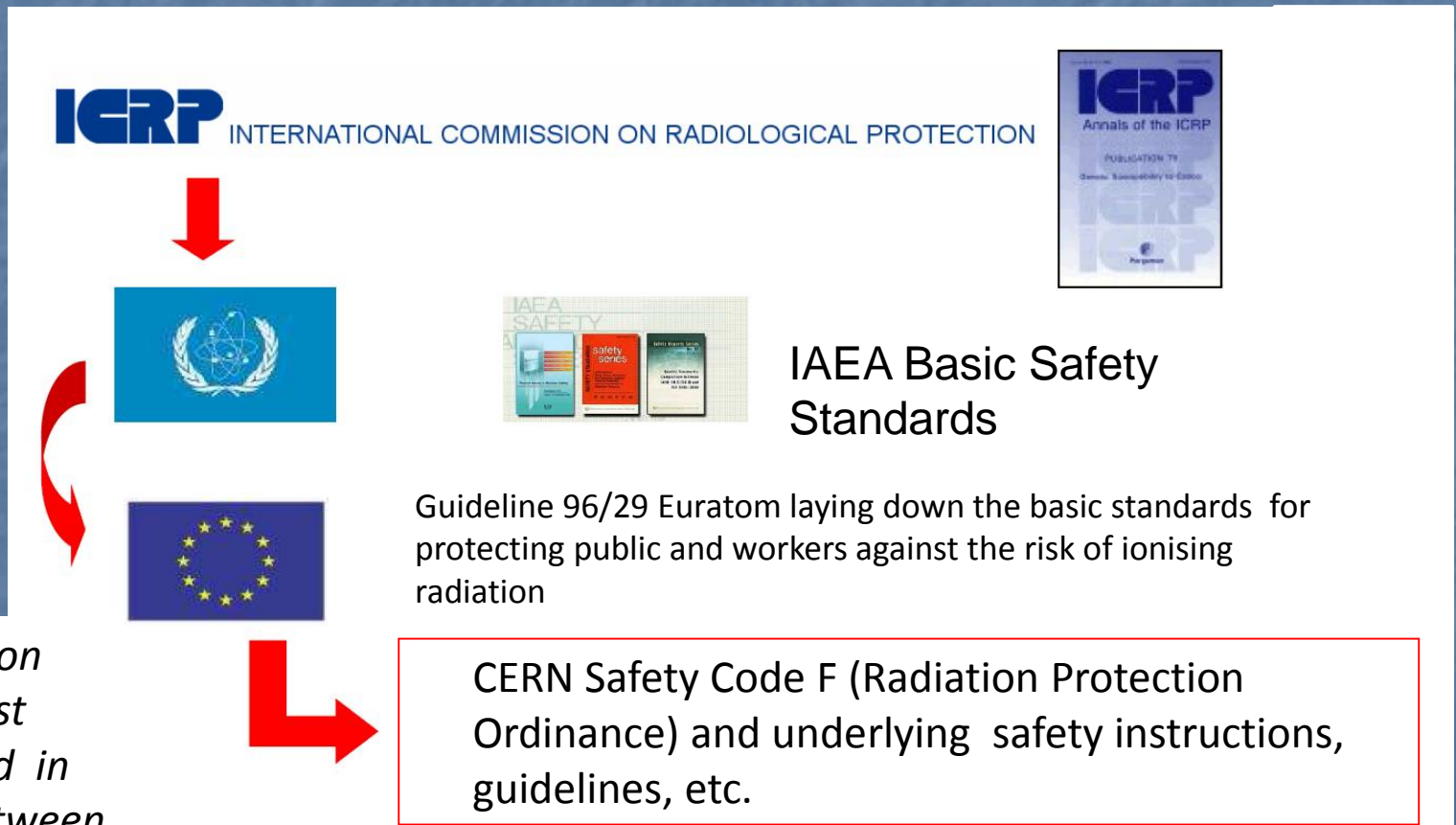
the personal doses have to be kept below the legal limits

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



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



« A bientôt les protons » - rétrospective sur l'exploitation des premiers protons du LHC.

Une grande étape pour la sécurité

Dernières nouvelles du LHC : passage aux ions lourds réussi

ATLAS : au-delà des espérances

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.

Pleine puissance pour le premier module du Lincac

Le CERN en détails

Un fonds dédié à l'innovation technologique

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)

Subscribe by RSS

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.



Le mot du DG

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 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



CERN

Unité HSE

RELATIONS TRIPARTITES

Accord tripartite du 15-11-2010 (Sûreté/Radioprotection)

Comité tripartite sûreté et radioprotection

RATIFICATION OF THE TRIPARTITE AGREEMENT ON SAFETY AND RADIATION PROTECTION

(September 2011)

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

Rolf Heuer

Directeur général

Pour le Conseil fédéral suisse

Pascal Strupler

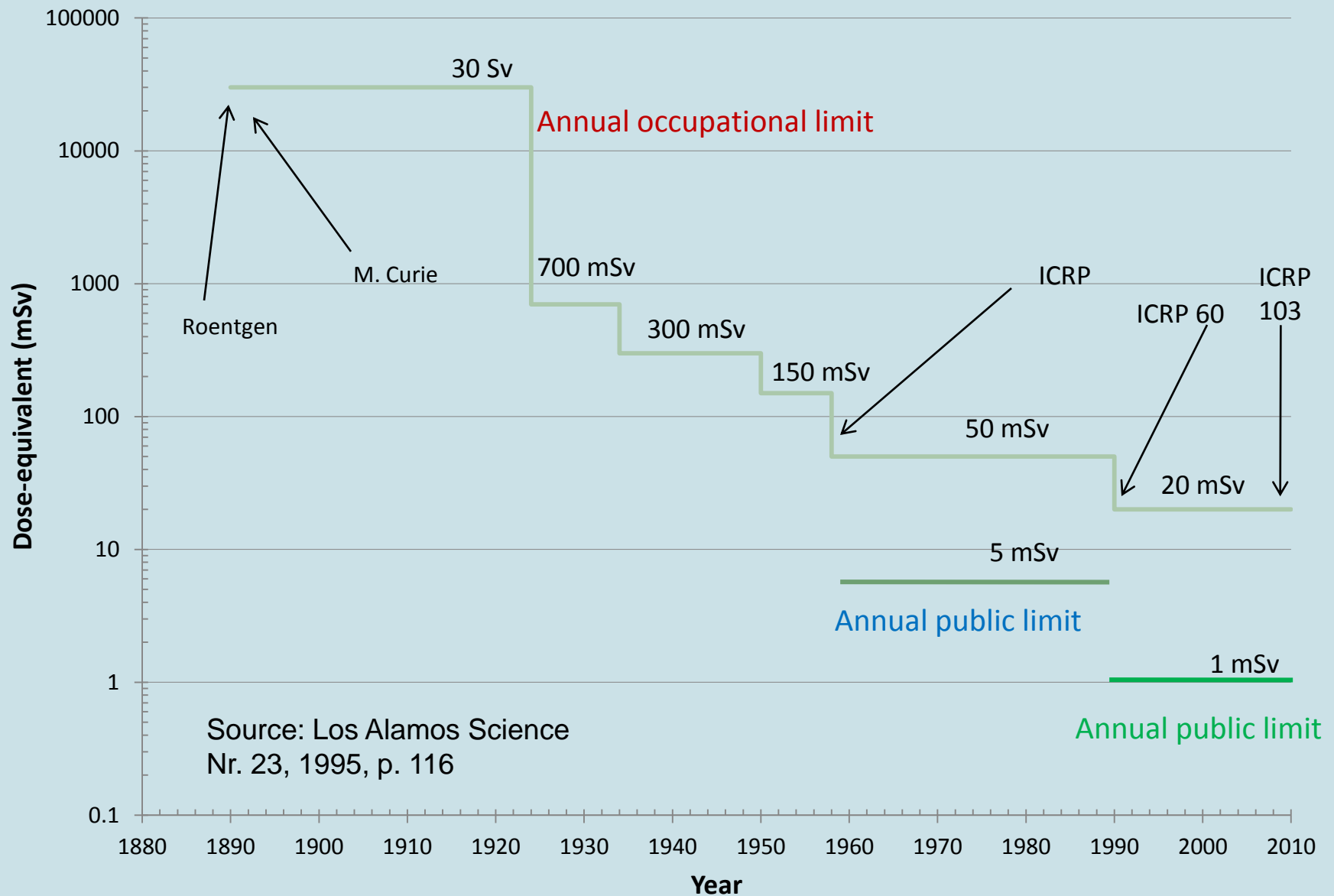
Directeur de l'Office fédéral de santé publique

Pour le Gouvernement français

André-Claude Lacoste

Président de l'Autorité de sûreté nucléaire

History of Radiation Protection



Dose Limits

	<i>Dose limits for 12 months consecutive (mSv)</i>		
	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
Reference group of the public	< 10 μSv
Non-professionally exposed personnel	< 100 μSv
Professionally exposed personnel	< 6 mSv

