Residual Radiation Exposure

Radiation Protection Topical Course

25-27 November 2024, CERN

Outline

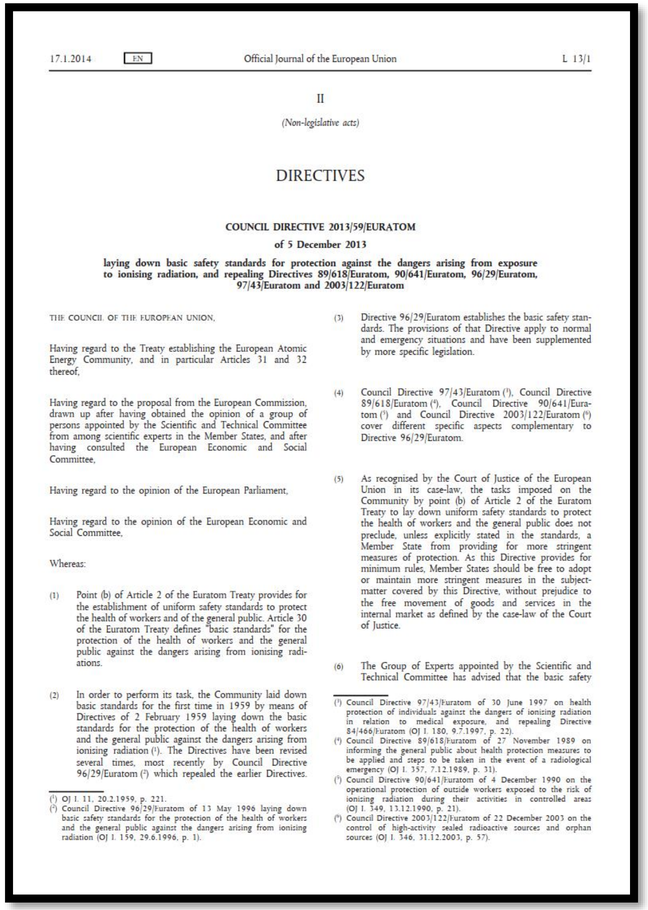
- Residual Radiation Exposure
  - Motivations for RP studies
  - Residual Radiation Exposure: general concepts
  - Input cards & settings for residual studies
  - Geometry modifications:
    - ASSIGNMAT
    - SESAME
    - DORIAN
- Application examples
- Summary

Introduction & motivation

Motivation

- Radiation Protection quantities (RP, operational) & legal framework presented in the Radiation Protection fundamentals lecture.
- General principles of radiation protection (EURATOM Directive 59/2013):
  - **Justification**: Decisions introducing a practice shall be justified in the sense that such decisions shall be taken with the intent to ensure that the individual or societal benefit resulting from the practice outweighs the health detriment that it may cause. Decisions introducing or altering an exposure pathway for existing and emergency exposure situations shall be justified in the sense that they should do more good than harm.
  - **Optimisation**: Radiation protection of individuals subject to public or occupational exposure shall be optimised with the aim of keeping the magnitude of individual doses, the likelihood of exposure and the number of individuals exposed as low as reasonably achievable [ALARA] taking into account the current state of technical knowledge and economic and societal factors. […] This principle shall be applied not only in terms of effective dose but also, where appropriate, in terms of equivalent doses, as a precautionary measure to allow for uncertainties as to health detriment below the threshold for tissue reactions.
  - **Dose limitation**: In planned exposure situations, the sum of doses to an individual shall not exceed the dose limits laid down for occupational exposure or public exposure. Dose limits shall not apply to medical exposures.

Q: is this directive telling us how to compute doses?



17.1.2014 EN Official Journal of the European Union L 13/1

II

(Non-legislative acts)

DIRECTIVES

COUNCIL DIRECTIVE 2013/59/EURATOM

of 5 December 2013

laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom

THE COUNCIL OF THE EUROPEAN UNION,

Having regard to the Treaty establishing the European Atomic Energy Community, and in particular Articles 31 and 32 thereof,

Having regard to the proposal from the European Commission, drawn up after having obtained the opinion of a group of persons appointed by the Scientific and Technical Committee from among scientific experts in the Member States, and after having consulted the European Economic and Social Committee,

Having regard to the opinion of the European Parliament,

Having regard to the opinion of the European Economic and Social Committee,

Whereas:

(1) Point (b) of Article 2 of the Euratom Treaty provides for the establishment of uniform safety standards to protect the health of workers and of the general public. Article 30 of the Euratom Treaty defines "basic standards" for the protection of the health of workers and the general public against the dangers arising from ionising radiations.

(2) In order to perform its task, the Community laid down basic standards for the first time in 1959 by means of Directives of 2 February 1959 laying down the basic standards for the protection of the health of workers and the general public against the dangers arising from ionising radiation [1]. The Directives have been revised several times, most recently by Council Directive 96/29/Euratom [2] which repealed the earlier Directives.

(3) Directive 96/29/Euratom establishes the basic safety standards. The provisions of that Directive apply to normal and emergency situations and have been supplemented by more specific legislation.

(4) Council Directive 97/43/Euratom [3], Council Directive 89/618/Euratom [4], Council Directive 90/641/Euratom [5] and Council Directive 2003/122/Euratom [6] cover different specific aspects complementary to Directive 96/29/Euratom.

(5) As recognised by the Court of Justice of the European Union in its case-law, the tasks imposed on the Community by point (b) of Article 2 of the Euratom Treaty to lay down uniform safety standards to protect the health of workers and the general public does not preclude, unless explicitly stated in the standards, a Member State from providing for more stringent measures of protection. As this Directive provides for minimum rules, Member States should be free to adopt or maintain more stringent measures in the subject-matter covered by this Directive, without prejudice to the free movement of goods and services in the internal market as defined by the case-law of the Court of Justice.

