Radioactivation at Supercolliders

M. Huhtinen

CERN
CH-1211 Geneva, Switzerland

Outline

Supercollider (LHC) parameters

Hadron fluxes in (LHC) experiments

Production of radioactivity

Computational methods

Parametrisations

Experimental verification

How to cope with radioactivation

The issue of radioactive waste

Extrapolations to next generation colliders

The is not a talk on radiation protection legislation, but a physicists talk on predicting radioactivity levels

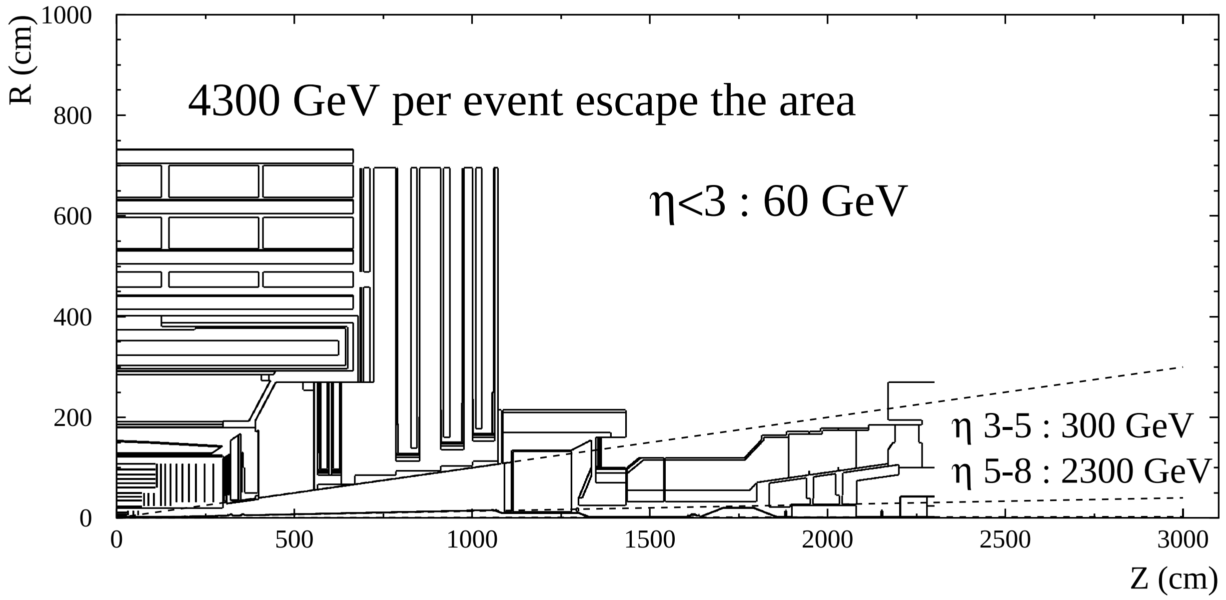
Supercollider (LHC) parameters

Beams: 2×7 TeV protons

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

Collision rate: 8×10^{8} pp per second

Energy dissipation in experimental area



Most energy deposited in very forward region

$\Downarrow$

Highest activation in very forward region

The LHC Environment

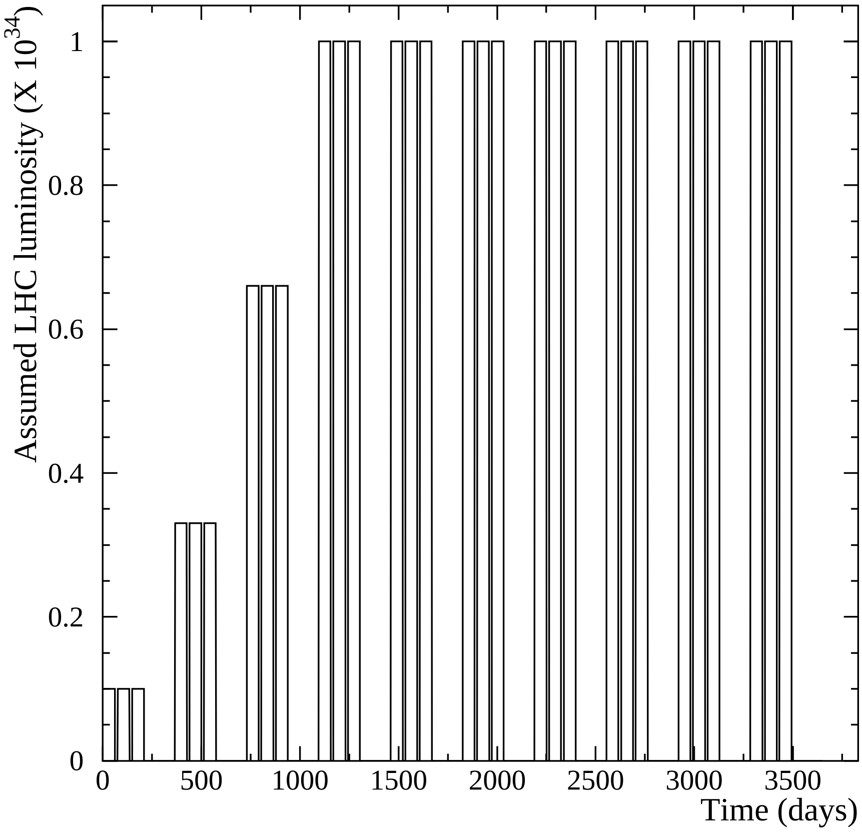
Day-average luminosity is about 5×10^{33} cm^{-2}s^{-1}

We assume

3 periods of 60 days consecutive running per year

and a slow luminosity increase

10% – 33% – 67% for first 3 years, thereafter 100%



Important input for activity buildup and decay calculations

Radioactivity Production and Accelerators

High-energy inelastic hadronic interactions

Usually dominant at hadron machines ($\sigma \sim$1 b)

“All” isotopes below target $A_T + 1$, $Z_T + 2$ produced

Neutron reactions (thermal–20 MeV)

Can be important for some materials (Al)

Can be dominant for some materials (Ag, Au,...)