Dosimetry, Operational Radiation Protection and Radiation Monitoring

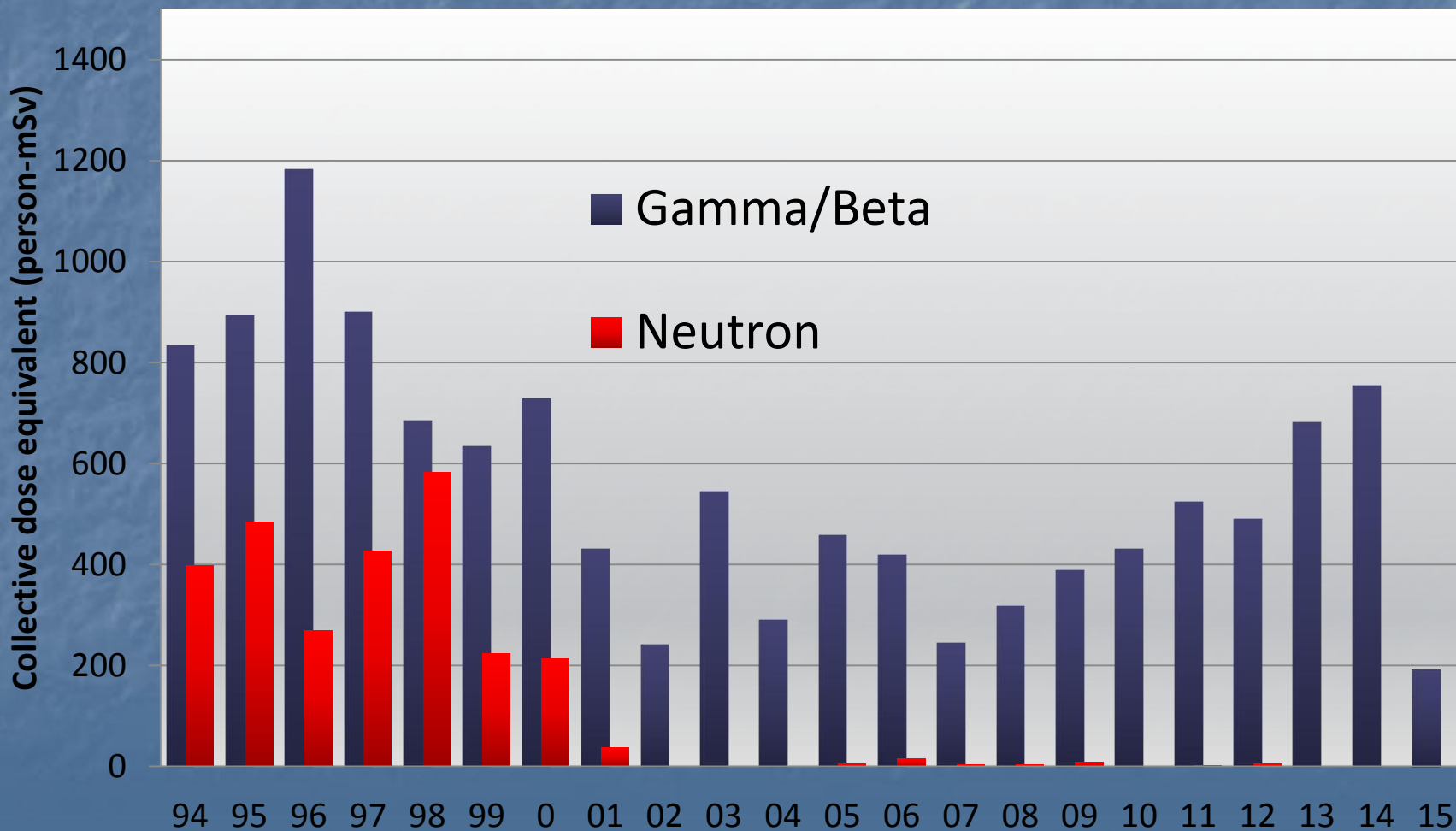
Individual Dosimetry

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

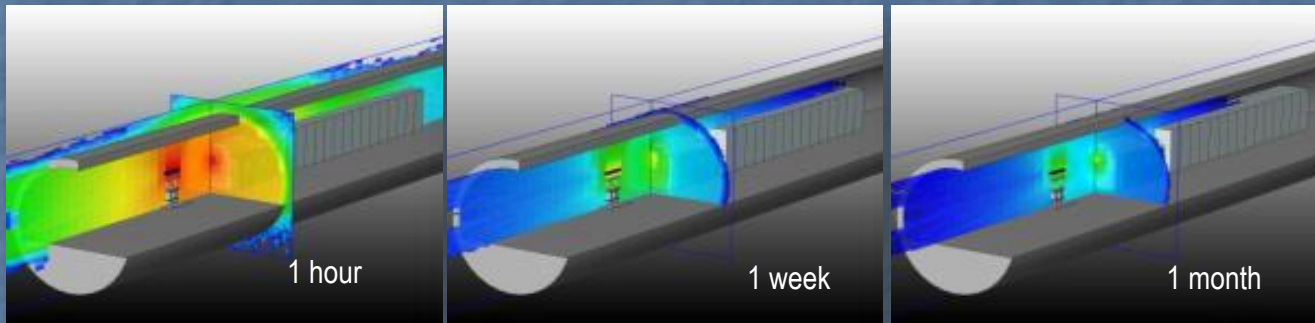


- ~ 7000 monitored persons per year
- 98 - 99% of individual doses < 1 mSv

Collective Personal Dose Equivalent Summary over the last 22 years



Operational Radiation Protection



From design

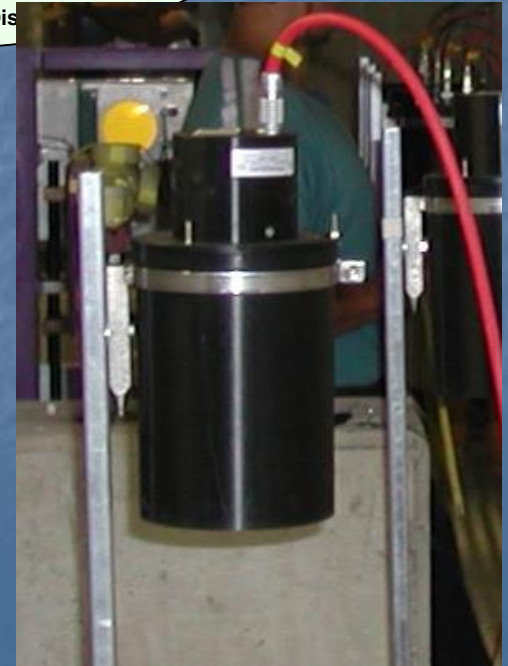
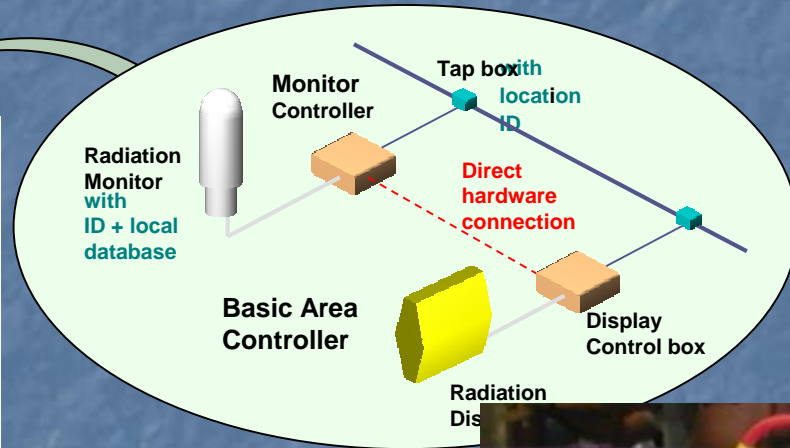
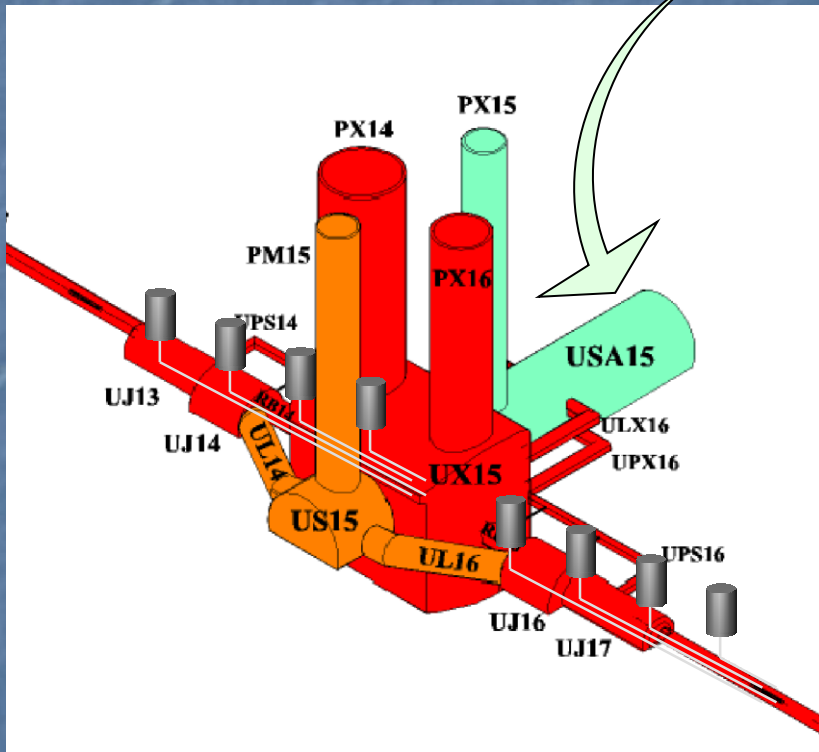