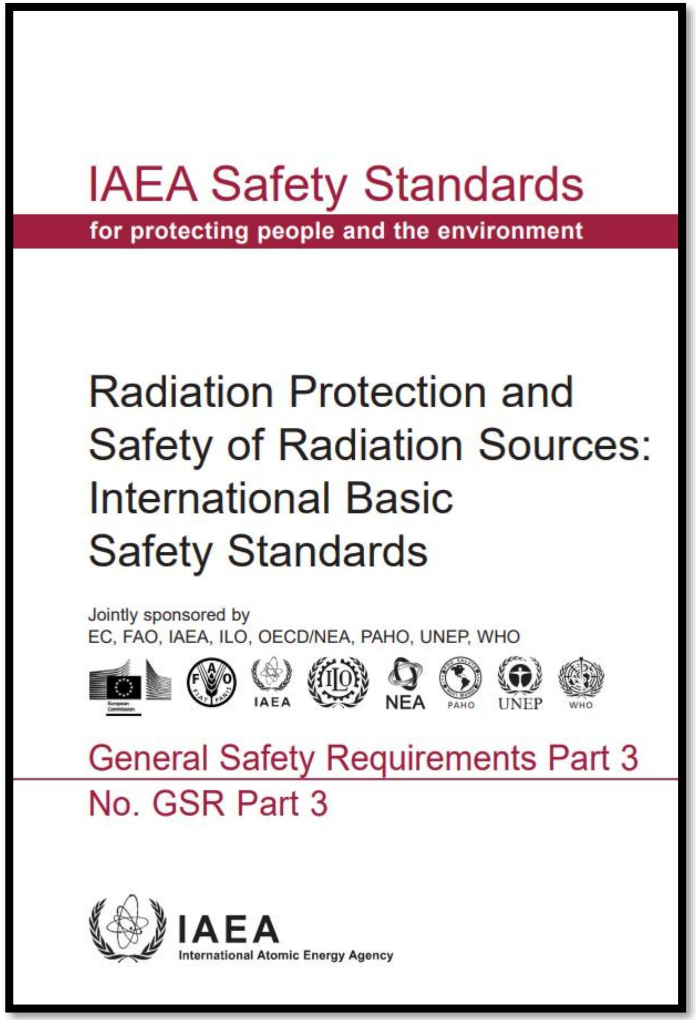
(6) The Group of Experts appointed by the Scientific and Technical Committee has advised that the basic safety

(1) OJ L 11, 20.2.1959, p. 221.
(2) Council Directive 96/29/Euratom of 13 May 1996 laying down basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionising radiation (OJ L 159, 29.6.1996, p. 1).
(3) Council Directive 97/43/Euratom of 30 June 1997 on health protection of individuals against the dangers of ionising radiation in relation to medical exposure, and repealing Directive 84/466/Euratom (OJ L 180, 9.7.1997, p. 22).
(4) Council Directive 89/618/Euratom of 27 November 1989 on informing the general public about health protection measures to be applied and steps to be taken in the event of a radiological emergency (OJ L 357, 7.12.1989, p. 31).
(5) Council Directive 90/641/Euratom of 4 December 1990 on the operational protection of outside workers exposed to the risk of ionising radiation during their activities in controlled areas (OJ L 349, 13.12.1990, p. 21).
(6) Council Directive 2003/122/Euratom of 22 December 2003 on the control of high-activity sealed radioactive sources and orphan sources (OJ L 346, 31.12.2003, p. 57).

Motivation

- The International **Basic Safety Standards** for Protection against Ionizing Radiation and for the Safety of Radiation Sources (**BSS**) specify requirements for the protection of health against exposure to ionizing radiation and for the safety of radiation sources.
- The person or organization responsible for facilities and activities that give rise to radiation risks shall have the prime responsibility for protection and safety.
- The principal parties shall ensure that protection and safety are effectively integrated into the overall management system of the organizations for which they are responsible.
- The person or organization responsible for a facility or activity that gives rise to radiation risks shall conduct an appropriate safety assessment of this facility or activity.
- Employers, registrants and licensees shall ensure that protection and safety is optimized and that the dose limits for occupational exposure are not exceeded.

In essence: in Radiation Protection we have the **legal responsibility** for our assessments and international/nation standards set the legal framework in which we operate.



Residual Radiation Exposure – General Concepts

- **Exposure of persons and activation of components and materials** are the core considerations for Radiation Protection (RP) related simulations.
- The particle cascades induced by the beam particle (**prompt radiation**) may trigger nuclear reactions that result in unstable radionuclides (**activation**).
- The decay of these radionuclides leads to **residual radiation**, which is present even when the beam has stopped.
- Persons can be exposed to **prompt radiation** and/or **residual radiation**; both need to be estimated (in normal and potentially abnormal situation)!

Beam Target Target

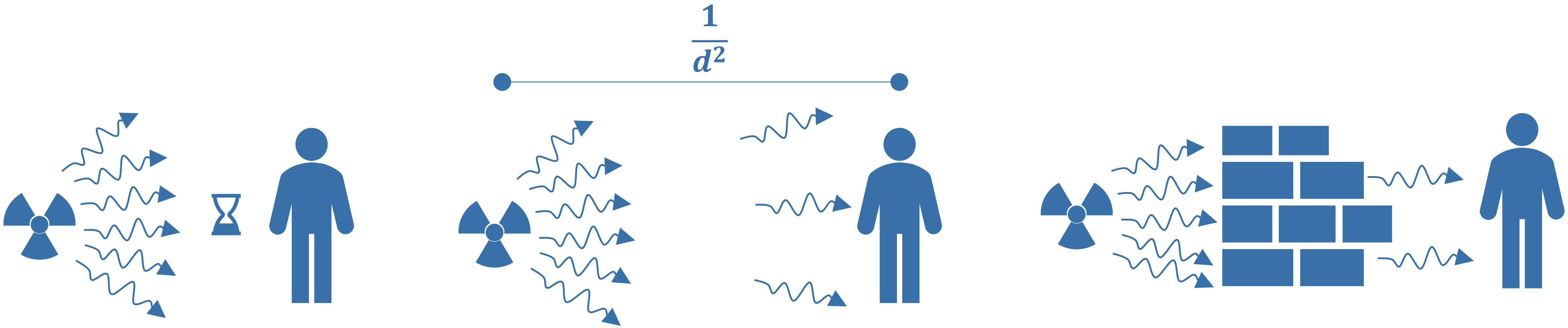
Residual Radiation Exposure – General Concepts