Cross sections 0–50 kb

Photo-nuclear reactions

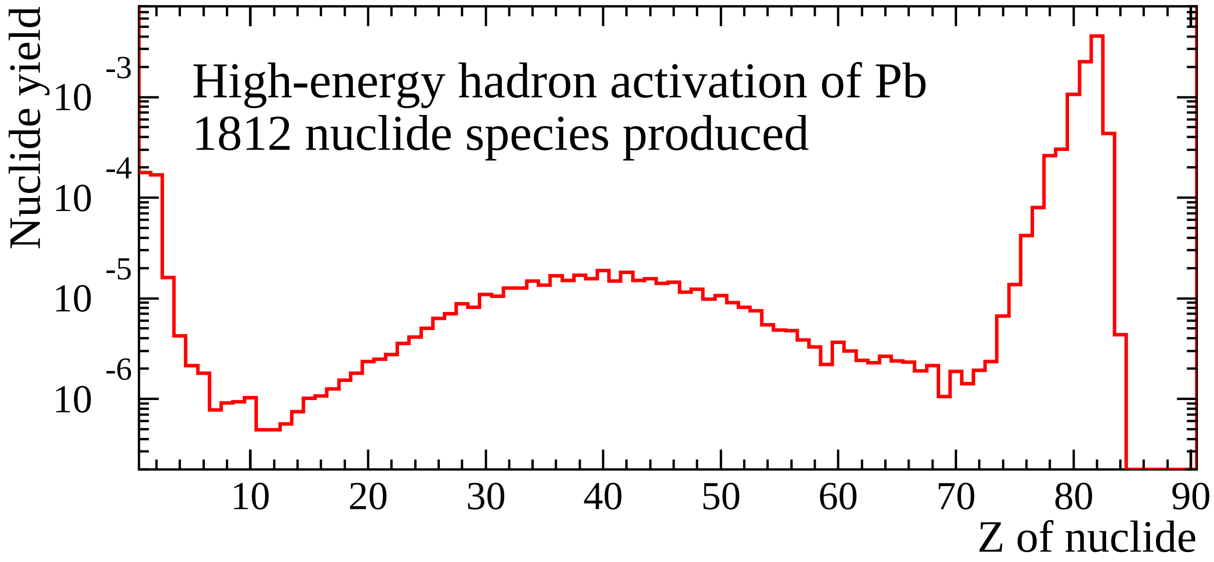
Important only at e^+e^- machines

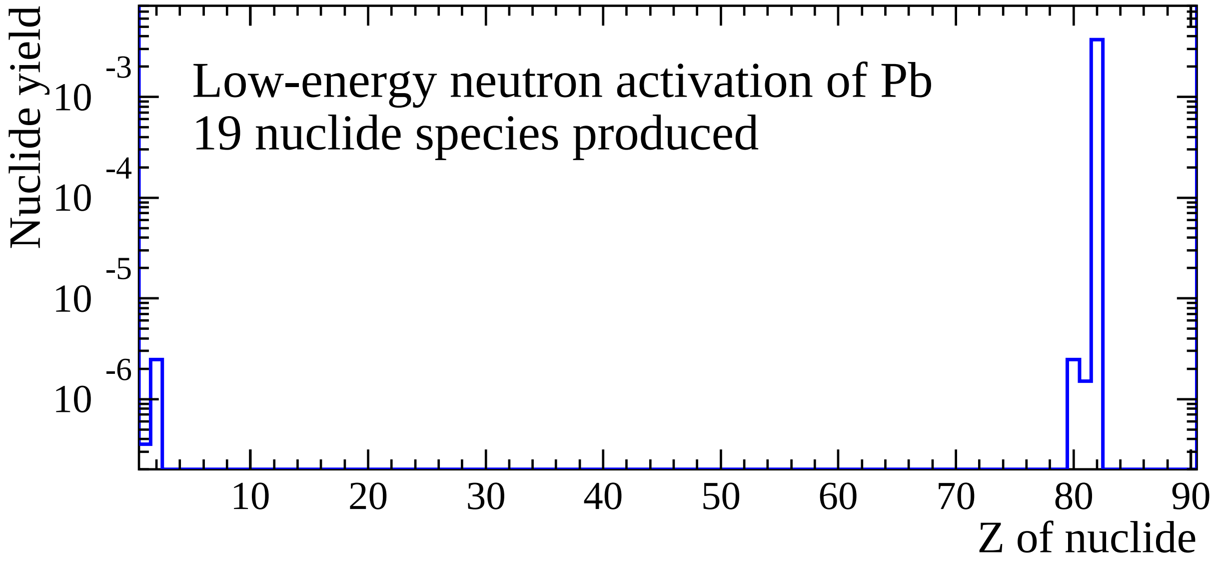
Muon-nuclear interactions

Negligible in high-radiation areas

Due to deep penetration significant for environment (ground water & rock activation)

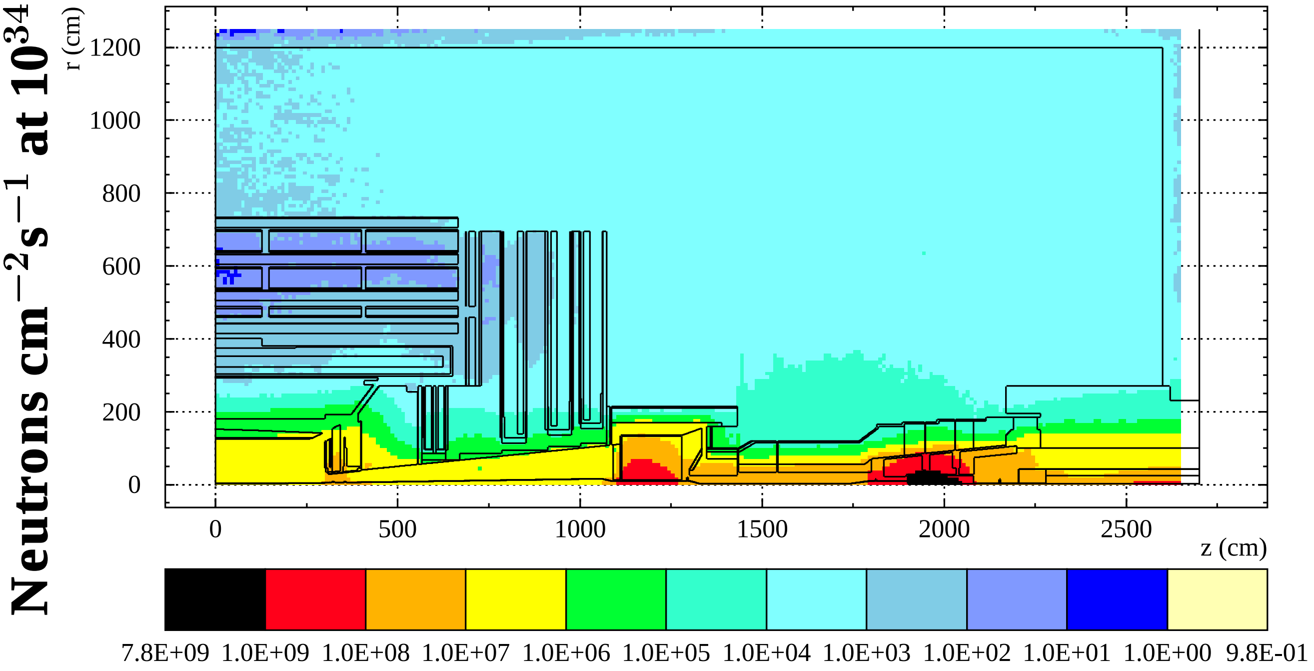
Nuclide yields in lead

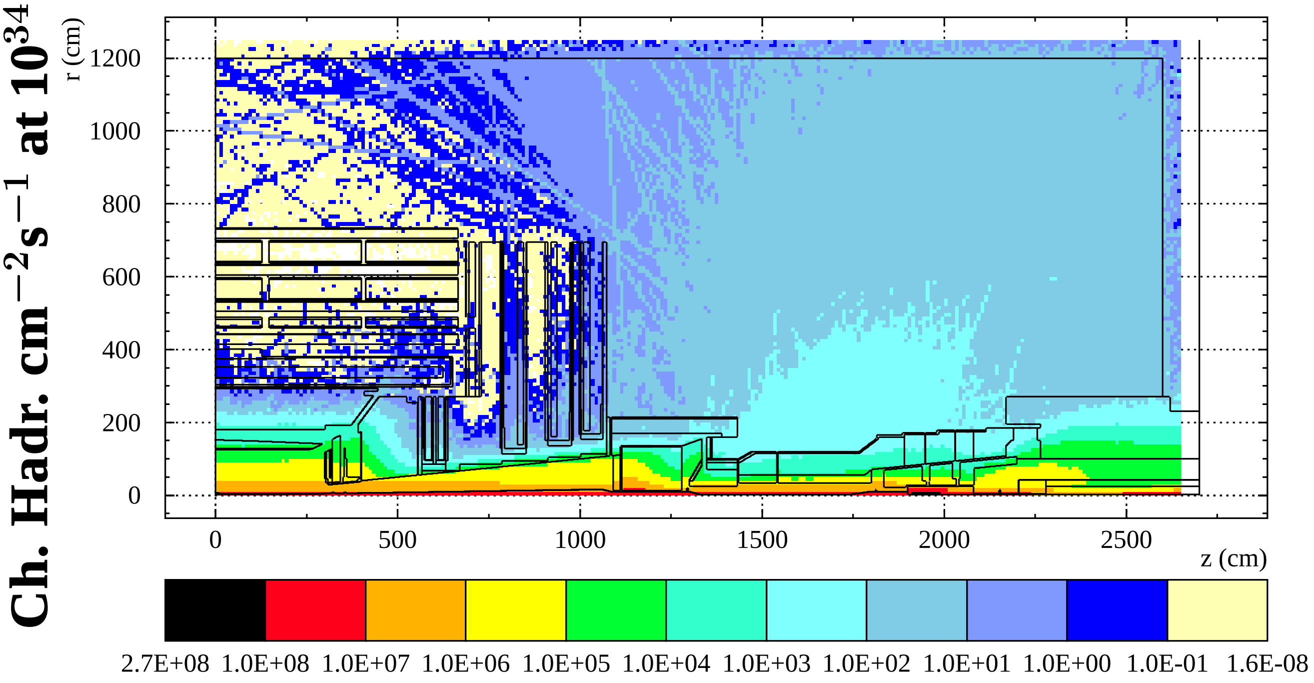




(Simulated data)

CMS Neutron and Charged Hadron Fluxes





Radiological quantities etc

Activity (A): **Bq $\equiv$ one decay per second**

Dose (D): **Sv (for γ,$e^{\pm}$) $\equiv$ Gy $\equiv$ J/kg**

At distance r from a point source:

$$\dot{D}\left[\frac{\mathrm{Sv}}{\mathrm{h}}\right] = \frac{10^{-8}EA}{7r^2}$$

where E is the emitted γ-energy in MeV

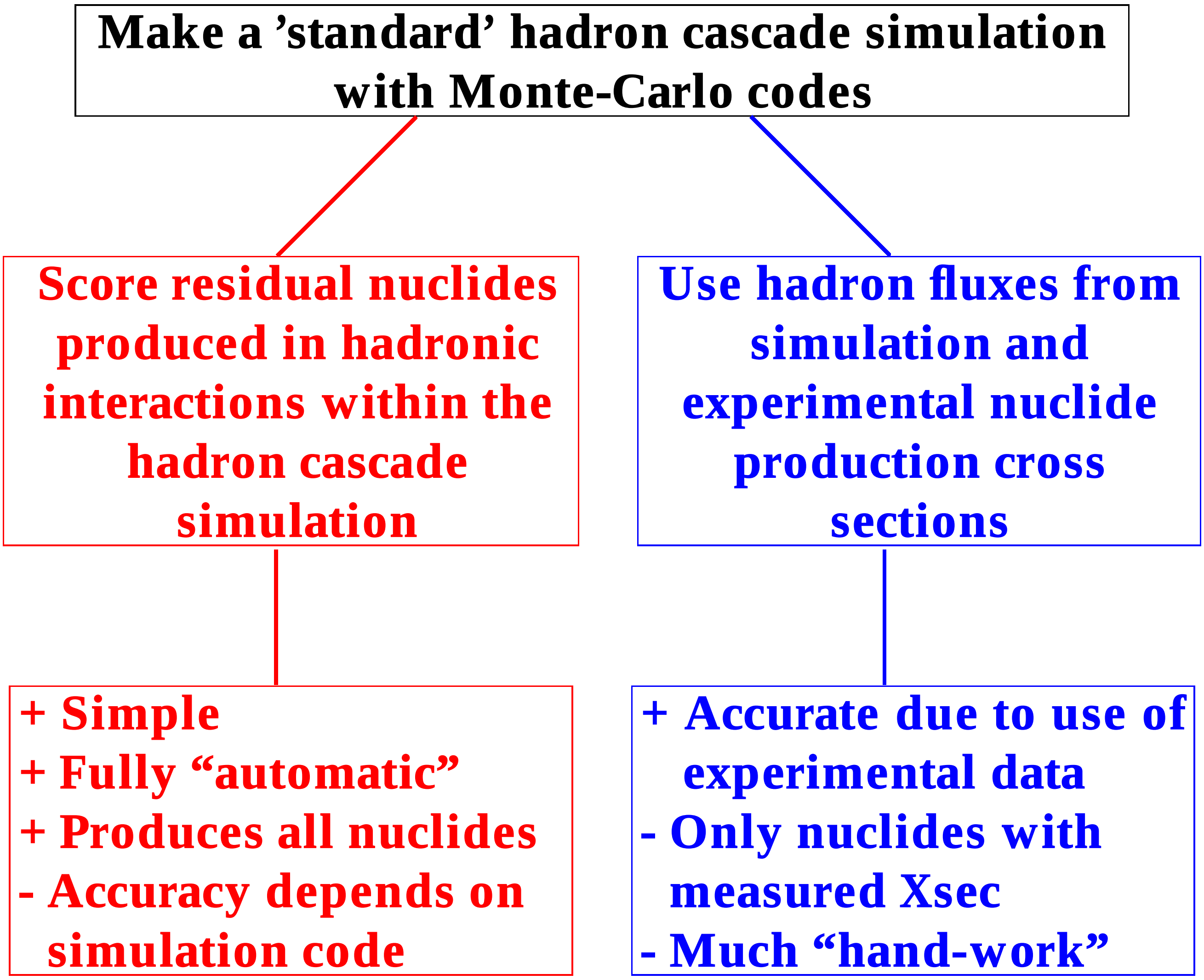
$$\Downarrow$$

Very useful unit

EA: Rate of γ-Energy emission (MeV/s)

Good indication of the radiological danger
(due to photon emission)

Computational Methods



Make a 'standard' hadron cascade simulation with Monte-Carlo codes

Score residual nuclides produced in hadronic interactions within the hadron cascade simulation

Use hadron fluxes from simulation and experimental nuclide production cross sections

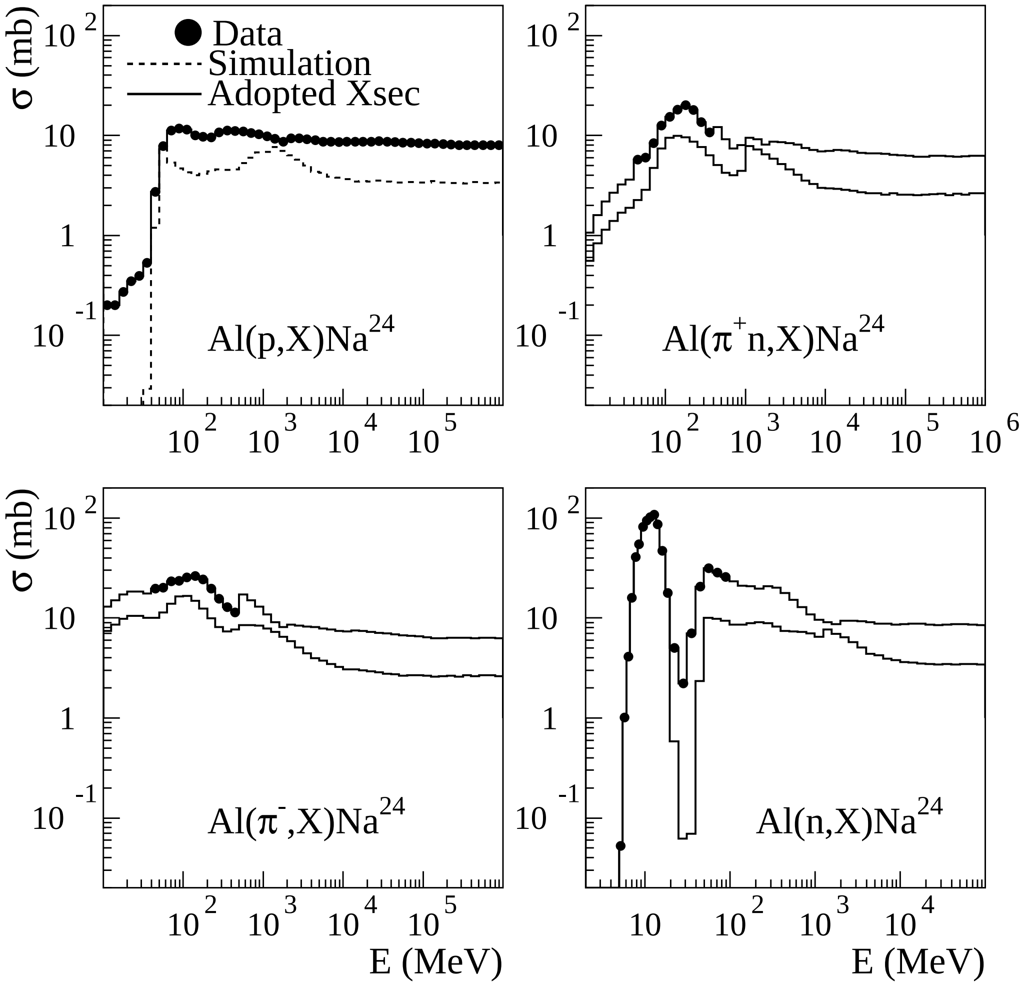
+ Simple
+ Fully "automatic"
+ Produces all nuclides
- Accuracy depends on simulation code

+ Accurate due to use of experimental data
- Only nuclides with measured Xsec
- Much "hand-work"

Best results often obtained with a hybrid of these two approaches

Typical cross sections

Cross section for ^{24}Na production in aluminium



One of the best known reactions

Still very incomplete data

Star density & activation

STAR = Inelastic hadronic interaction above given threshold (e.g. 20 or 50 MeV) for the incident hadron

In general:

For each star $\longrightarrow$ one residual nuclide

thus

Induced radioactivity $\propto$ star density

but

Activation by neutrons E<20 MeV has to be added

	Aluminium	Iron	Lead
stars E>50 MeV	28.0	33.8	34.1
stars E>20 MeV	38.2	48.1	53.6
stars E> 0	40.0	50.0	55.4
n-“flux” 1–20 MeV (cm)	1740	1720	13400
thermal n-“flux” (cm)	6.2	8.1	820
energy deposition (GeV)	7.6	8.4	7.6

Values in big cylinder hit by 10 GeV proton beam

The ω-factors

Assumption $\Longrightarrow$

The rate of γ-energy emission is proportional to star density production rate

From simple energy conservation:

The energy (E) absorbed by a unit volume (V) of an *infinite* body with *uniform* energy emission density (EA/V) is equal to the energy emitted within V

thus the dose rate in the body (density ρ) is

$$\dot{D} = \frac{EA}{V\rho}$$

The ω-factor gives the dose rate at the surface of a *semi-infinite* body with uniform star density production rate (unit [Sv/h]/[stars/(cm^{3}s)]).

ω is a function of material, irradiation and decay time

(but in reality also of the hadron spectrum...)

How to obtain the ω-factors

Well... by simulation of course !!!