to reality



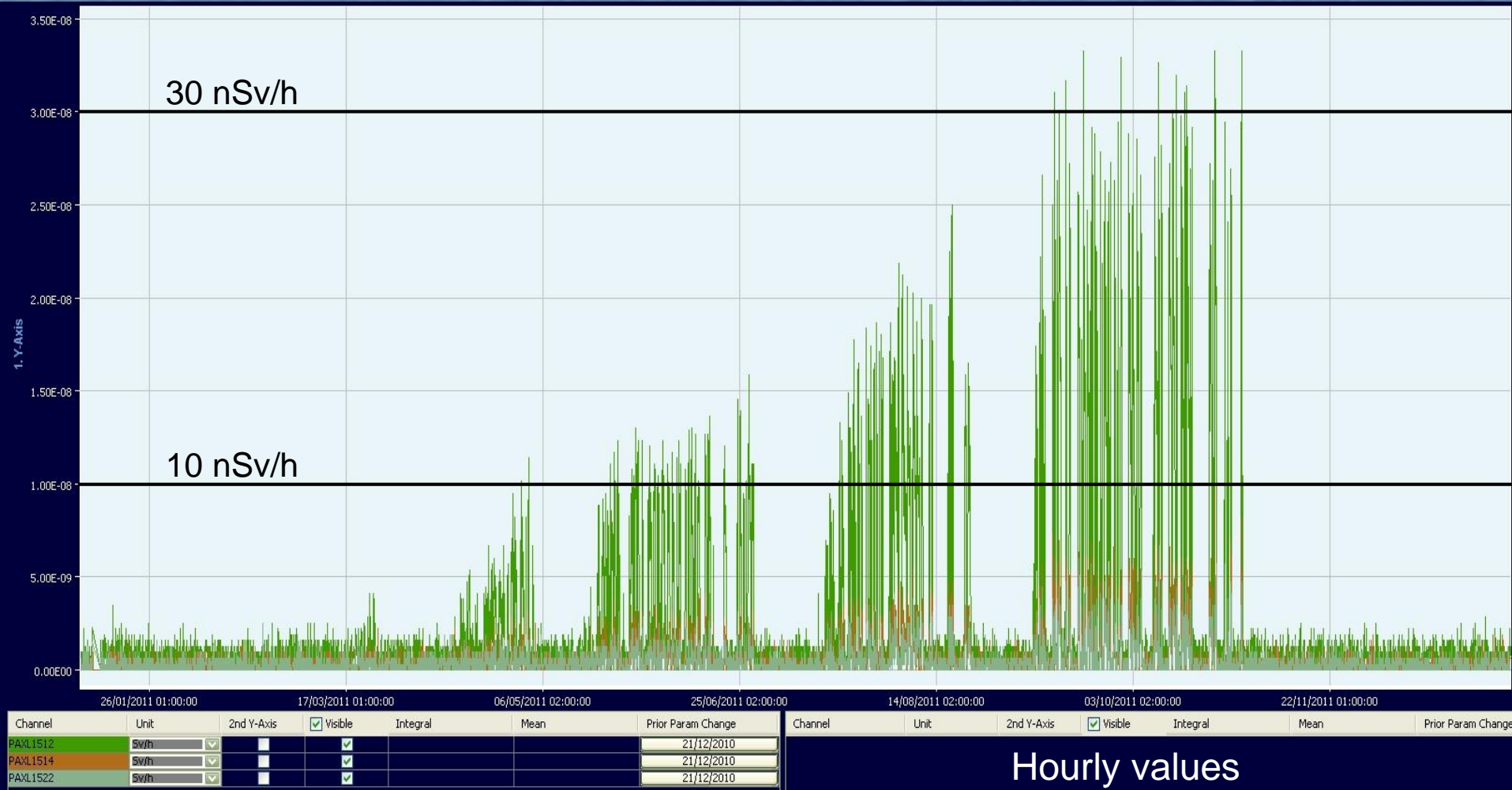
Radiation Monitoring

96

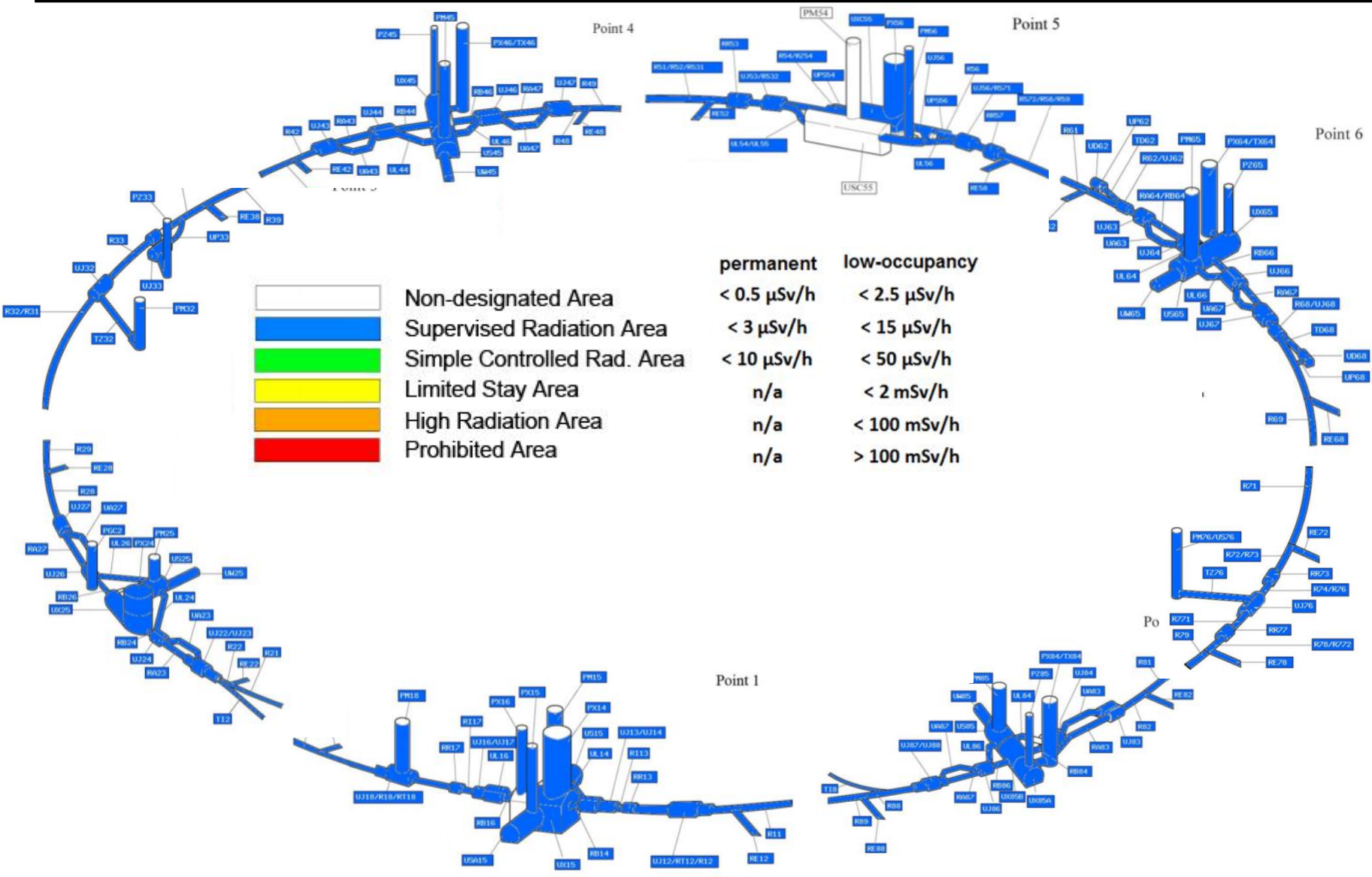


Instrumentation

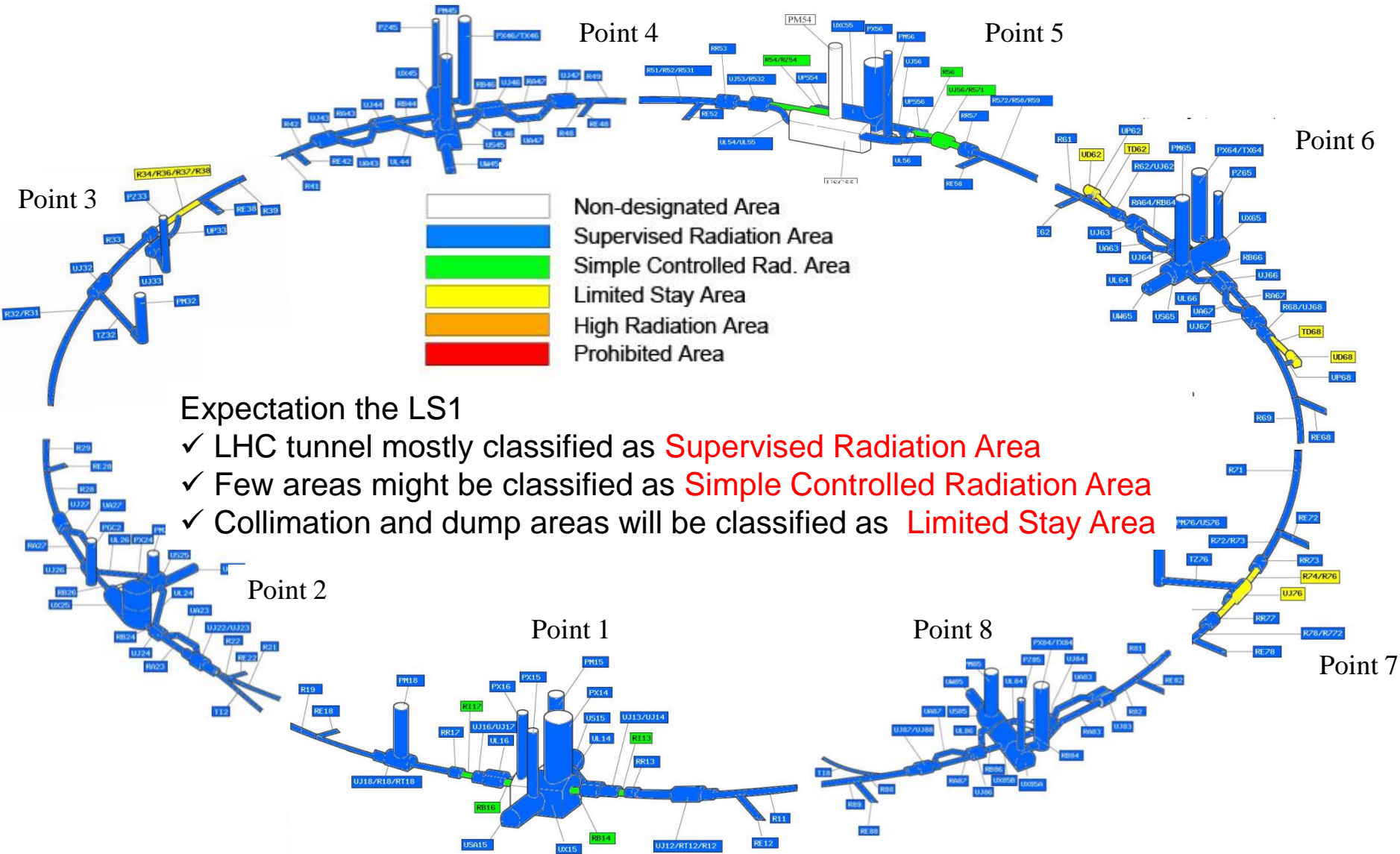
Run 2011 – Seen by neutron monitors in USA15



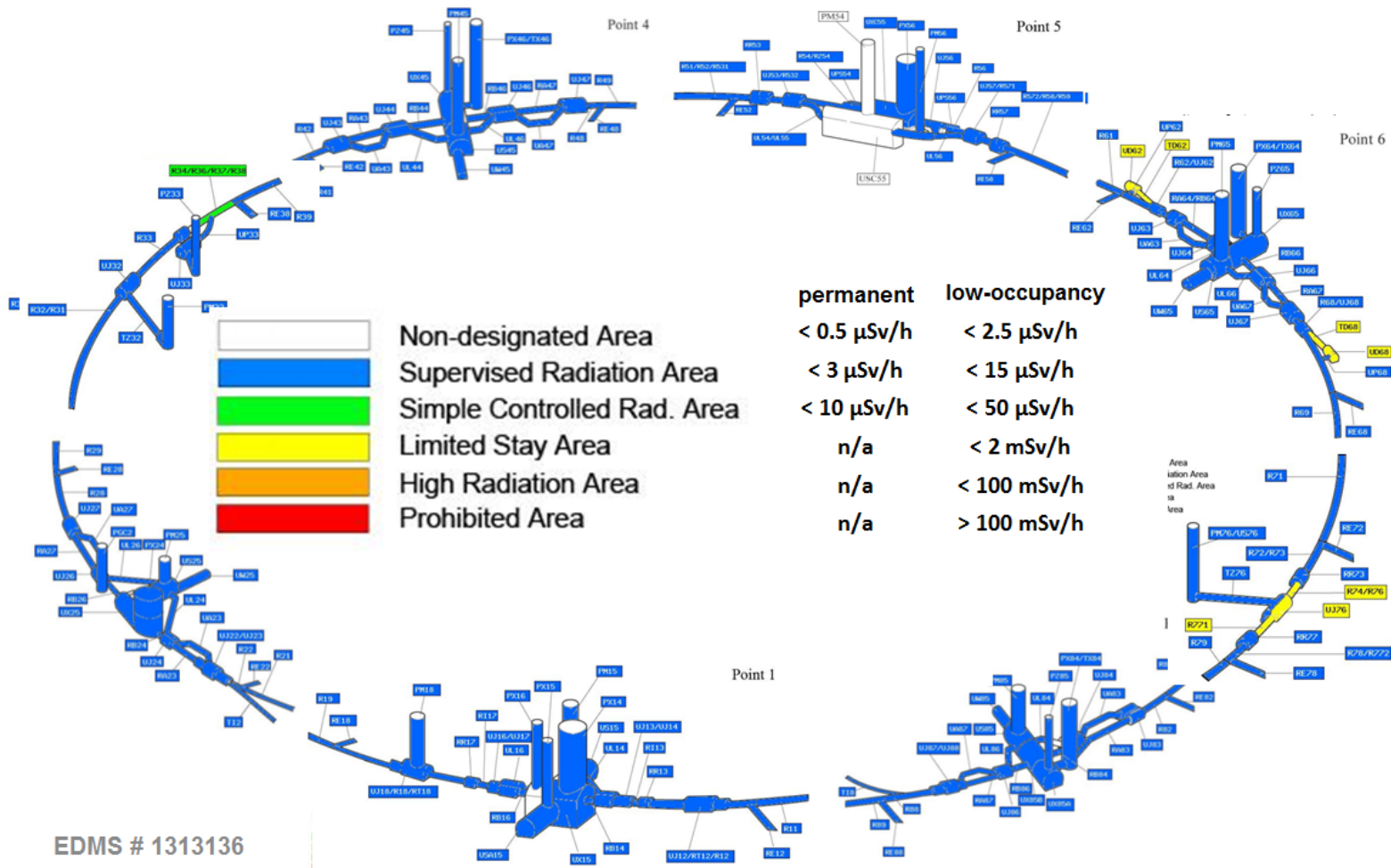
Area classification: LHC - 2010



LHC - 2012



LHC during LS1

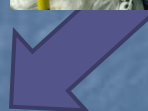


Radioactive waste: treatment and elimination

Waste received



Waste received per year



Analyzed



Conditioned



Eliminated to final repository

ALARA at CERN

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 $\mu\text{Sv}\cdot\text{h}^{-1}$		2 mSv·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	


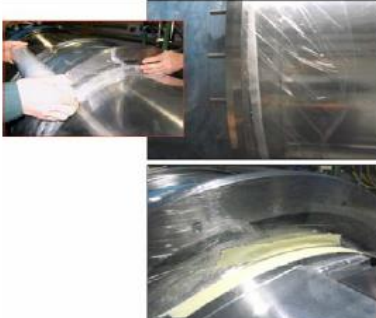


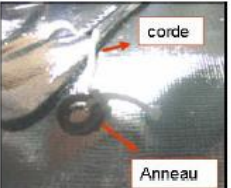


ALARA procedure – 3 Levels:

- 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

	<p>technicien aidera à soutenir la manchette pour la déplacer sur le coté</p> <ul style="list-style-type: none"> • il faut 3 personnes pour cette opération 		
5	<ul style="list-style-type: none"> • Protéger l'entrée des interconnexions avec du film plastique avant de retirer les écrans thermiques • Mettre du scotch pour fixer le film de plastic  <ul style="list-style-type: none"> • Mettre du film plastique des deux cotes de l'interconnexion 		8' (2 personnes)
6	<ul style="list-style-type: none"> • Enlever la première couche de matelas de MLI  <ul style="list-style-type: none"> • Mettre des gants blancs pour réaliser cette opération (protéger le matelas MLI) 		3' (2 personnes)
7	<ul style="list-style-type: none"> • Attacher un petit anneau à la fin de la corde qui traverse le matelas MLI 		1' (1 personne)
8	<ul style="list-style-type: none"> • Plier le matelas de MLI  <ul style="list-style-type: none"> • 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 area reduced by a factor of 3.2