- After the beam is shut off, residual radiation is still present inside the accelerator housing, at much lower level compared with prompt radiation.
- Materials can be activated by the high-energy particles and neutrons of all energies, which are produced when the beam hits an accelerator component.
- At high-energy accelerators, all isotopes with atomic and mass number lower than those of the irradiated material can be produced. Of those isotopes, some are stable, while others are radioactive with a wide range of half-lives.
- The radioactivity of nuclides with short half-lives is quickly saturated during beam on and quickly disappears by decay when beam is off, while very long-lived activities build up and decay very slowly (important for long cooling times!).
- Most residual radionuclides emit beta and gamma radiation, which is easily measured with common radiation detectors. In general, gamma radiation is the most important issue and is the source of the largest fraction of total individual doses at most accelerators. Beta radiation is only important when handling very radioactive thin objects: in those cases, it can be a concern for the eye and extremity doses.

Source: S. H. Rokni et al. Radiation Protection Dosimetry (2009), Vol. 137, No. 1–2, pp. 3–17

Residual Radiation Exposure – General Concepts

Radiation Protection Triangle: Time, Distance, Shielding are the key parameters for protecting from external exposure (residual radiation).



Exposure Time **Distance** **Shielding**

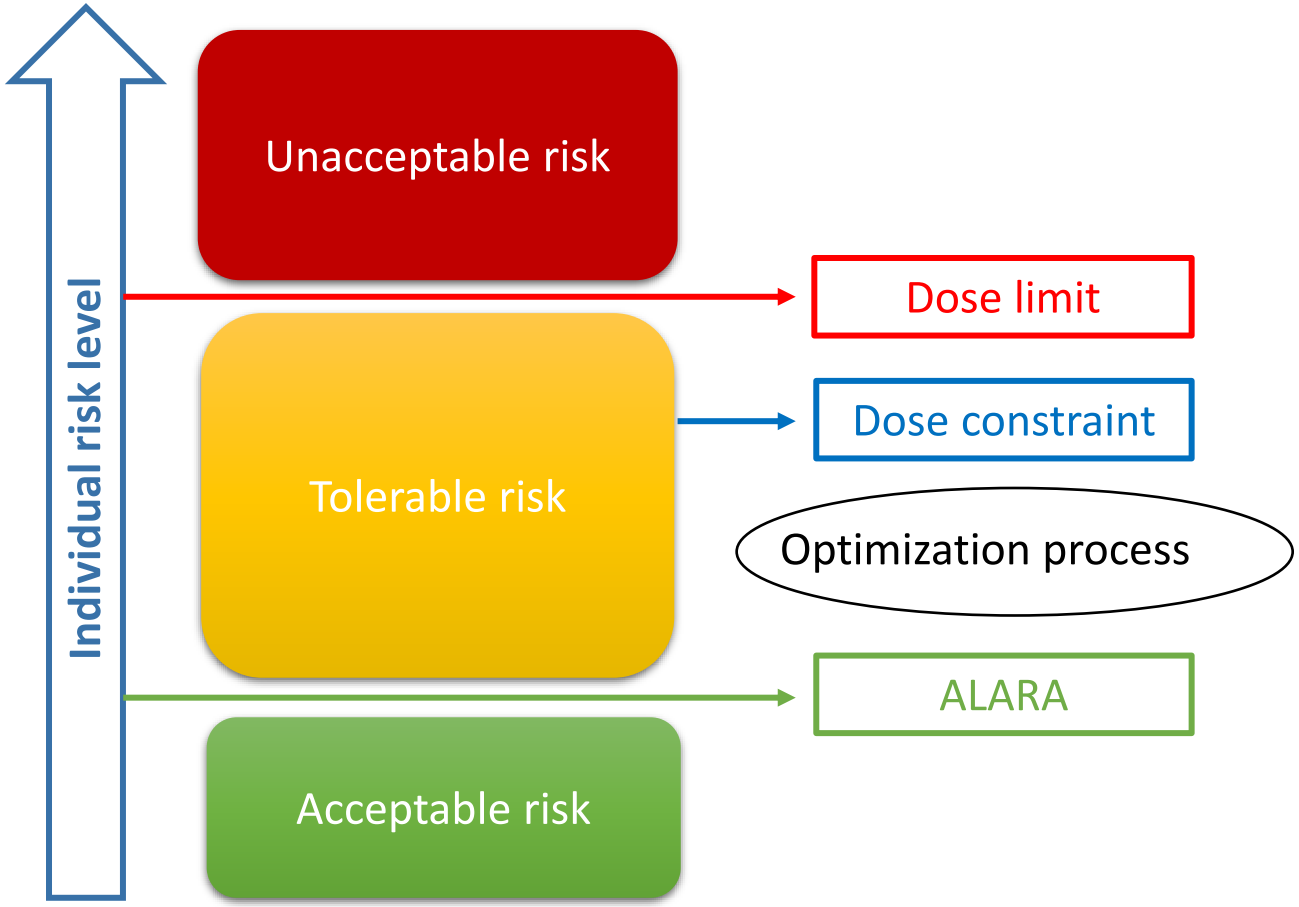
$$D(t_c, t_e, d, \mu x) = \dot{D}_{t_c,1m} \times t_e \times \frac{1}{d^2} \times e^{-\mu x}$$

Assuming that the exposure time is much shorter than $t_{1/2}$.