The recipe

1. **Pick a hadronic spectrum**
2. **Choose a material**
3. **Extract radionuclide yield from simulation**
4. **Simulate the buildup and decay of activity**
5. **Calculate the energy emission rate EA**
6. **Calculate the dose rate $\dot{D} = EA/V\rho$**
7. **Divide by 2**
8. **Correct by $\mu_{\mathrm{EN}}^{\mathrm{tissue}}/\mu_{\mathrm{EN}}^{\mathrm{material}}$**
9. **Normalise by the (simulated) star density**

The whole issue is to get points 3 and 4 correct.
And to make sure that the hadron spectrum is representative of the case to be studied

Values of ω-factors

Values in 10^{-8} (Sv/h)/(stars/cm^3/s) for $>$20 MeV stars

High-energy hadron spectrum (CMS Tracker):

Material	$\omega(\infty,0)$	ω(30d,1d)	ω(10y,1y)
Aluminium	46	0.88	0.84
Iron	1.8	0.45	0.15
Silver	87	5.2	19
Lead	2.2	0.30	0.0055

Neutron dominated spectrum (CMS Cavern):

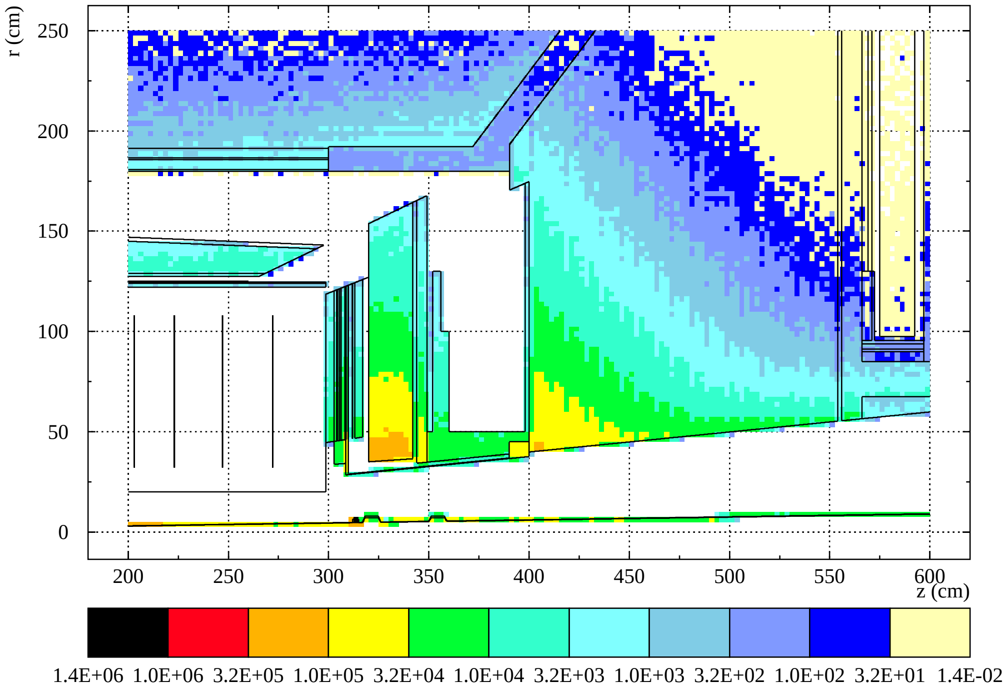
Material	$\omega(\infty,0)$	ω(30d,1d)	ω(10y,1y)
Aluminium	73	1.3	1.0
Iron	1.4	0.23	0.22
Silver	170	9.5	40
Lead	1.2	0.11	0.00062

Neutrons NOT $\propto$ stars $\rightarrow$ ω depend on spectrum

For activation the difference between 30 days irradiation and infinity is rather small

Application of ω-factors

Calculate the star density (stars/cm^3/s) with a hadron cascade code



For big* objects and uniform star density: multiply by ω-factor

For small* objects and/or non-uniform star density: see next transparency...

*(*Big and small wrt the attenuation length ∼1 MeV photons)*

Non-uniform star densities and ω-factors

...in case of non-uniform activation:

Derive emitted energy (EA) from ω-factor and integrate over the star density distribution

$$E = \left[\frac{\text{MeV}}{\text{star}}\right] = \frac{2\rho}{3600 \times 1.6 \times 10^{-10}}\omega$$

The dose at distance r (cm) is then given by

$$\dot{D}\left[\frac{\text{Sv}}{\text{h}}\right] = \frac{10^{-8}EA}{7r^2}\exp\left(-\sum_i \frac{x_i}{\lambda_i}\right)$$

where x_i is the distance in material i with attenuation coefficient λ_i and A=stars/s.

Integrate over all positions, i.e. r-values

Decay of induced radioactivity

0^{th} order rule of thumb

The effective half life of remaining induced activity is equal to the time since the end of irradiation

A better approximation

The Overton-Sullivan formula for "iron"-like materials:

$$\dot{D}(t) = D_0 \ln \frac{t_i + t_c}{t_c}$$

t_i=irradiation time and t_c=cooling time

For best accuracy & general validity

Simulate production of individual radionuclides and solve *analytically* set of coupled differential equations describing the decay

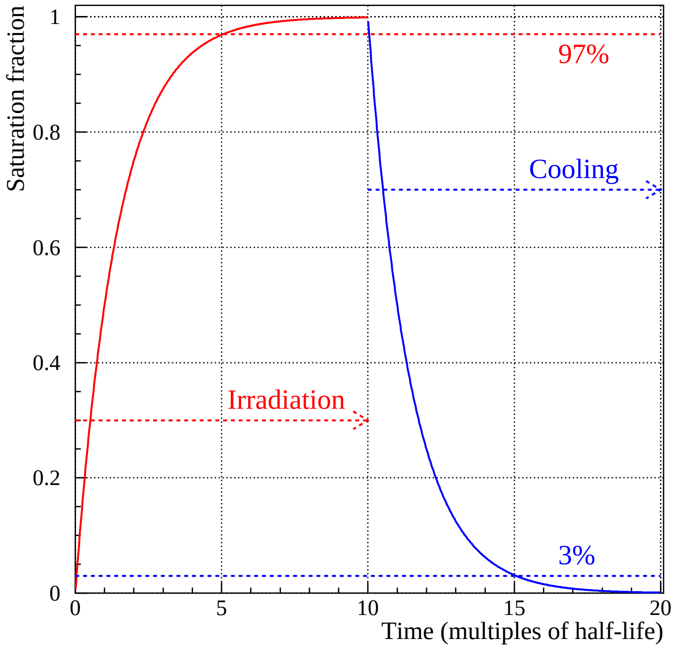
Build-up, saturation and decay

For a single nuclide with production rate P and decay constant $\lambda = \ln 2/T_{1/2}$ the activity evolves as

$$A(t_i, t_c) = P(1 - e^{-\lambda t_i})e^{-\lambda t_c}$$

where t_i and t_c are the irradiation and cooling times.

For $t_i \to \infty$ and $t_c \to 0$
$\underline{A = P\text{, i.e. saturation activity}}$