Before removal

- Remote handling with robots
- Special equipment allowing for dose optimization

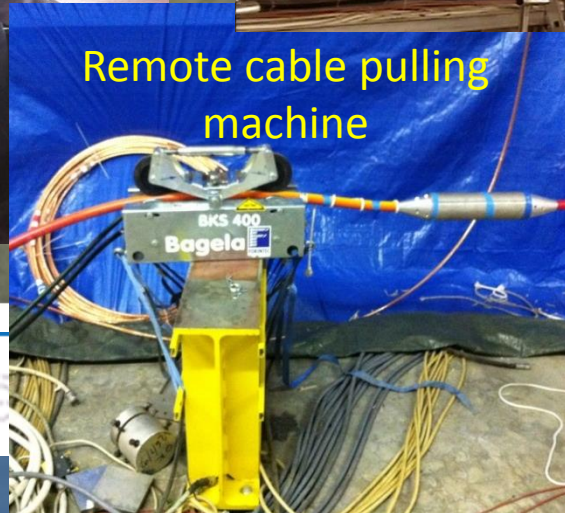
After removal

Optimized cable removal and cutting

Cables combs replacing cable ties

Remote cable pulling machine

mSv/h

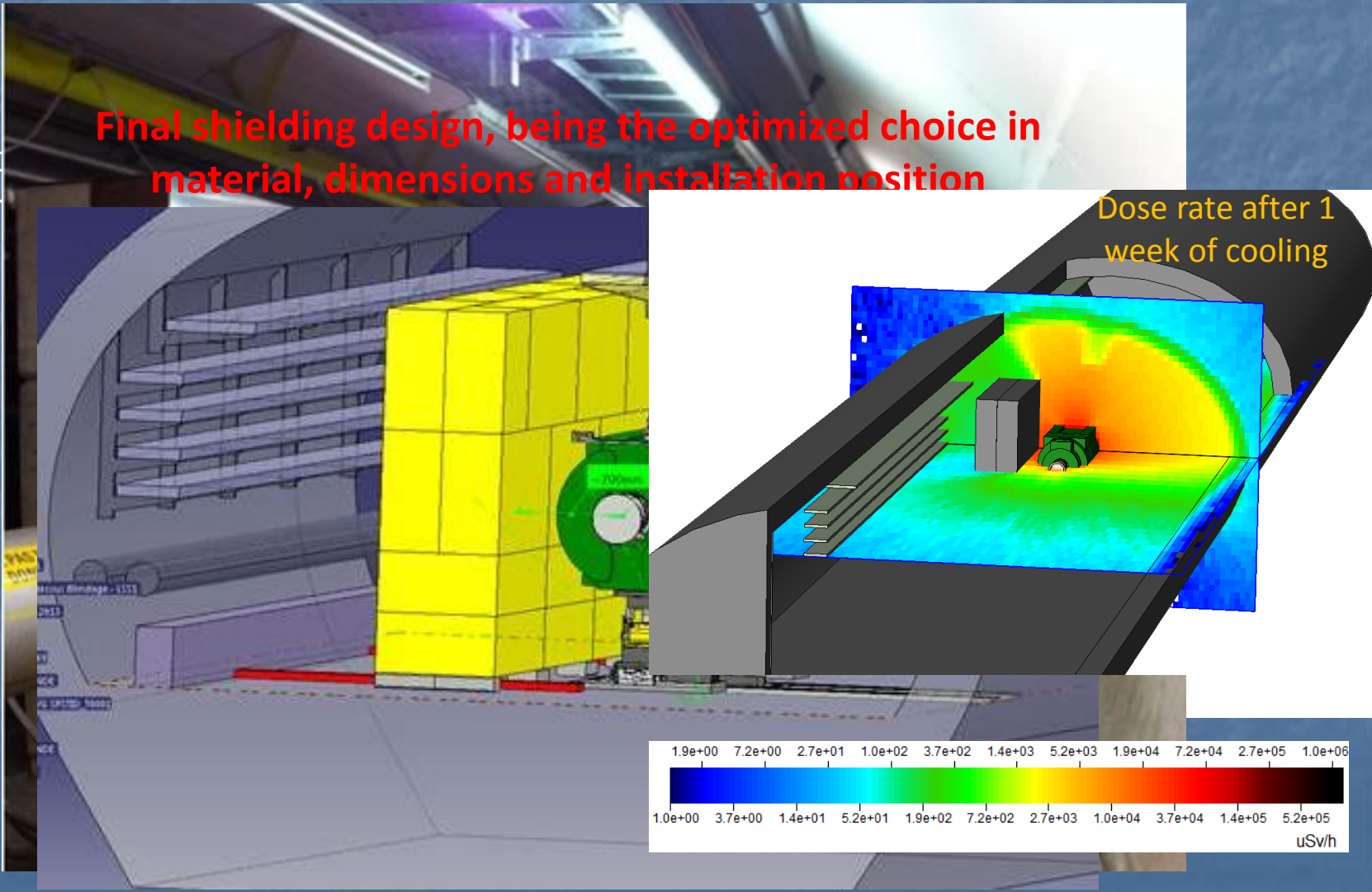


SPS beam dump shielding

- The former shielding located beside the TIDV dump caused significant problems due to its high activation and contamination levels.

- In the shield
- Ten d
- optir

Final shielding design, being the optimized choice in material, dimensions and installation position



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.

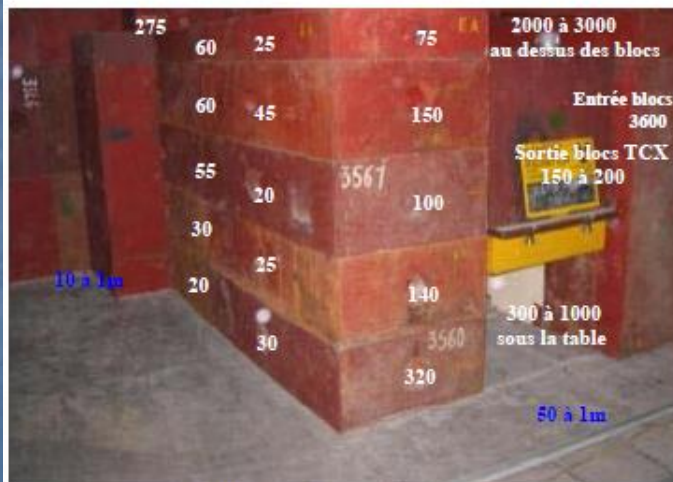
$$\text{Total dose} = \sum_i \text{Dose rate}_i \times \text{Time}_i$$

Dose rates based on measurements and simulations

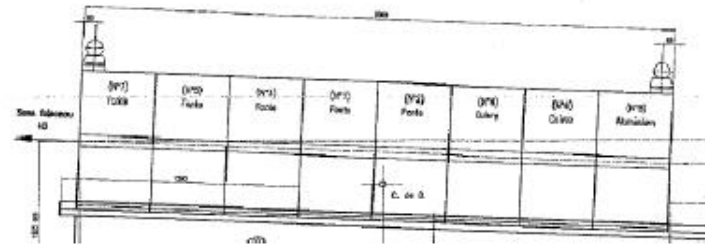
Example: Work in a former SPS target area

Dose estimate based on:

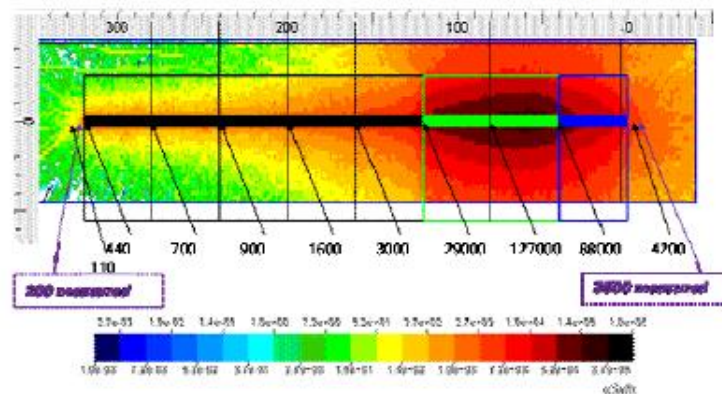
- Real measurements (accessible areas)
- Fluka calculation



SURVEY TCX shielding 17/12/09
Dose rates [$\mu\text{Sv/h}$] 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 and Reflector Repair

level II

→ optimisation and documentation

→ 1.6 mSv collective dose



Shielded cabin

Mobile lead shield



End of lecture in 2016

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 \leftrightarrow 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)

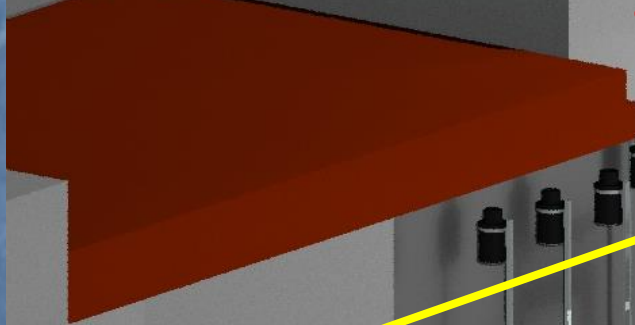
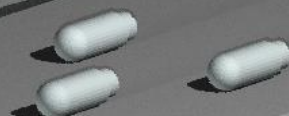
- PMI chambers: exposed to high-energy particles occurring close to a target
- IG5 chambers: exposed to the same radiation field, however attenuated by 80 cm of concrete.



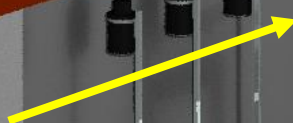
IG5: High pressure ionization chamber



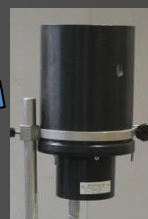
Concrete shielding



Hadron beam



Copper target



PMI: Air filled ionization chamber



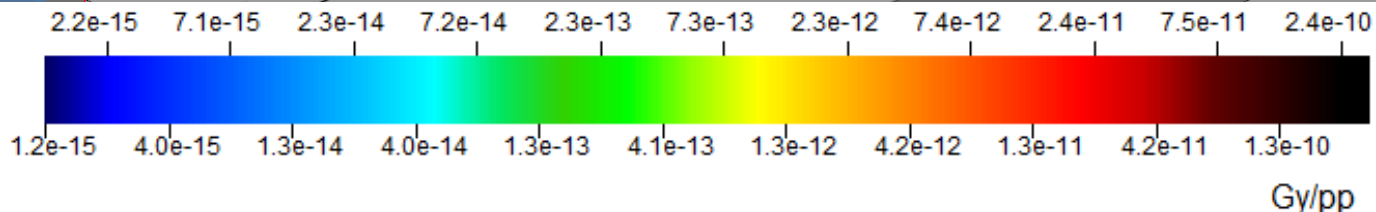
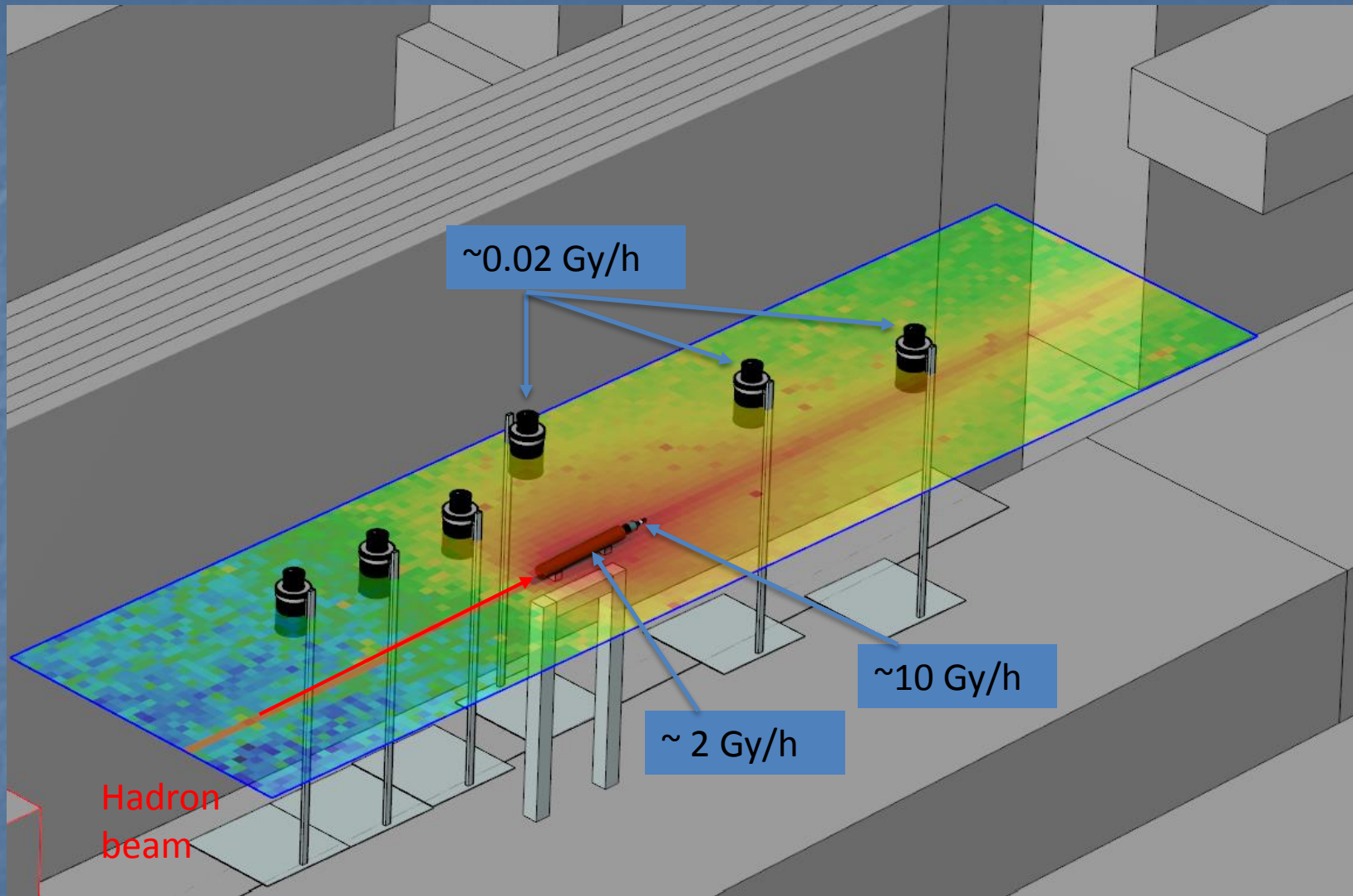
1 m

What is CERF?