Optimization tools

- Maintenance/repair activities conducted in radiation areas shall be reviewed by RP together with the workers/responsible for the intervention.
- A **risk assessment** shall be produced, based on the knowledge of:
  - Working location & relevant radiological information (dose rate, cooling time, distance, etc)
  - Step-by-step intervention procedure
  - Time spent at each step
  - Number of workers involved in each step
- This risk assessment (in CERN jargon "**Work-Dose Plan**", or **WDP**) aims at optimizing the intervention by identifying the steps which contribute the most to the individual and collective doses.
- Key optimization tools: advance planning of the intervention, cooling time, dry-runs, remote handling, shielding, …
- For both planned and unplanned intervention, and in absence of measured values, **accurate simulations** of the projected residual radiation levels become an essential optimization tool!

Optimization tools



- The term Dose Constraints was first introduced in ICRP Publication 60 (1990) recommendations and evolved in ICRP Publication 103 (2007).
- Dose Constraint (ICRP 103): A prospective and source-related restriction on the individual dose from a source, which provides a basic level of protection for the most highly exposed individuals from a source, and serves as an upper bound on the dose in optimisation of protection for that source
- In planned exposure situations, it should be planned that exposures will be below the selected dose constraint
- Optimisation of protection is required for all exposures, even those below the dose constraint
- A Dose Constraint is not a limit!

Residual Radiation Exposure – Input cards

External Exposure

- The **prompt radiation** is related to the **cascade generated by the primary beam**
  - E.g., radiation penetrating a shielding structure when the beam is operating
  - Scored in pSv/primary
  - Normalization with beam intensity (e.g., protons/h) is needed to get dose rates (e.g., mSv/h)

- The **residual radiation** is related to an **irradiation profile** and a **cool-down time**
  - Radiation emitted by radionuclides generated during the irradiation and cool-down time
  - Scored in pSv/s
  - Normalization for beam intensity is done via irradiation profile

External Exposure - Residual radiation

- **The generation and transport of decay radiation** (including α, β, γ, X-rays, and conversion electrons emissions) is possible during the same simulation which produces the radionuclides (**one-step method**)
- Consequently, **results for production of residual nuclei, their time evolution, and residual doses due to their decays can be obtained in the same run**, for arbitrary decay times and for a given irradiation profile.
  - **Two notions of time** for the prompt and residual transport.
  - **Scoring** during **residual transport weighted** by irradiation profile and cool-down time
- **Different transport thresholds** can be set for the **prompt** and **decay radiation** transport as well as some (limited) biasing differentiation (see later slides).

External Exposure

Exposure of persons due to radiation fields

- RP quantities are **not physical quantities** directly simulated

Effective dose; Radiation weighting factor; Mean absorbed organ dose (**physical**)

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

Tissue weighting factor; Organ equivalent dose

- FLUKA estimates of these quantities are based on particle fluence: fluence-to-dose conversion coefficients [pSv cm^2] are applied to translate radiation fields into generalized particles

Generalized Particle Name	Units	Description
DOSE	GeV/g	Dose (energy deposited per unit mass)
DOSE-EQ	pSv	Dose Equivalent (`AUXSCORE`) based on ICRU sphere or human phantom
ACTIVITY	Bq/cm^3	Activity per unit volume – particularly useful with `AUXSCORE` and/or user routines
ACTOMASS	Bq/g	Activity per unit mass – particularly useful with `AUXSCORE` and/or user routines

Input options: PHYSICS and packages

Please activate the following cards if scoring of residual nuclei is of interest:

Evaporation of heavy fragments

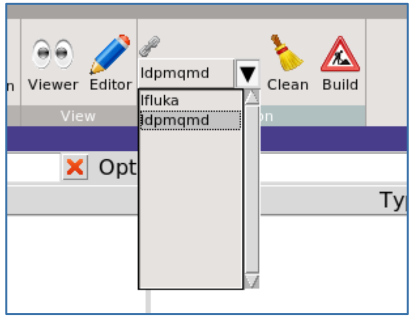
PHYSICS Type: COALESCE ▼ Activate On ▼

Activation of **coalescence** treatment

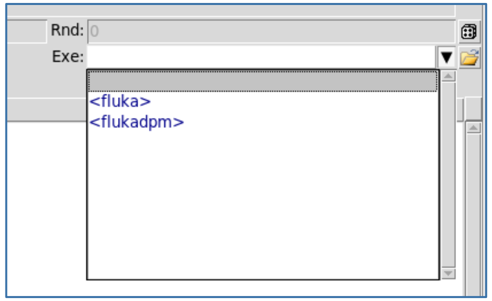
PHYSICS Type: EVAPORAT ▼ Model: New Evap with heavy frag ▼

Please remember to run with flukadpm or to link RQMD and DPMJET if producing a custom executable.