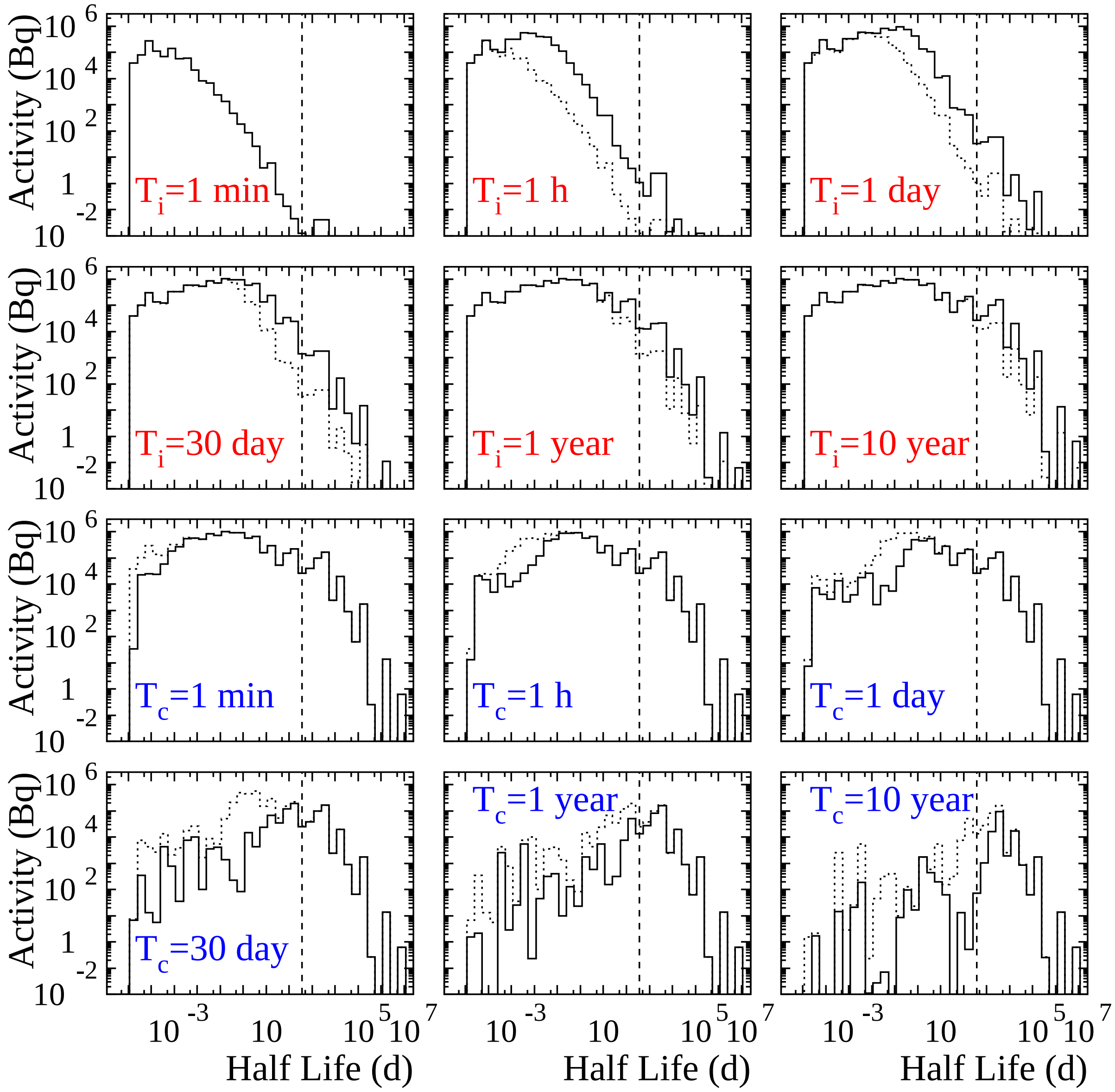


97% of saturation activity after 5 half-lives irradiation

3% of saturation activity left after 5 half-lives cooling

Half-life distributions in Pb

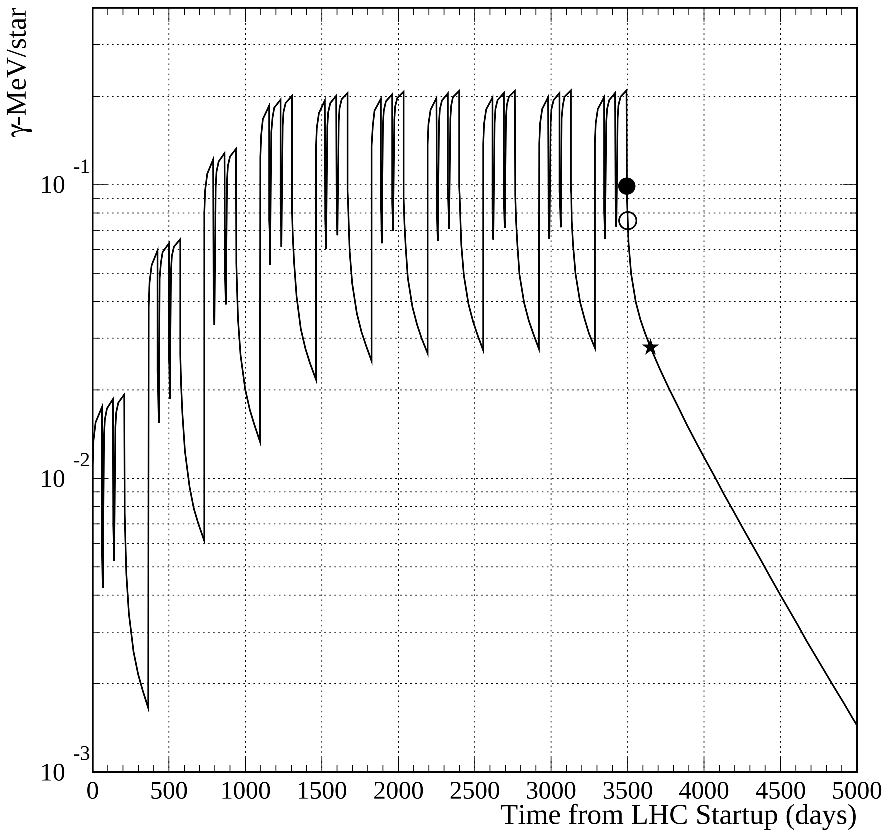
Pb sample irradiated for 10 years,
cooled down for 10 years



Activity saturation at the LHC

Example:

Activity of the steel of the CMS forward calorimeter



Luminosity increase is slow during first 3 years

0.1 γ-MeV/star $\Longleftrightarrow$ ω=3.7$\times 10^{-9}$ (Sv/h)/(stars/cm^3/s)

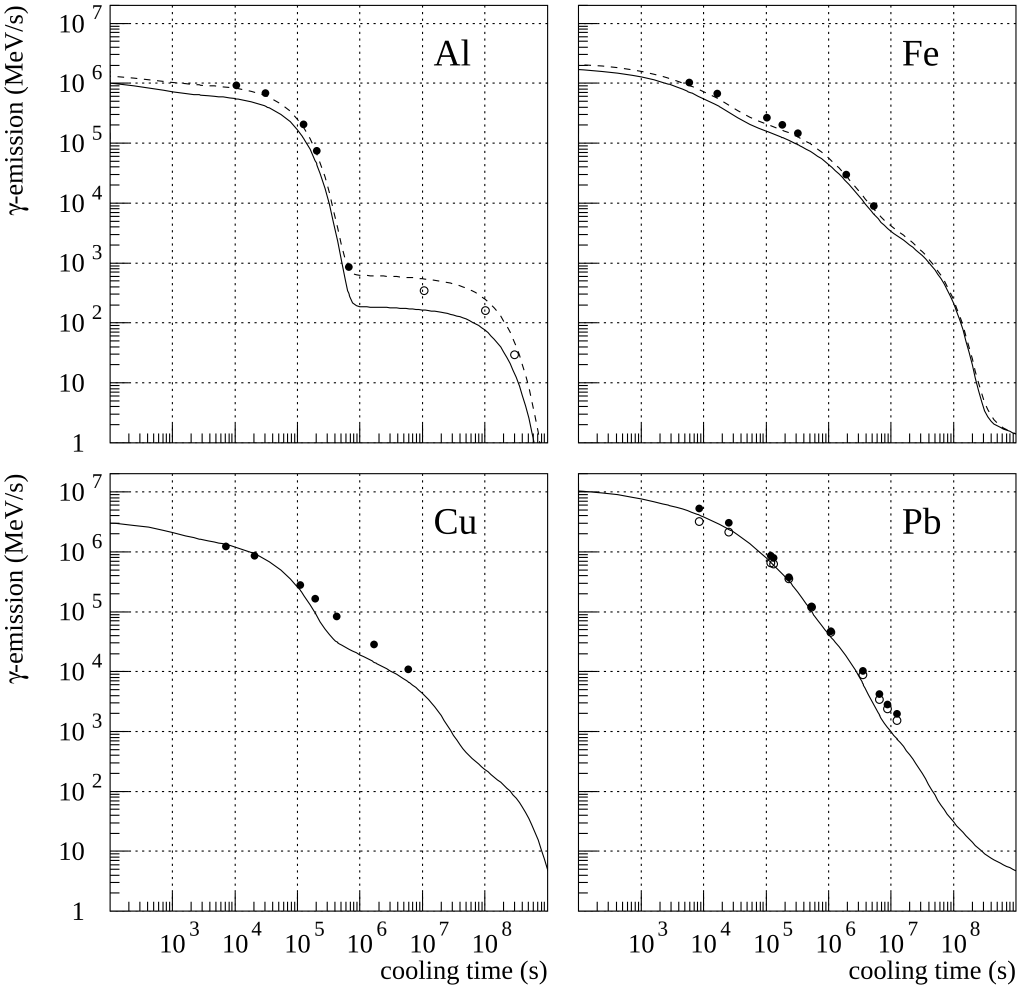
Use of "standard" $\omega(30d, 1d)$ centers nicely the dose rate predictions for LHC conditions

Induced radioactivity $\propto$ average luminosity

Benchmarking the simulations

Irradiated Al, Fe, Cu, Pb samples at CERN IRRAD2

(FLUKA for nuclide yield, DeTra for decay chains)