An irradiation facility at CERN providing high-energy mixed radiation fields

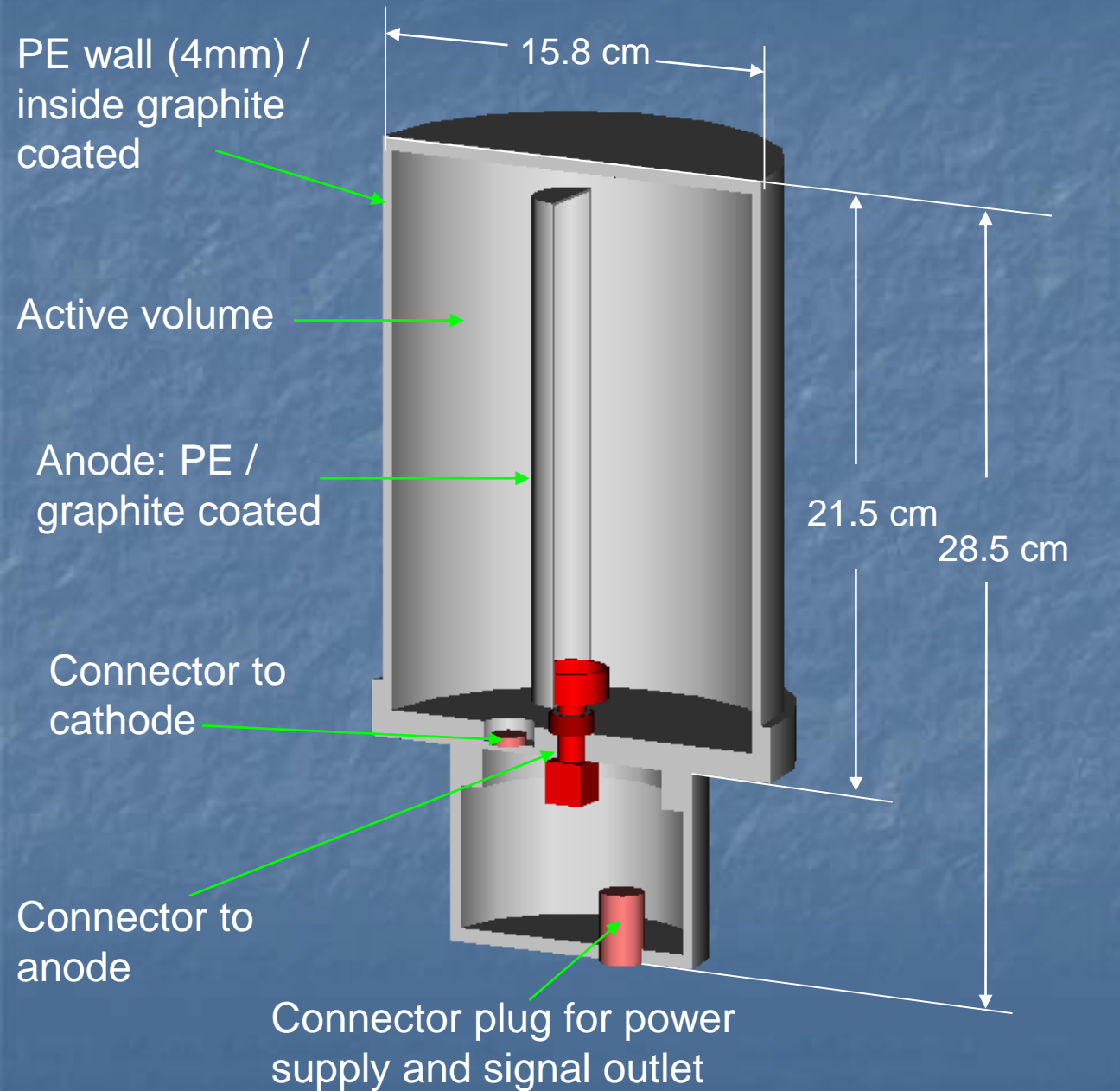
How? → A mixed hadron beam (in this setup 120 GeV/c) is intercepted by a copper target → high-energy mixed radiation field produced by EM and hadronic cascades

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-H₂

Filling gas: air
atmospheric pressure

Active volume: 3l

Working voltage:
~460 V

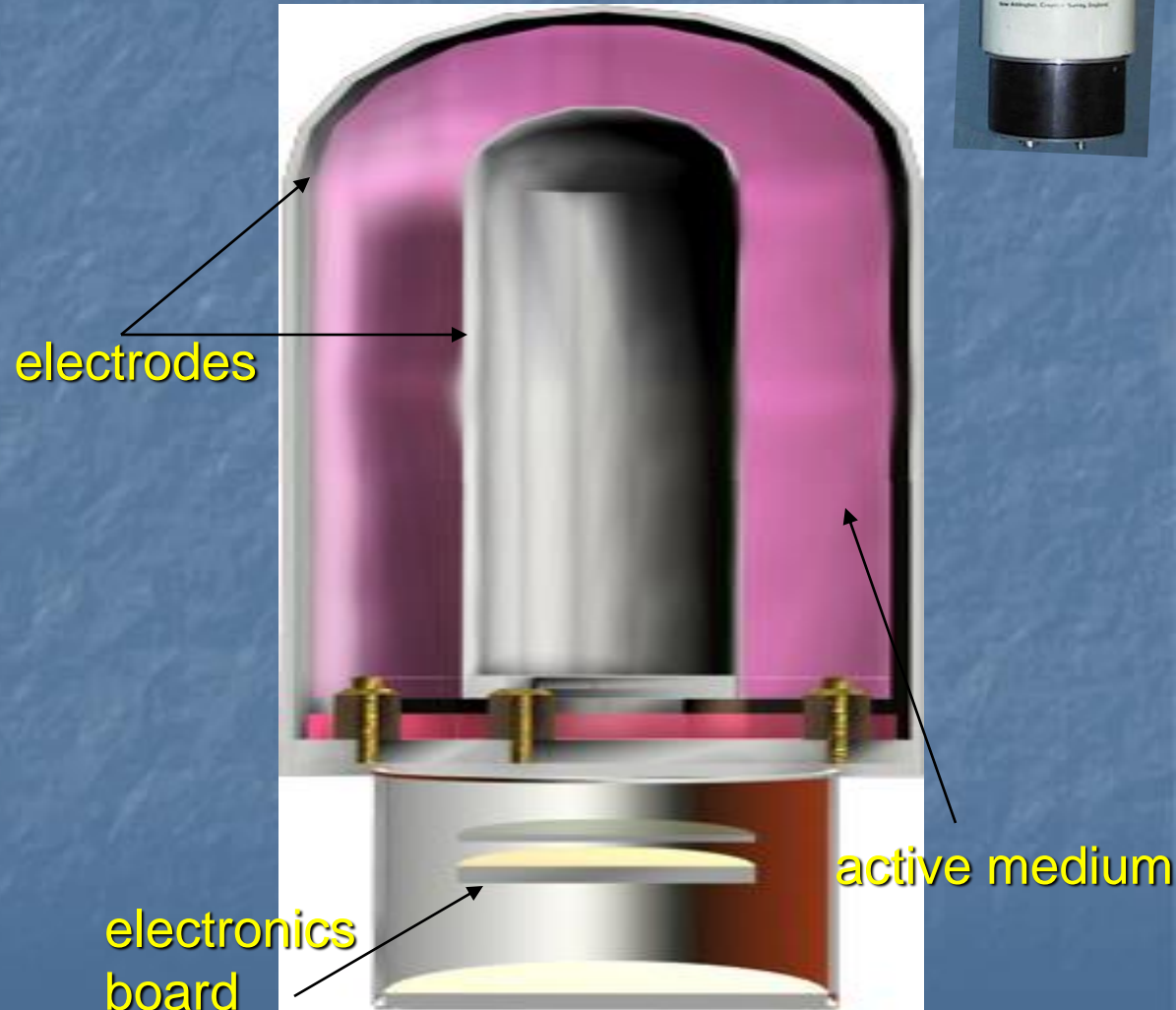
IG5 - Geometry

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 [$C\text{ cm}^2$]

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

C) Combination of A and B



Simulated counting rate of detector

A) Simulation of Response Functions

Circular parallel beam

Energy deposition in active volume

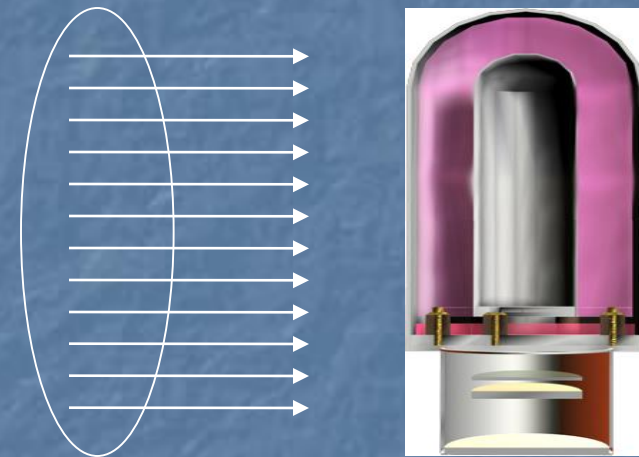
Calculate number of ion pairs created

Charge created within active volume

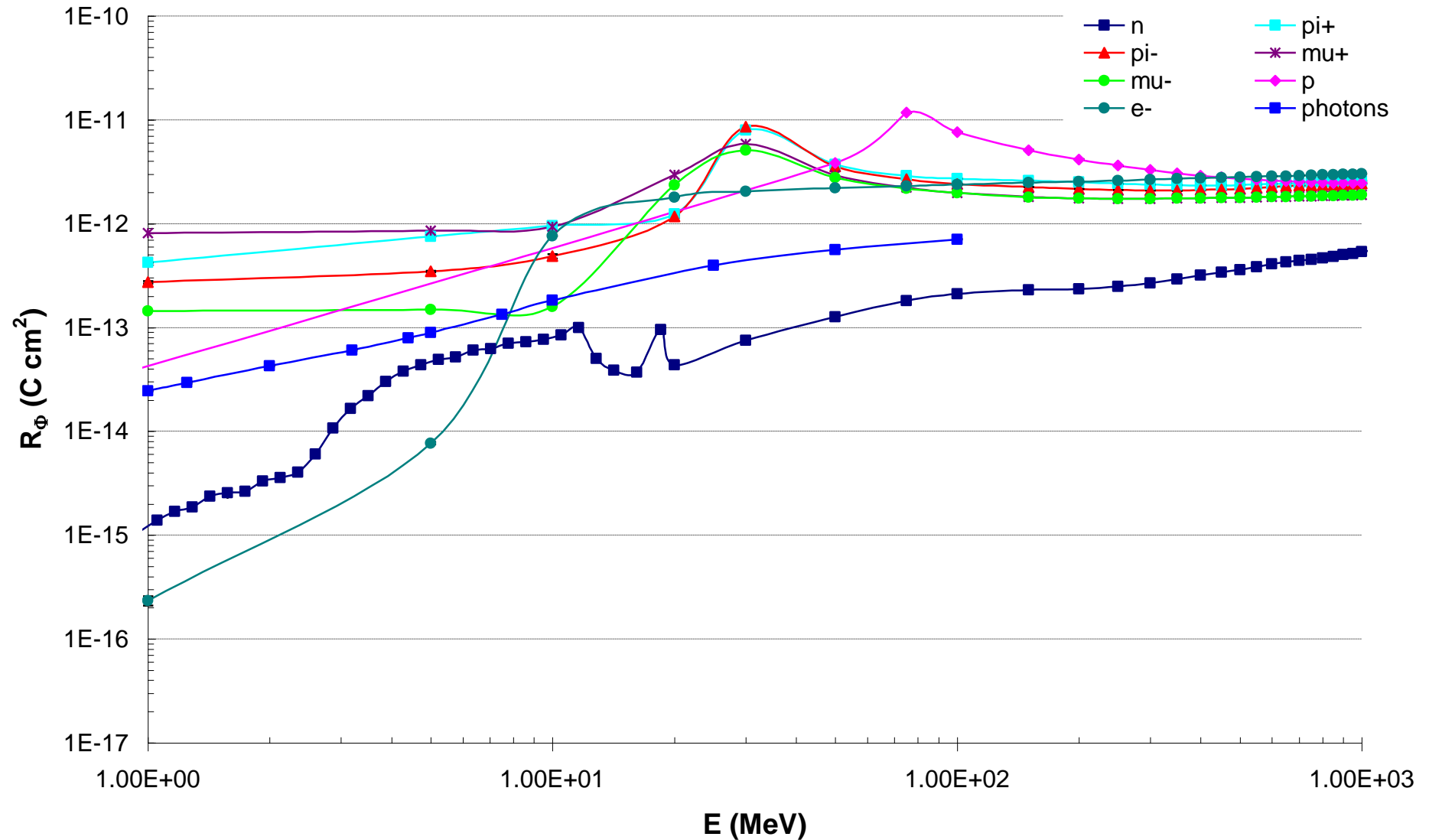
Conversion factors

Response R_{Φ} [C cm²]