Compile tab



Run tab



Transport thresholds

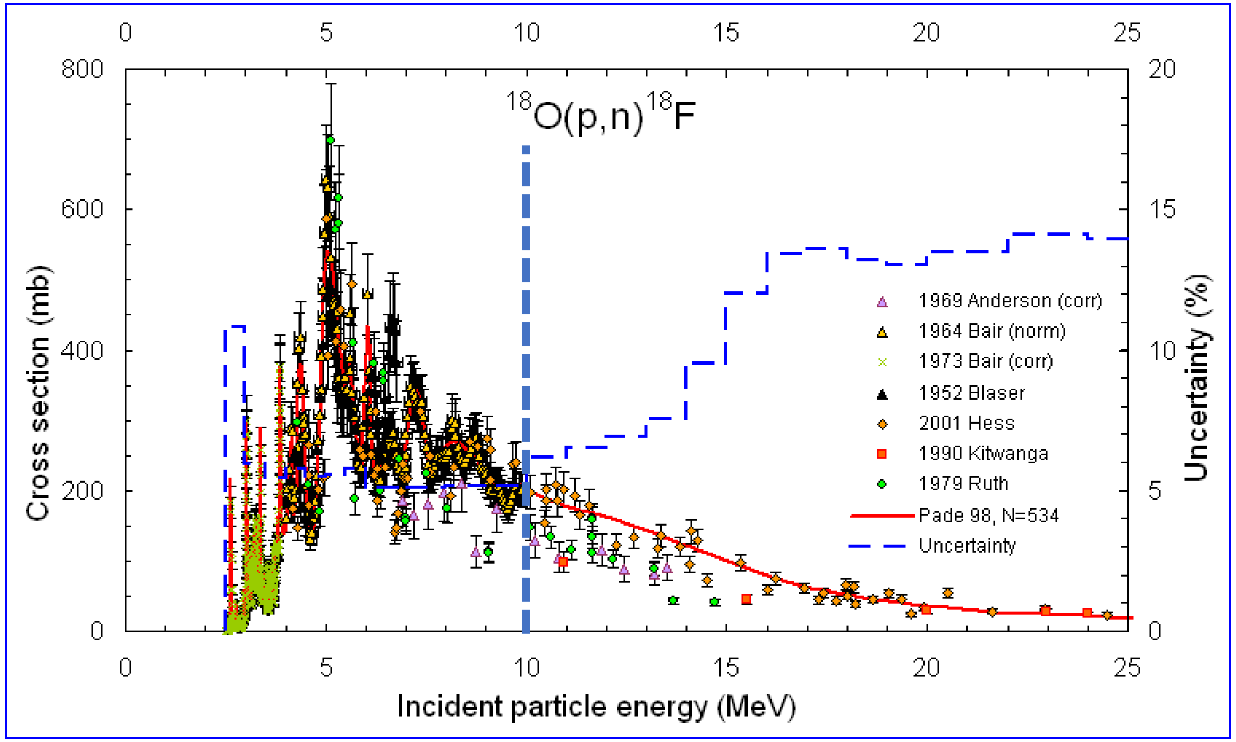
- **Disclaimer**:
  - Simulations where **only effective dose** and **activation** are relevant
  - Typical values for **hadron machines**
- Prompt transport
  - Neutrons down to thermal
  - Charged hadrons: couple of MeV
  - Muons: couple of tens of MeV
- Activation: **threshold energies** of relevant nuclear reactions
    - Charged hadrons: couple of MeV
    - Photons: 2-8 MeV depending on materials (threshold for photo-nuclear reactions); if needed
- Residual dose rate: depends on **contributing radionuclides**
  - 30 keV to 100 keV for photons and e+/e- are typical choices
  - Recommendation (when EM thresholds prompt > EM thresholds residual)
    - Set **thresholds** for **residual** transport in **EMFCUT**
    - Go to **thresholds** for **prompt** transport via **RADDECAY** (prompt cut)

Transport thresholds

- Thresholds used during prompt transport may have an impact on your activation/residual!
- E.g. Production of medical radioisotopes using NEW-DEFA default without any further tweaking.

Recommended cross sections for the $^{18}O(p,n)^{18}F$ reaction

Source: IAEA



Updated: May 2021.

`NEW-DEFAults` :

The standard defaults are active even if the DEFAULTS card is not present.

- EMF on, with electron and photon transport thresholds to be set using the EMFCUT command.
- Inelastic form factor corrections to Compton scattering activated (no need for EMFRAY).
- Low energy neutron transport activated down to thermal energies included, (high energy neutron threshold at 20 MeV) with point-wise cross sections.
- Non analogue absorption for low energy neutrons with probability 0.95 for the last (thermal) groups.
- Particle transport threshold set at 10 MeV, except for neutrons (1E-5 eV), and (anti)neutrinos (0, but they are discarded by default anyway).
- Multiple scattering threshold for secondary charged particles lowered to 20 MeV (equal to that of the primary ones).
- Delta ray production on with threshold 1 MeV (see option DELTARAY).
- Restricted ionisation fluctuations on, for both hadrons/muons and EM particles (see option IONFLUCT).
- Heavy particle e^+/e^- pair production activated with full explicit production (with the minimum threshold of $2m_e$).
- Heavy particle bremsstrahlung activated with explicit photon production above 1 MeV.
- Muon photonuclear interactions activated with explicit generation of secondaries.

Input option: RADDECAY [1/2]

- **Activates** the simulation of the **decay** of the **radioactive nuclides** produced
- Allows to **modify biasing** and **transport thresholds** for the transport of decay radiation

RADDECAY		Decays:	Active ▼	Patch Isom:	▼	Replicas:	3.0
h/μ Int:	ignore ▼	h/μ LPB:	ignore ▼	h/μ WW:	ignore ▼	e-e+ Int:	ignore ▼
e-e+ LPB:	ignore ▼	e-e+ WW:	ignore ▼	Low-n Bias:	ignore ▼	Low-n WW:	ignore ▼
		decay cut:	0.0	prompt cut:	99999.0	Coulomb corr:	▼

Decays — **Activation mode**

radioactive decays activated for requested cooling times

"activation mode": time evolution calculated analytically for *fixed* (cooling) times. Daughter nuclei as well as associated radiation is considered at these (fixed) times

Semi-Analogue mode

radioactive decays activated in semi-analogue mode

each radioactive nucleus is treated like all other unstable particles (random decay time, daughters and radiation), all secondary particles/nuclei carry time stamp ("age")

Necessary to simulate radioactive sources [See beginner course]

Patch Isom — On — **isomer "production" activated**

Replicas — # — **number of "replicas" of the decay of each individual nucleus**, i.e. in activation study mode, each radioactive nucleus can be decayed several times, to improve statistics.