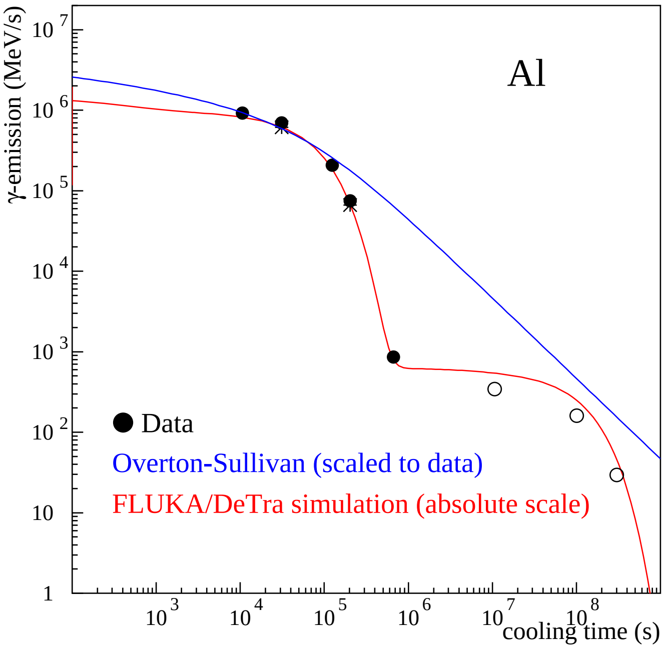


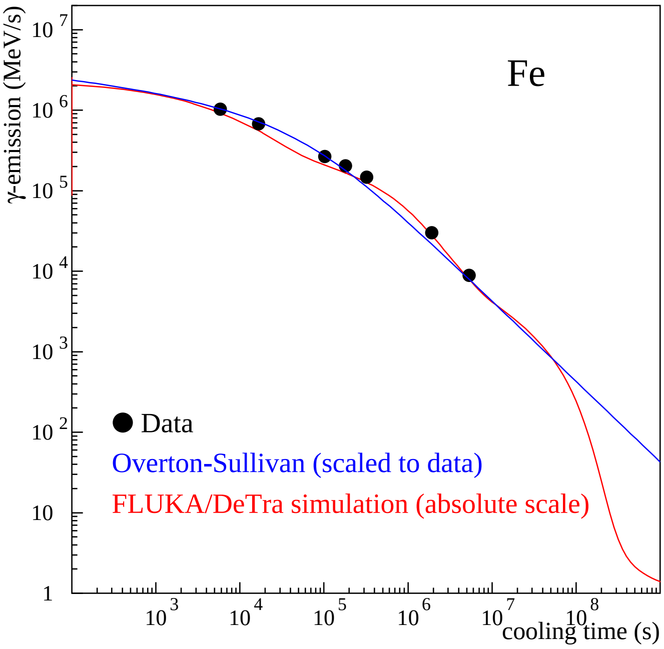
Dots: data measured with HPGe detector

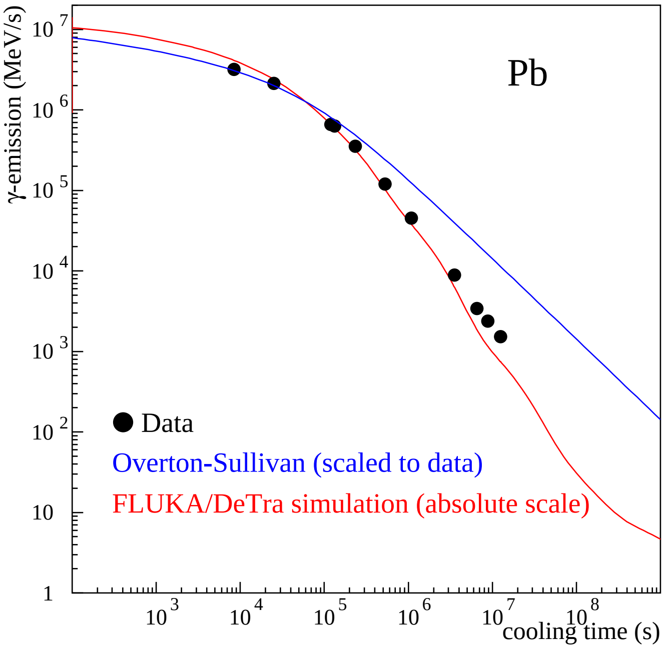
Solid lines: FLUKA ResNuc + DeTra calculation

Dashed lines: FLUKA using expt. Xsecs + DeTra

Accuracy of O-S formula







Overton-Sullivan

Is nonsense for Al,

gives good results for Fe

but fails quite badly for Pb

...but it was never claimed to be good for anything than “Fe-like” materials

Exposure limits and consequences

Annual exposure from natural radioactivity $\sim$1 mSv

CERN annual limit for radiation workers: 15 mSv

BUT

EU regulations likely to come down

Need also (safety) margin in design wrt reality

$\Downarrow$

Use a limit of 5 mSv per year per person for *design* of LHC, experiments and all access scenarios

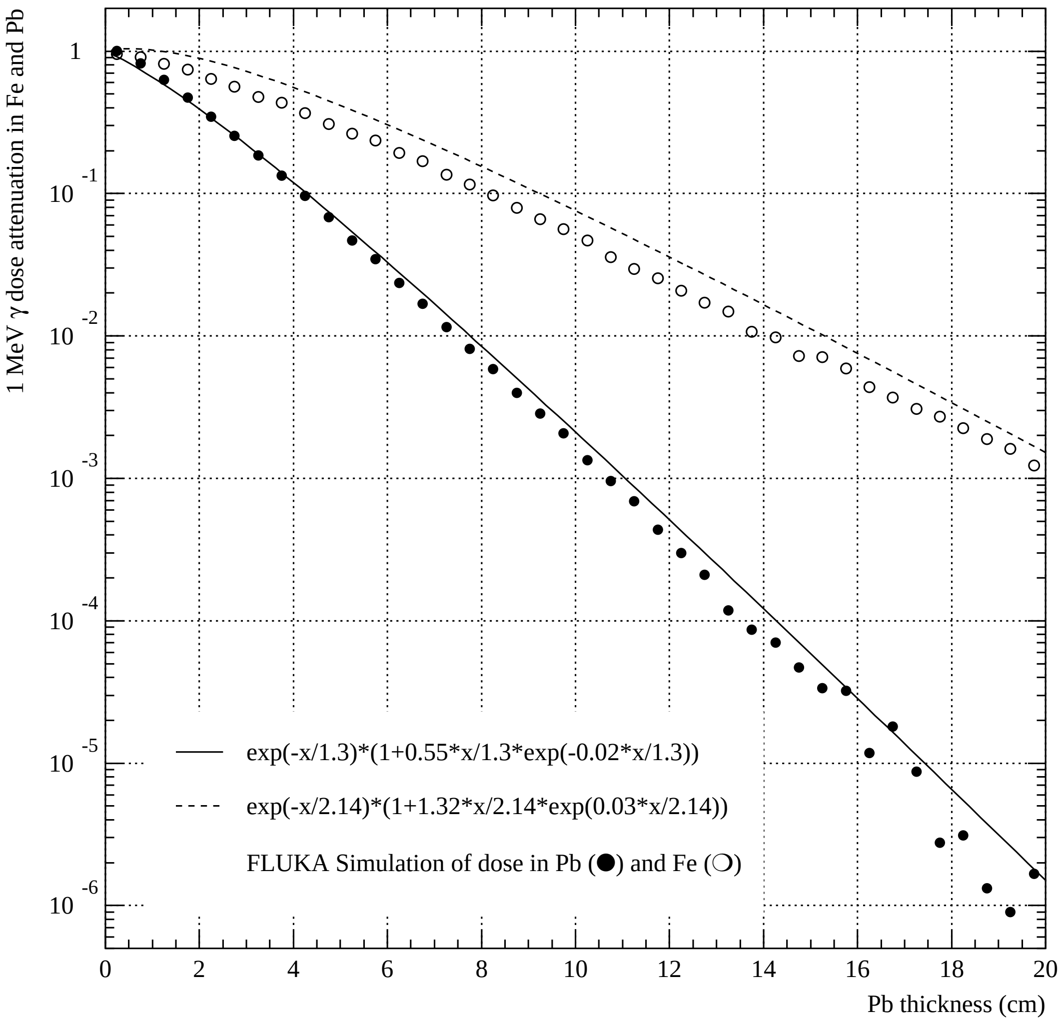
$\Downarrow$

100 hours annual access time for one person in a (typical LHC/CMS) environment with 50 μSv/h

Design of all access and maintenance has to be done within the 5 mSv annual limit

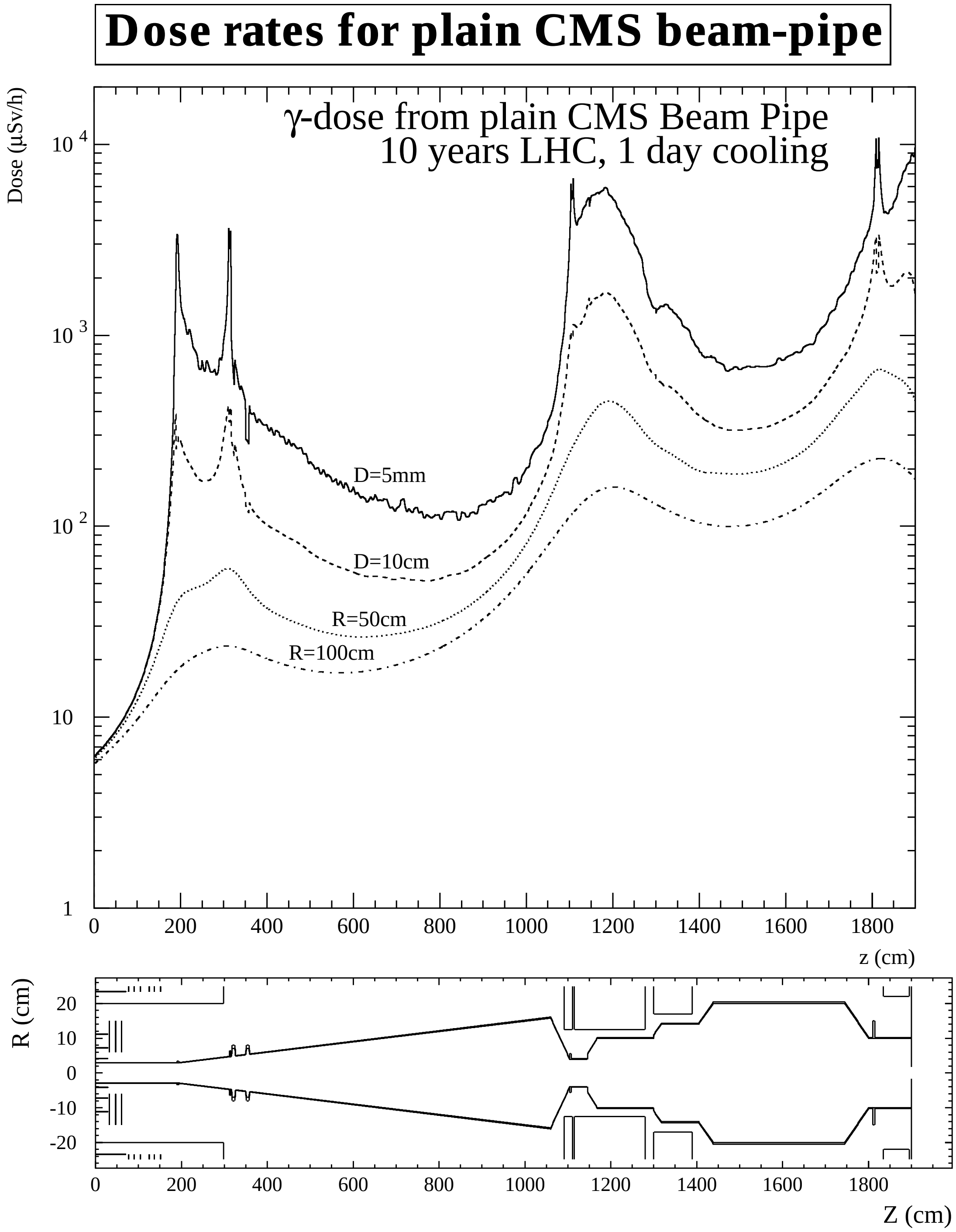
1 MeV γ-dose attenuation in Pb shields

FLUKA simulations vs. empirical parametrisations



4 cm of Pb give factor of 10 at 1 MeV photon energy

Dose rates around the Beam Pipe



(β-dose rates)