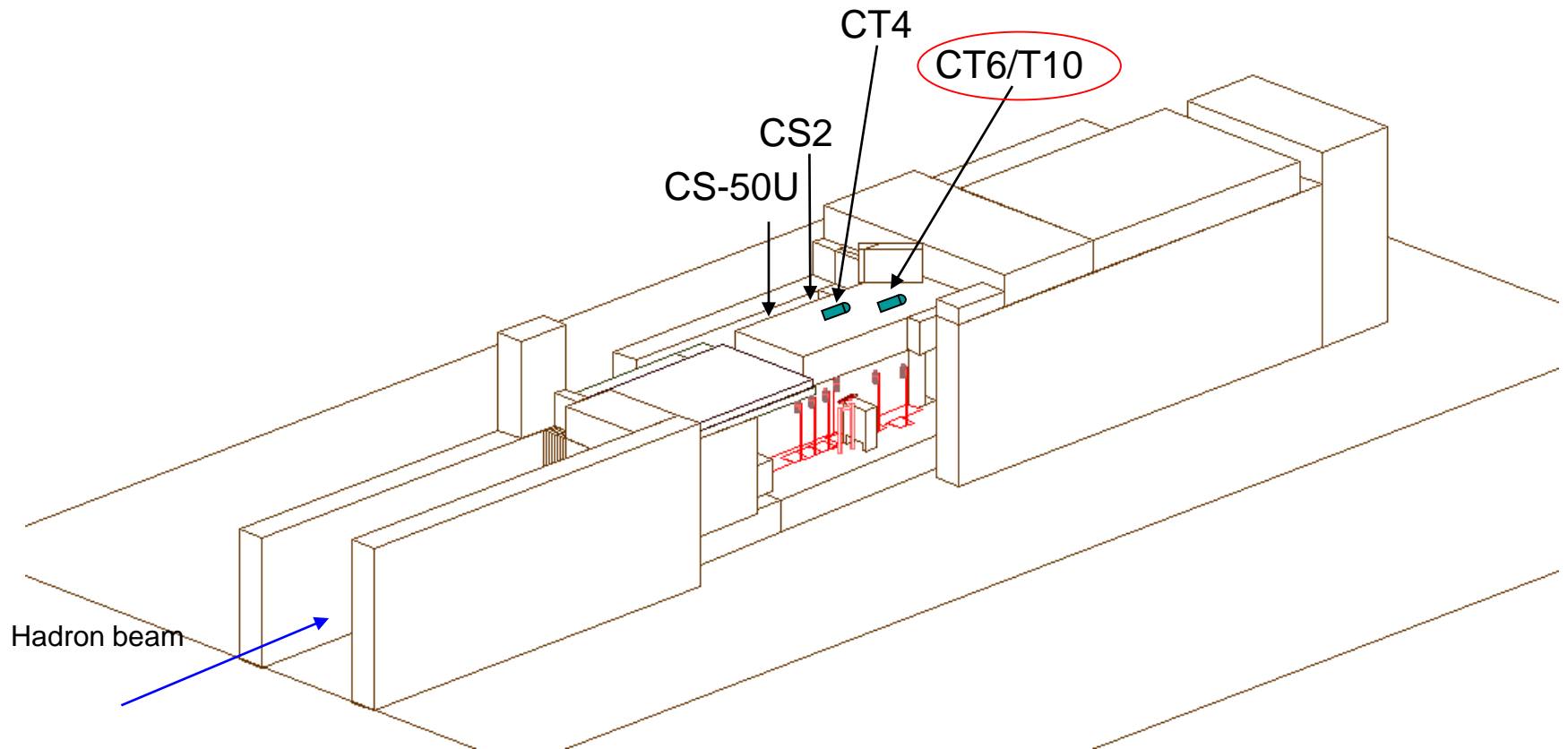
Response R_{K_a} [C/Gy], $R_{H^{*10}}$ [C/Sv]



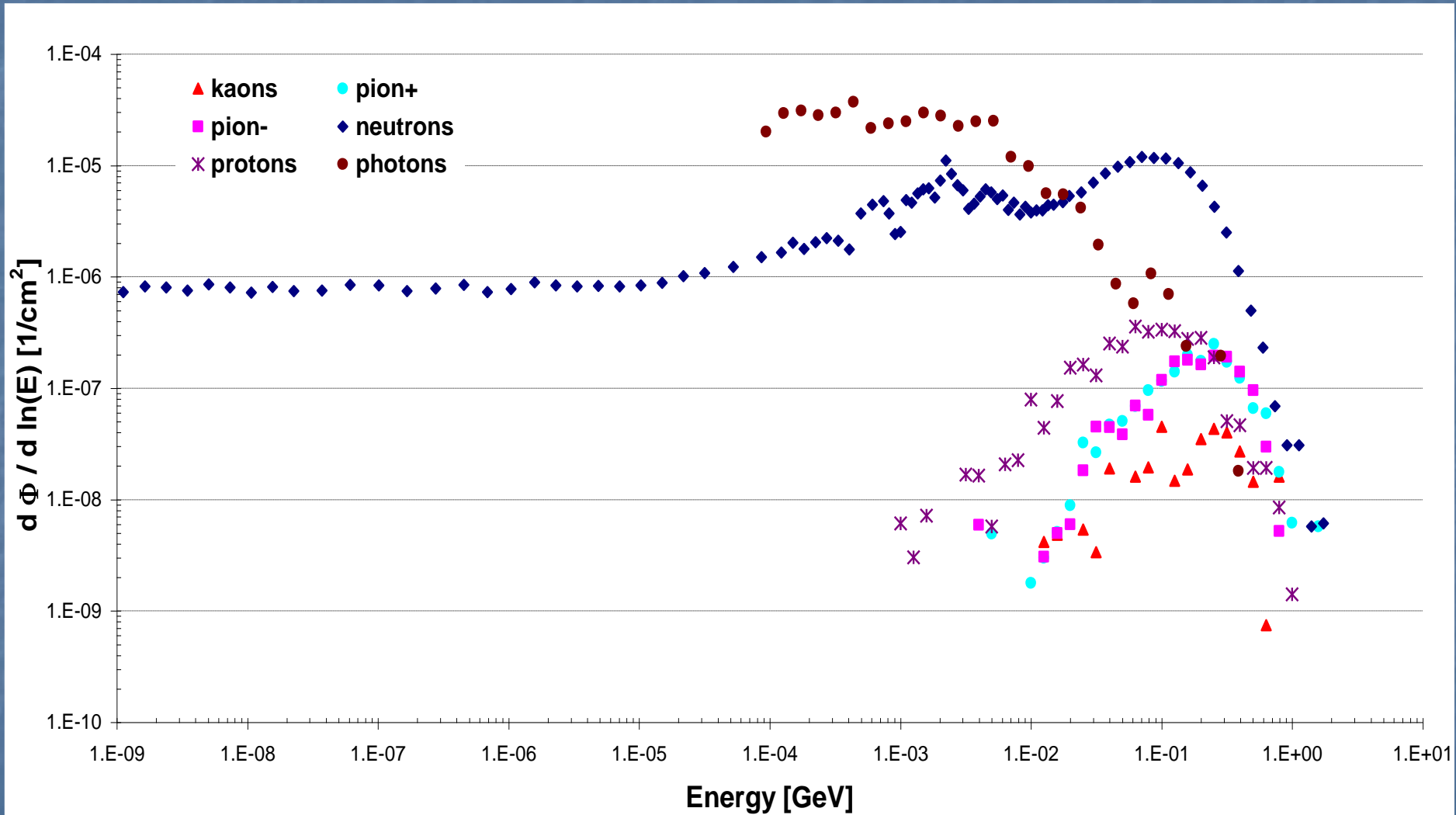
Response to var. particles (R_{Φ} for Ar)



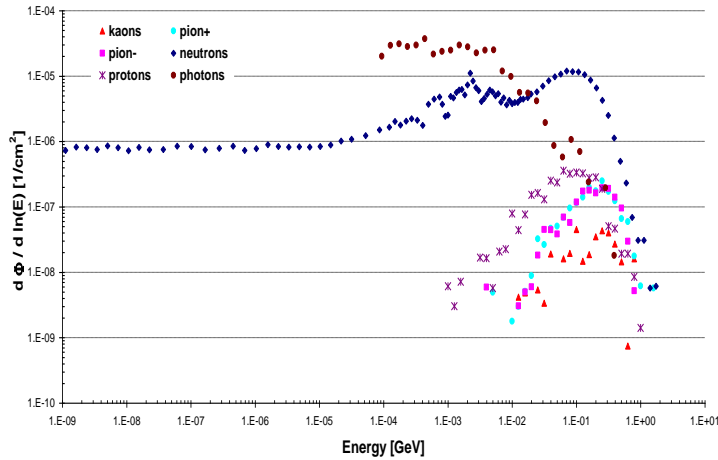
B) Calculation of fluence in the range of the measurement positions



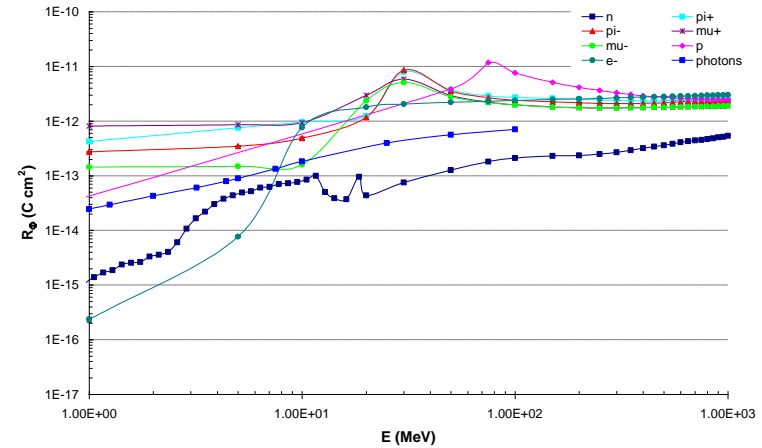
B) Particle fluence at detector position (CT6/T10)



C) Combination of A and B



X



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

Charge leads to counting rate of detector

Convolution between fluence and response functions (CT6/T10)

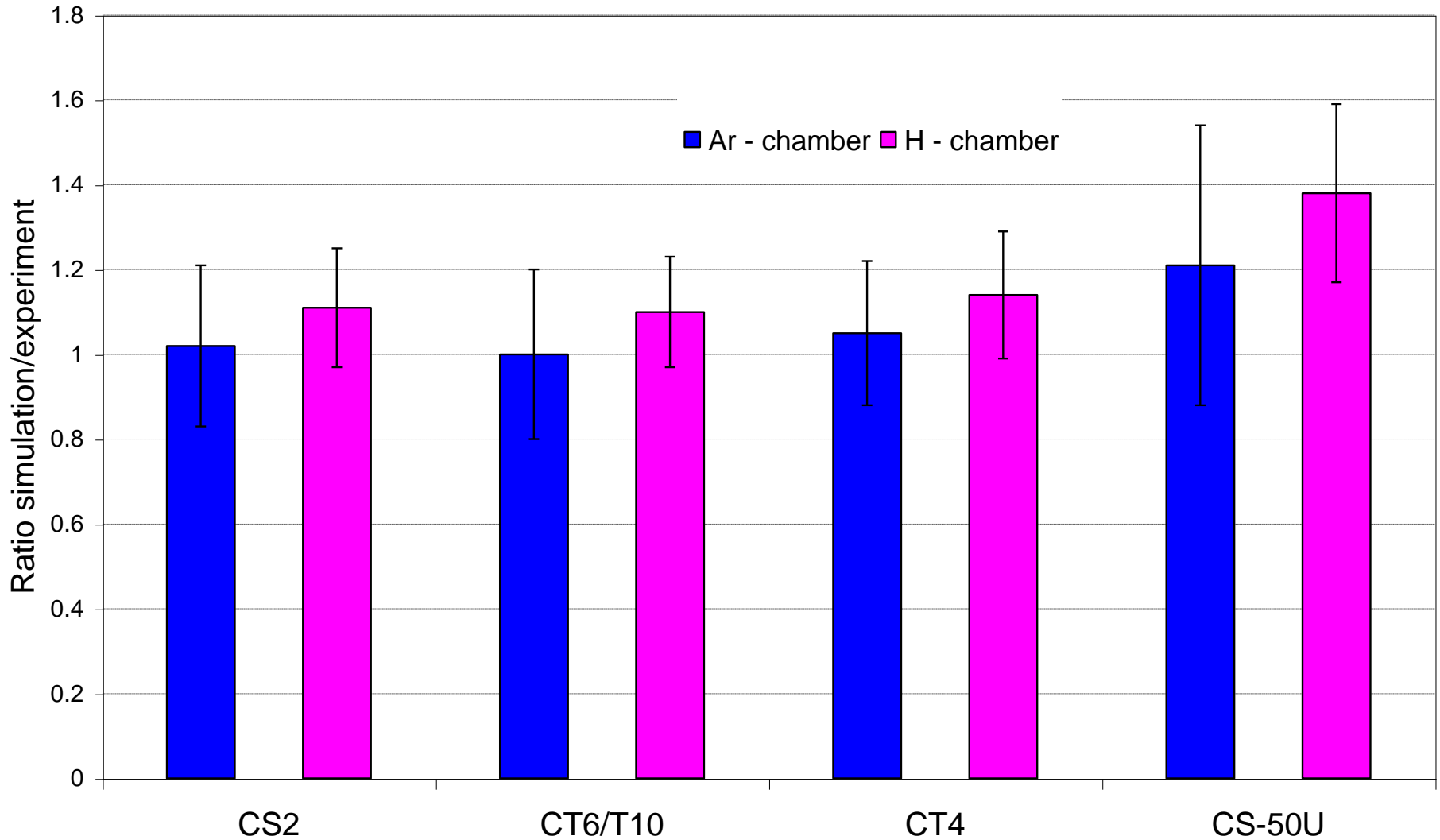
Total contribution to response (Ar)