Input option: RADDECAY [2/2]

Requests the calculation of radioactive decays

RADDECAY		Decays:	Active ▼	Patch Isom:	▼	Replicas:	3.0
h/μ Int:	ignore ▼	h/μ LPB:	ignore ▼	h/μ WW:	ignore ▼	e-e+ Int:	ignore ▼
e-e+ LPB:	ignore ▼	e-e+ WW:	ignore ▼	Low-n Bias:	ignore ▼	Low-n WW:	ignore ▼
		decay cut:	0.0	prompt cut:	99999.0	Coulomb corr:	▼

h/μ Int .. Low-n WW **switch for applying various biasing features to prompt radiation, to particles from radioactive decays, or both** – e-e+ WW is an important feature. More info in the manual.

decay cut, prompt cut **0.1 x input value** is used as **multiplication factors to be applied to e+/e-/gamma transport energy cutoffs** (defined with **EMF-CUT** cards). It is expressed in the form of a 10-digit number of which the first five for decay radiation, second five for prompt radiation (XXXXXYYYYY). Note: Both multiplication factors must be **≥ 1.0**, i.e. a maximum reduction factor of 10 possible

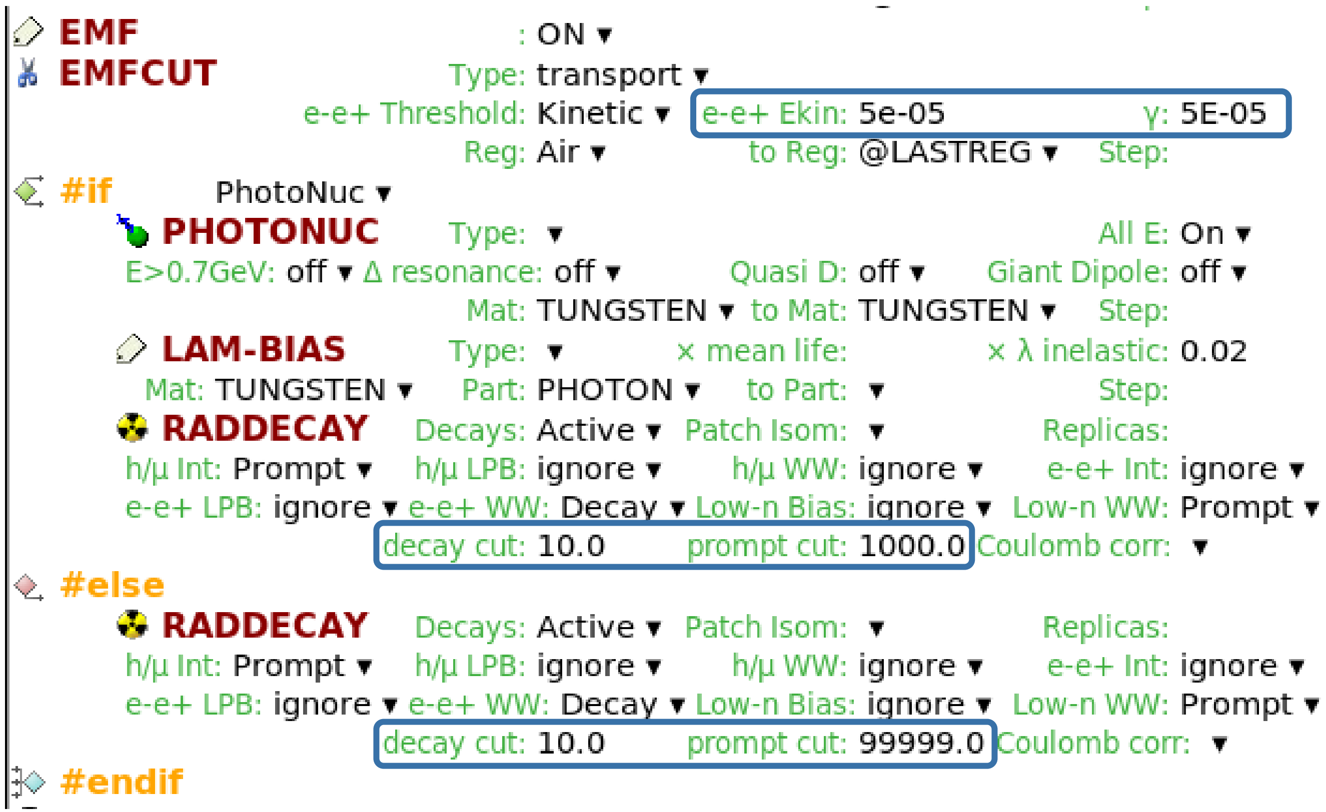
Examples:
input value for decay cut = 10 — decay radiation production and transport thresholds are not modified (0.1 x 10)
input value for prompt cut = 200 — prompt radiation threshold increased by factor of 20 (0.1 x 200)

Special cases:
decay cut = 99999 — kill EM cascade for residual radiation, while leaving it untouched in the prompt part.
prompt cut = 99999 — kill EM cascade for prompt radiation, while leaving it untouched in the decay part.

Transport thresholds

Example (RADDECAY):

1. EMF ON; switch from 50 keV (residual) to 5 MeV (prompt) for photons
2. EMF killed during prompt transport with RADDECAY



Decay: 0.1x10 = 1.0
Prompt: 0.1x1000 = 100

Decay: 0.1x10 = 1.0
Prompt: 0.1x99999 → ∞

Input option: IRRPROFI

- Defines the irradiation profile (irradiation times and beam intensities)