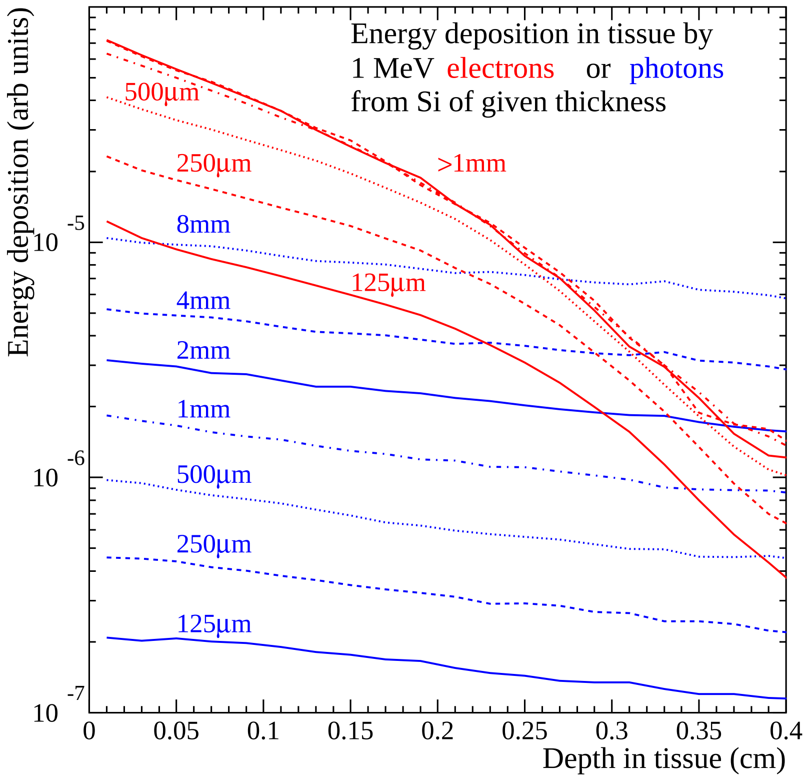
All of this talk is on γ-dose – except this slide

Most radionuclides emit electrons (or positrons)

Typical β (and γ)-energy around 1 MeV

$$\dot{D}(\beta) \propto A_\beta \left(\frac{dE}{dx}\right)_{\mathrm{mip}} \approx A_\beta \times 2\,\mathrm{MeV\,cm^2/g}$$

$$\dot{D}(\gamma) \propto \mu_{\mathrm{EN}} A_\gamma E_\gamma \approx A_\gamma E_\gamma \times 0.033\,\mathrm{cm^2/g}$$



β-dose is purely a surface effect

γ-dose dominates for thick sources

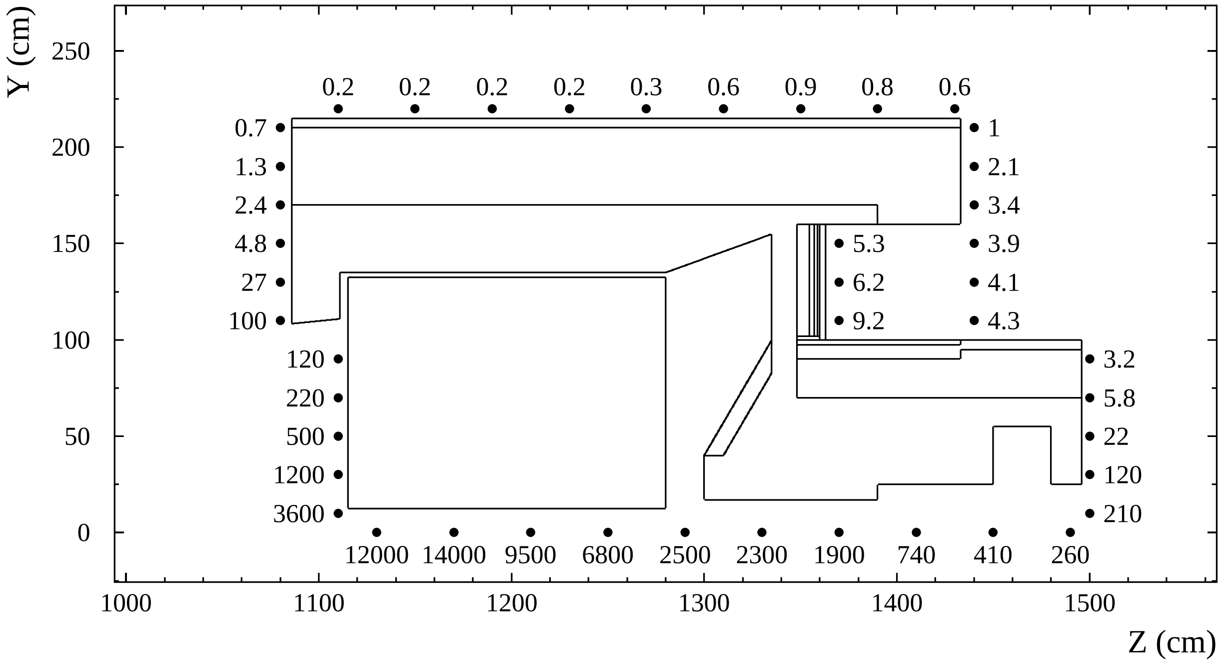
Usually less βs than γs emitted

$\Downarrow$

Figure likely to overestimate β/γ-ratio

Dose rates around CMS Forward Calorimeter

Dose rates μSv/h after 10 y LHC and 1 d cooling



Dose rates at outer periphery close to natural level

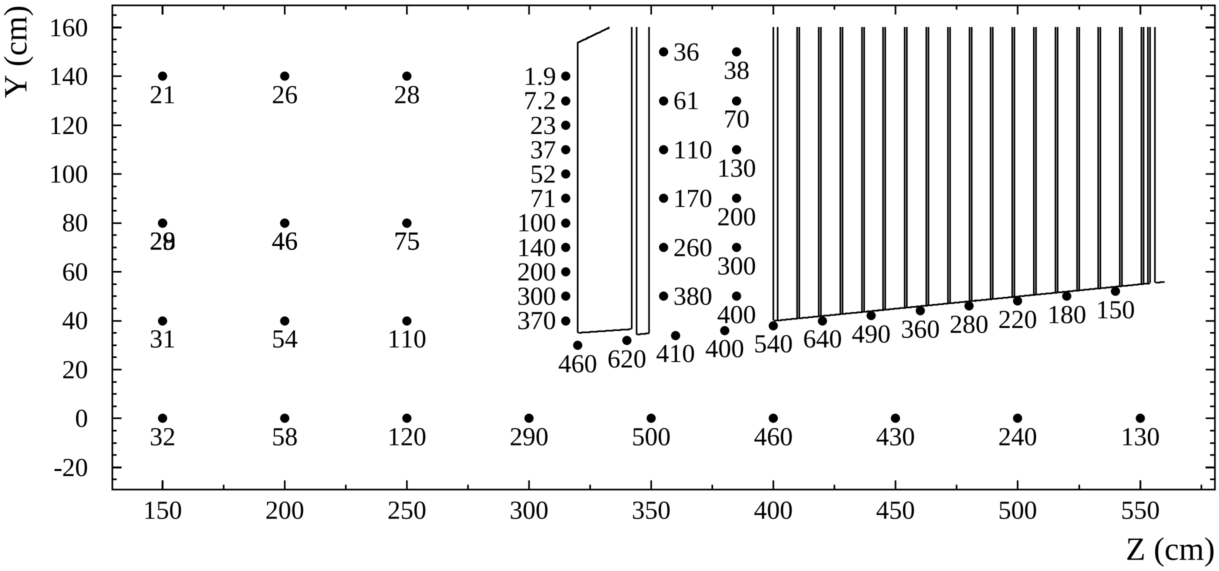
Dose in Readout Box location $<10\ \mu$Sv/h