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

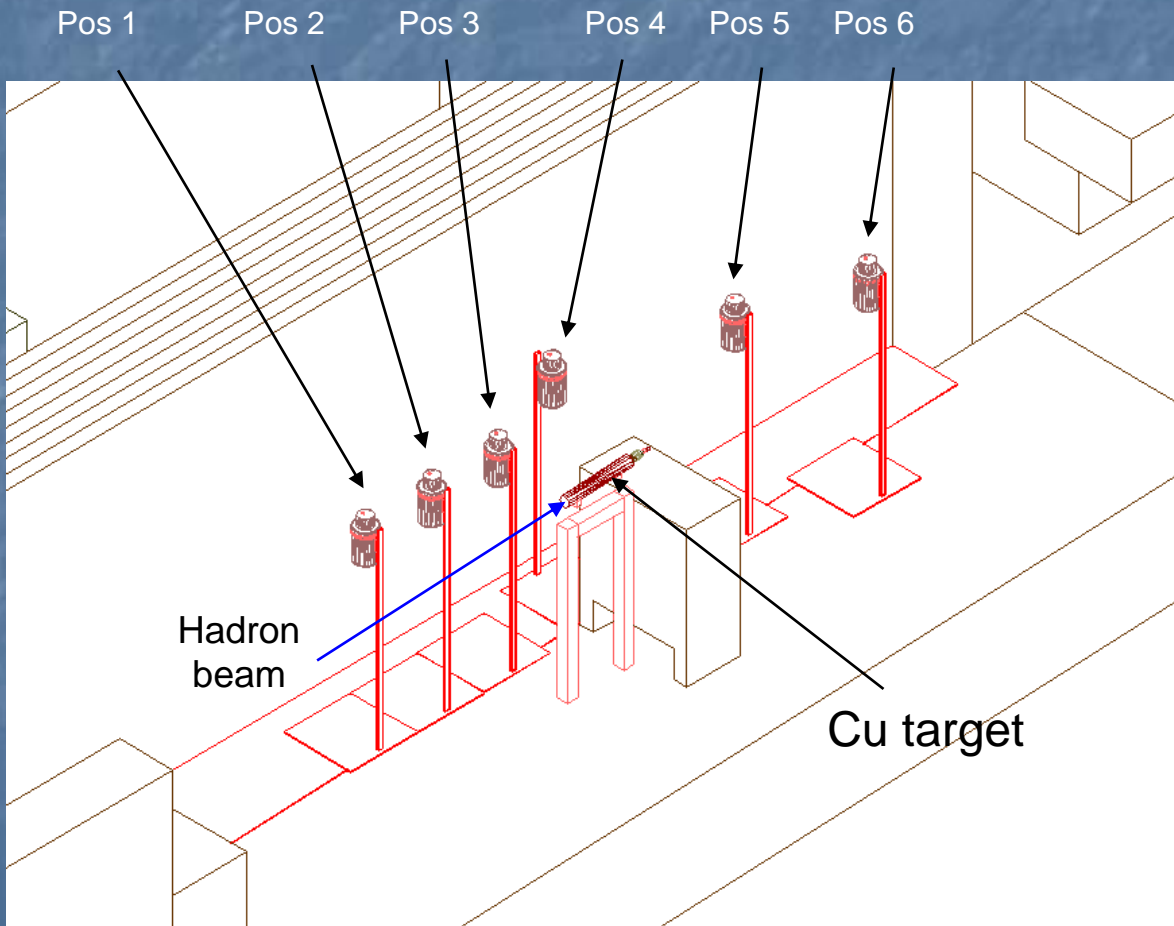
Total contribution to response (H)

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:

$9 \cdot 10^7$ 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

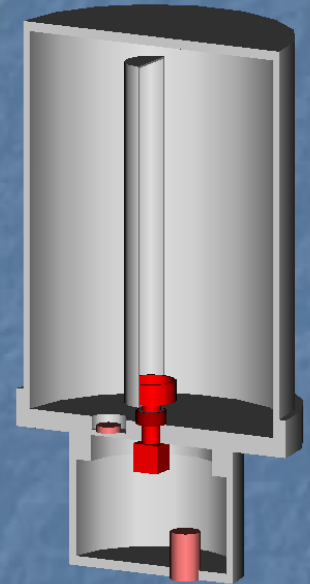
FLUKA calculation of the whole particle cascade
in the experimental setup

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.

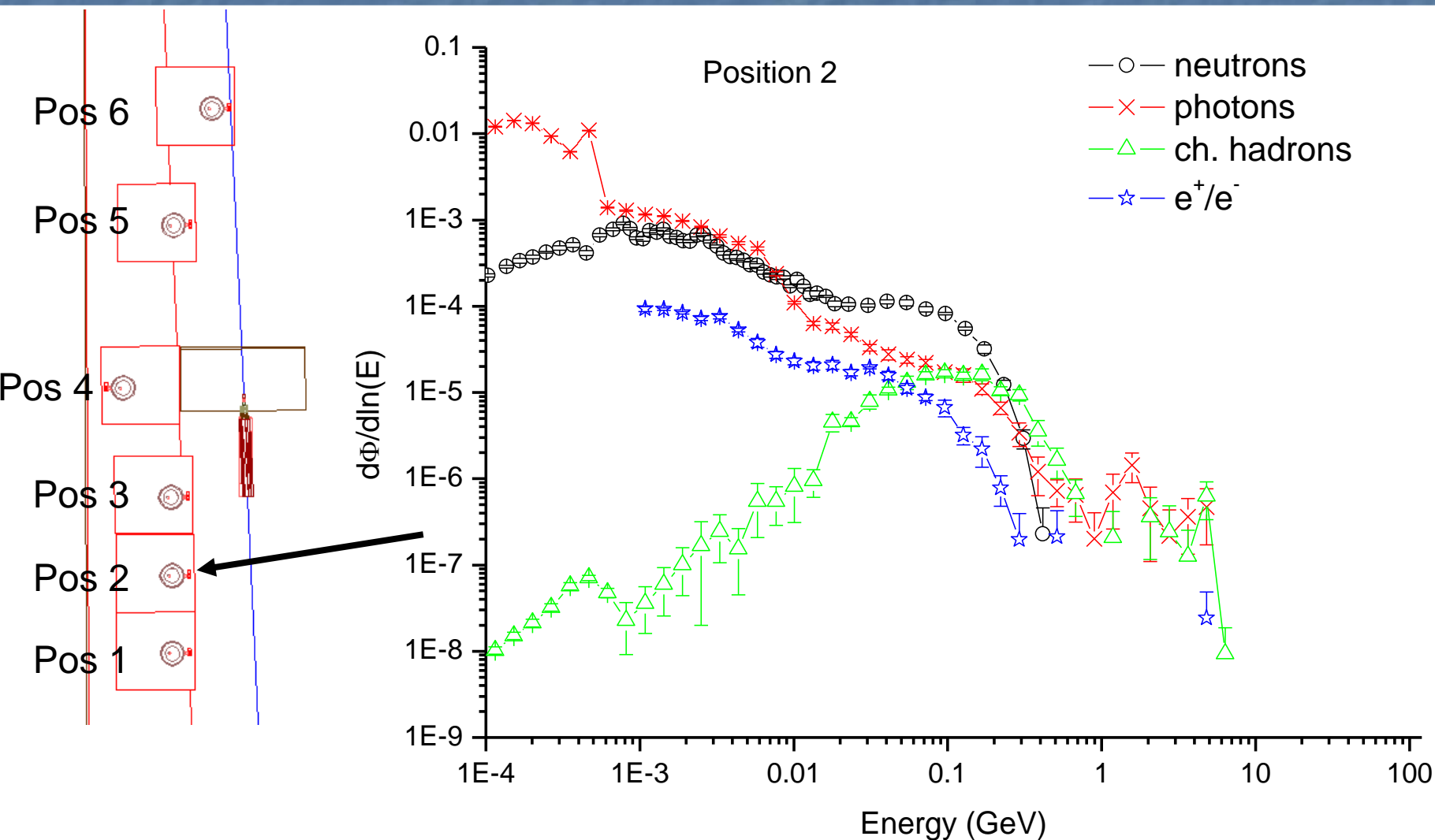
Conversion of number of ion⁺/e⁻ pairs into pC.

One pC corresponds with one
PMI counts.