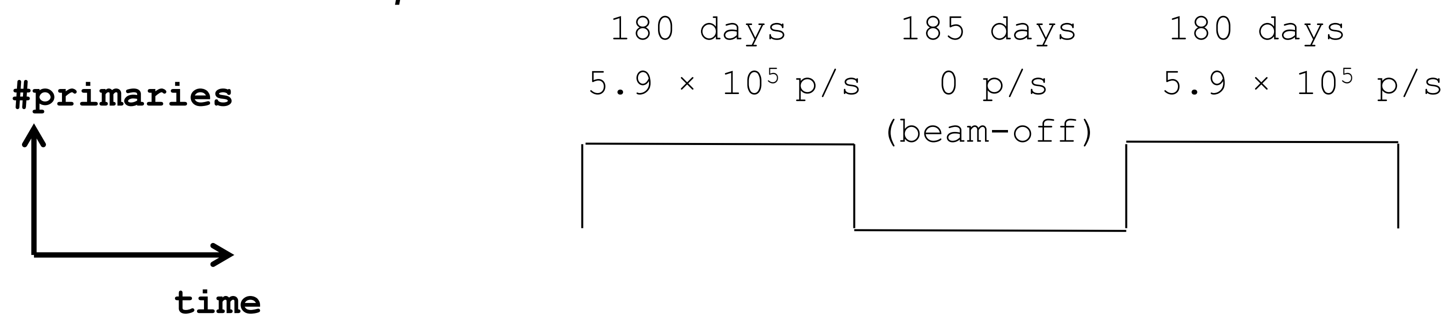
IRRPROFI	Δt: =180* day	p/s: 5.9e5
	Δt: = 185 * 86400	p/s: 0
	Δt: =1.553e7	p/s: 5.9e5

Δt #**irradiation time [second]**

p/s #**beam intensity [particles per second]**

- zero intensity is accepted and can be used, e.g., to define beam-off periods
- Each card has 6 inputs with 3 durations / intensities (intercalated)
- Several cards can be combined.
- Sequence order is assumed from first card (top) to last (bottom)

Example:

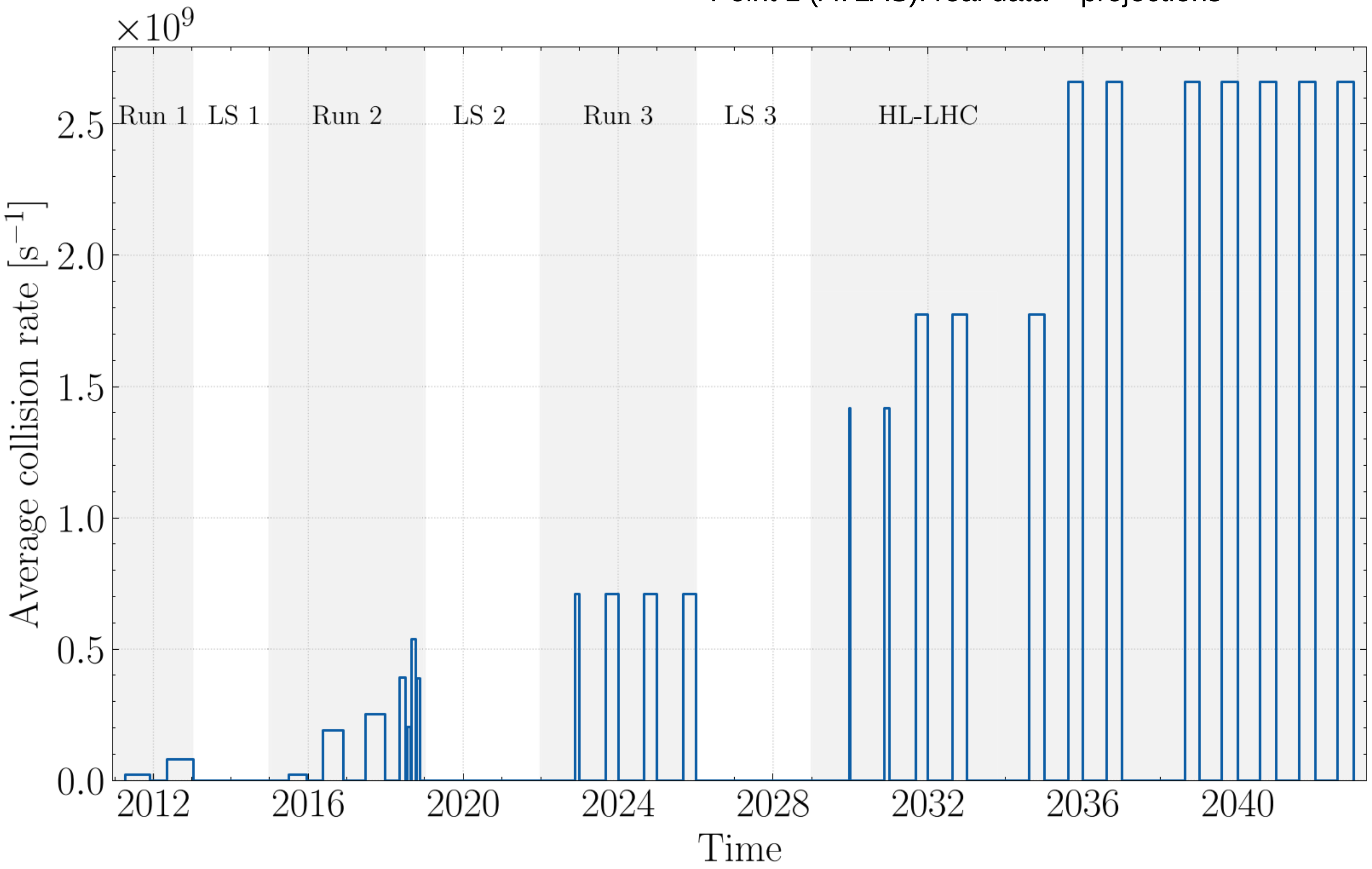


Input option: IRRPROFI

- The irradiation profile is a **key information** for residual radiation studies.
- An irradiation profile can be built on the base of existing information on the operation of your facility (e.g. delivered luminosity, beam intensity/current, etc) as well as on performance projection (e.g. design of new installations or future upgrades).
- The “beam intensity” field assumes a wider meaning, depending on the source term simulated. E.g. for LHC-like simulations, the beam intensity field assumes the meaning, for example, of proton-proton collisions rate (see next slide).
- Other examples: Proton/Particle-On-Target (POT), beam-gas interaction rate, protons lost in collimation, and more.
- The granularity of the irradiation profile plays an important role: long term activation is affected by the total integrated intensity while short term activation is affected by the last hours of beam operation.