Dose at back of end-plug $>100\ \mu$Sv/h

Highly activated front face must be shielded and be maintenance free

Dose rates around Endcap Calorimeters

Dose rates μSv/h after 10 y LHC and 1 d cooling



Concentrate maintenance work on outer periphery

$\Downarrow$

Typical dose rates $<$50 μSv/h

$\Downarrow$

Design operations to be reasonably fast

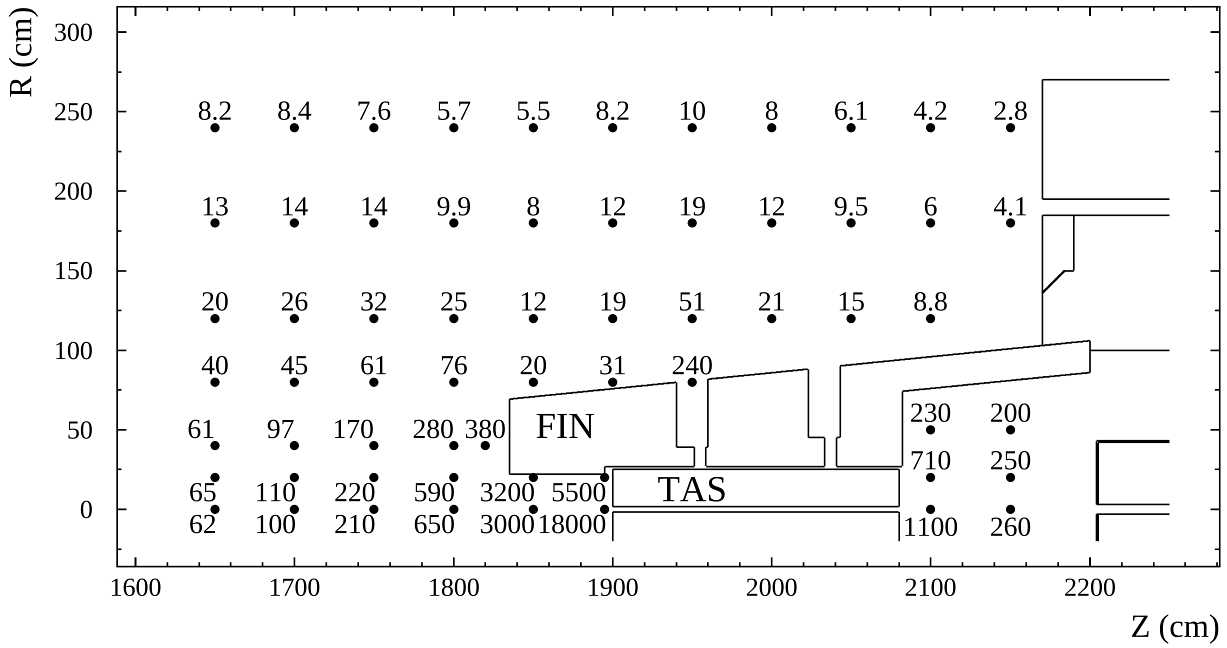
Minimise interventions on the inner periphery

No *in-situ* repair of high-η detectors

Dose rates around the “TAS absorber” region

The TAS is hit by ∼2300 GeV per pp-event

Dose rates μSv/h after 10 y LHC and 1 d cooling



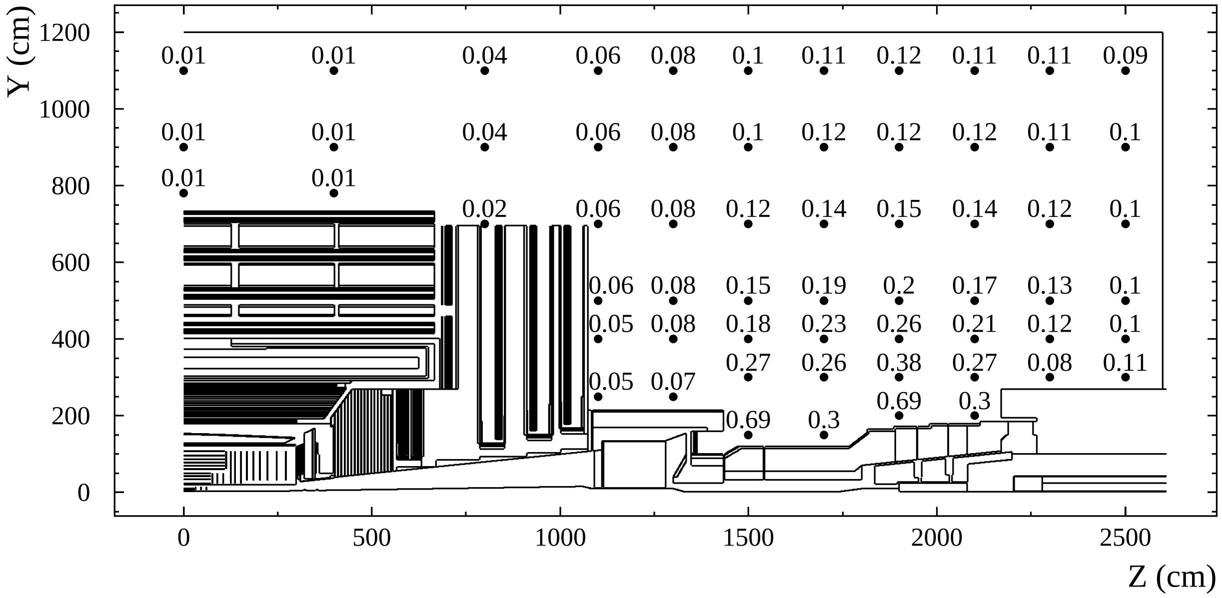
Dose rates up to 20 mSv/h just in front of TAS

Vacuum flanges remote controlled, no maintainable parts

Normally the whole TAS region is covered by the CMS Forward Shielding

Dose rates in the CMS Cavern

In μSv/h after 10 y LHC and 1 d cooling.



With experiment closed, dose rate is close to natural level (~0.1 μSv/h)

Caution

Possible local increase due to materials in electronics with high thermal neutron cross section (Ag, Au...)

The issue of radioactive waste

After 10 years operation, LHC/detectors will remain radioactive waste “forever”

“Forever” is at least a very long time
practically tens of years,
legally even longer

• • ••

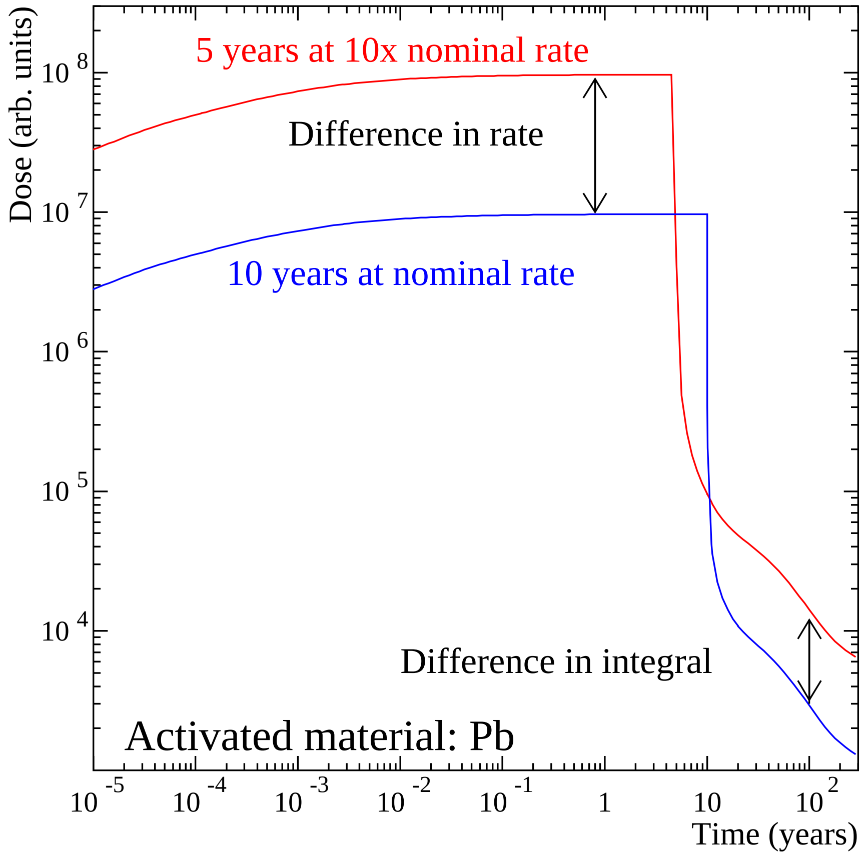
Estimate of radioactive material from CMS after 10 years LHC

Cooling time (years)	Slightly acitive (1–10 Bq/g)	Active (10-100 Bq/g)	Highly active ($>$100 Bq/g)
0.1	610 t	660 t	370 t
1	610 t	500 t	280 t
10	380 t	150 t	40 t
30	130 t	14 t	4 t

• • ••

All radioactive material has to be properly traced and disposed

Extrapolations to next generation



Dose at short cooling (maintenance) $\propto$ rate

Dose at long cooling (waste) $\propto$ integral

Most SLHC detector probably “not maintainable”

RATHER INCREASE THE ENERGY THAN THE LUMINOSITY