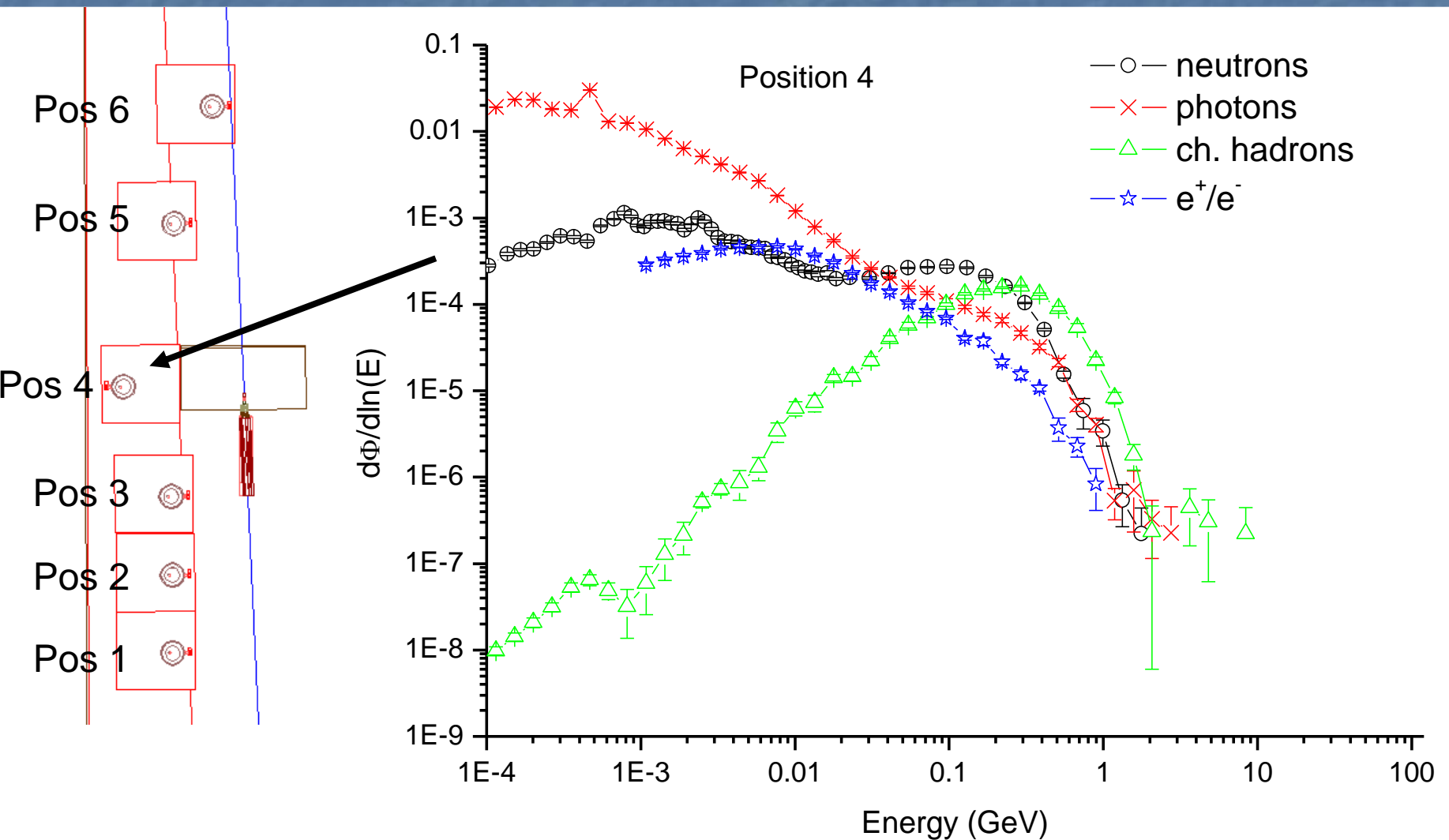


Analysis of the fluence reaching the various detector positions

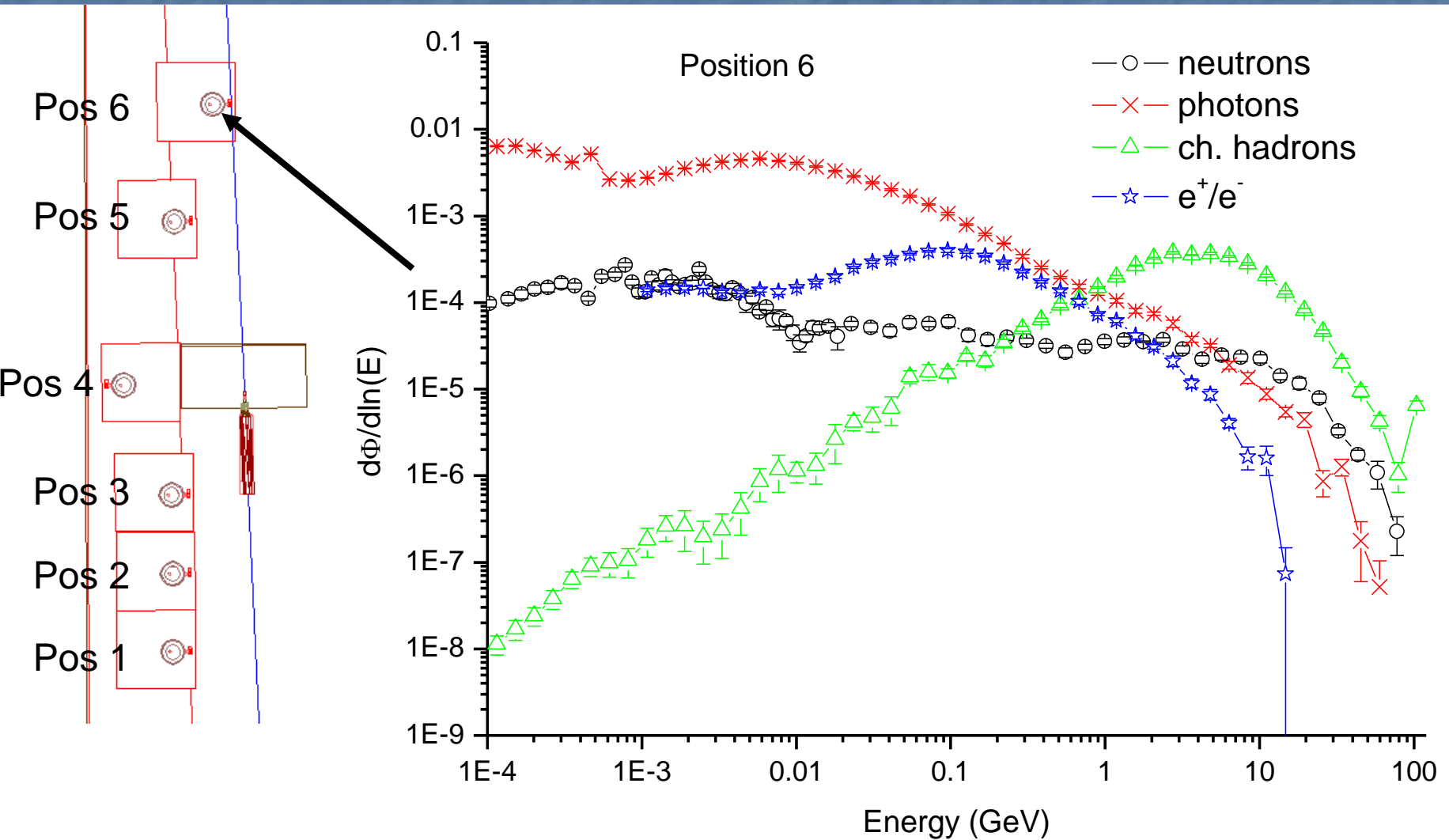
Particle fluence at detector position 2



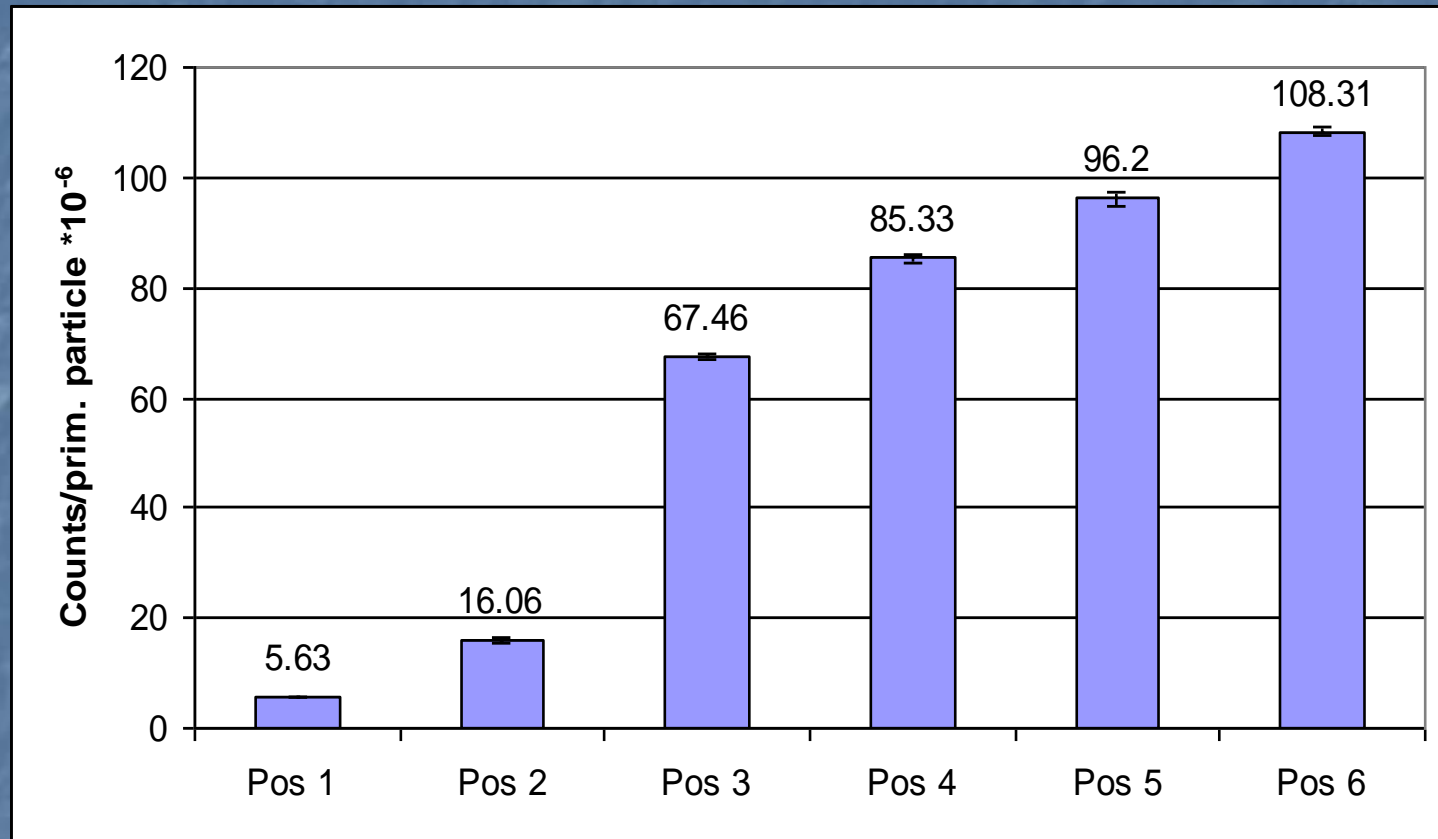
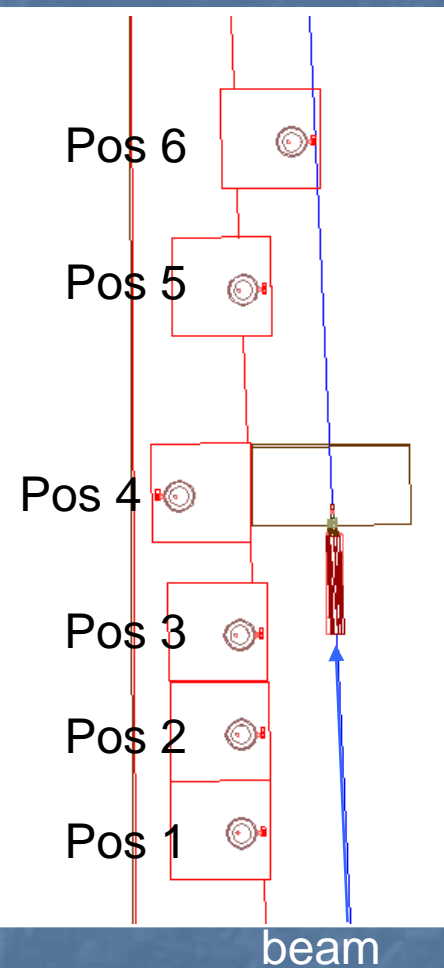
Particle fluence at detector position 4



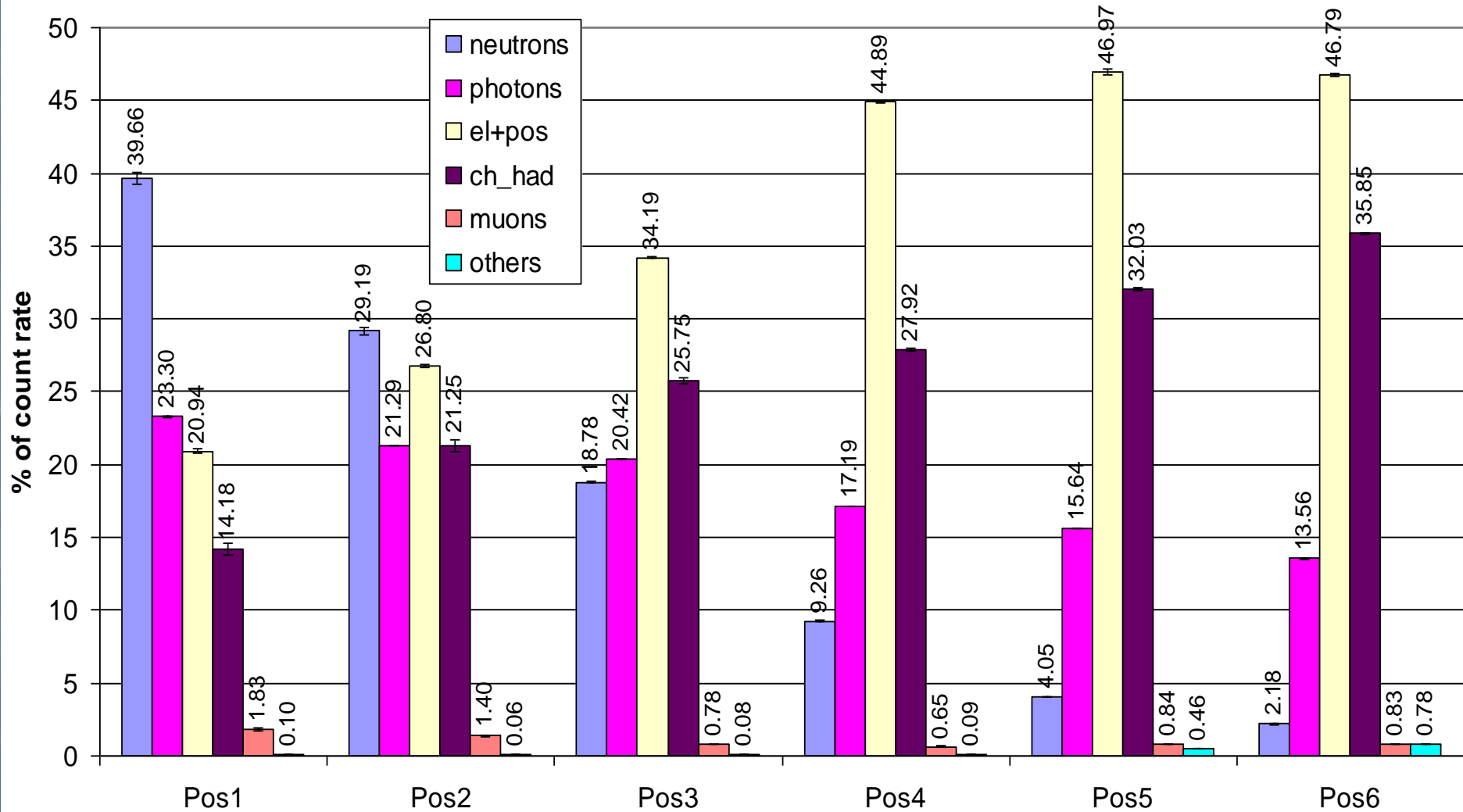
Particle fluence at detector position 6



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



Merci Beaucoup !