Input option: IRRPROFI

Example: Collision profile (proton-proton) for LHC Point 1 (ATLAS): real data + projections



Input option: DCYTIMES

- Defines the decay (cooling) times measured from the end of the last irradiation period (t=0)

	1hour	8hours	1day	7days	1month	4months

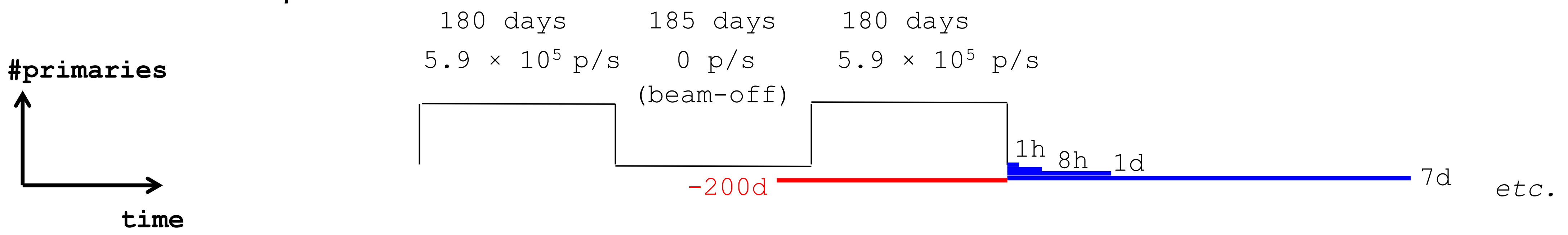
DCYTIMES

t1:	3600.	t2:	28800.	t3:	8.64E4
t4:	6.048E5	t5:	2.592E6	t6:	1.0368E7

t1 .. t6 **cooling time (in seconds) after the end of the (last) irradiation**
Note: Several cards can be defined.

Each cooling time is assigned an index, following the order in which it has been input.
This index can be used in option **DCYSCORE** to assign that cooling time to one or more scoring detectors.
A **negative decay** time is admitted: scoring is performed at the chosen time "during irradiation"

Example:



Input option: DCYTIMES

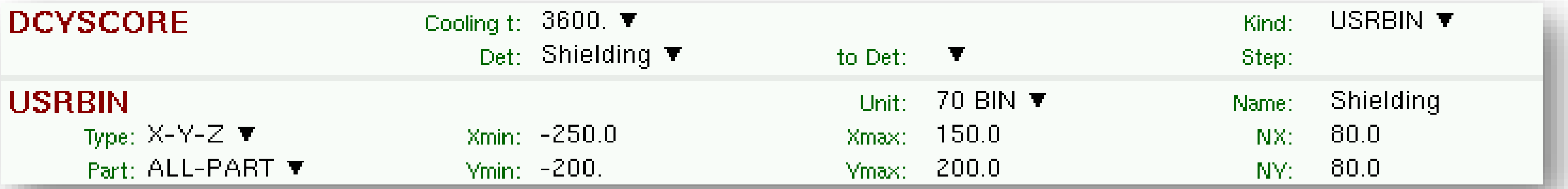
- Decay (cooling) times are chosen based on the duty-cycle of the facility or maintenance needs.
- Examples (purely indicative and based on the LHC duty-cycle):

Intervention	Decay times
Emergency access (special case)	From no cool down to a few minutes
Unplanned access (e.g. due to breakages)	From a few hours to a few days
Planned access (short maintenance)	From a few (hours) days to a week
Winter shutdown (long maintenance/minor upgrades)	From a few weeks to a few months
Long shutdown (major upgrades)	From a few weeks to a few years

- Example (I): Regular maintenance of a PET cyclotron → normally planned well in advance with at least a few days cool down.
- Example (II): LHC upgrade during long shutdown 3 → cooling times selected based on the different dismantling activities to be performed (from a few weeks to a few years).

Input option: DCYSCORE [1/2]

- Associates scoring detectors (radionuclides, fluence, dose) with different cooling times (and the irradiation profile)



DCYSCORE	Cooling t:	3600. ▼			Kind:	USRBIN ▼
	Det:	Shielding ▼	to Det:	▼	Step:	
USRBIN			Unit:	70 BIN ▼	Name:	Shielding
Type: X-Y-Z ▼	Xmin:	-250.0	Xmax:	150.0	NX:	80.0
Part: ALL-PART ▼	Ymin:	-200.	Ymax:	200.0	NY:	80.0

Cooling t — **Cooling time index to be associated with the detectors**
Drop down list of available cooling times

Kind — **Type of estimator:**
RESNUCLE, **USRBIN/EVENTBIN**, **USRBDX**, **USRTRACK**…

Det .. to Det — **Detector index/name of kind (SDUM/Kind)**
Drop down list of available detectors of kind (**Kind**)

Step — **step lengths in assigning indices**

Input option: DCYSCORE [2/2]

Important note:

All quantities are expressed per unit time when associated to a cool-down time

- For example: **RESNUCLE** Bq (= 1/s)
  USRBIN fluence rate / dose rate (e.g. pSv/s)

In the semi-analogue decay mode, estimators can include the decay contribution (on top of the prompt one) if associated to **DCYSCORE** with a cooling time index -1.0

External Exposure Scoring

- DOSE-EQ is a **track-length based** scoring
- Scoring options:
  - USRBIN **Mesh-based (cartesian or cylindrical)**:
    - Since volume of scoring bin in USRBIN mesh is known, **volume normalization** is **automatically applied**
    - pSv / primary particle for prompt radiation; pSv s^{-1} / primary particle for residual
  - USRBIN **Region-based**:
    - Volume of scoring region not know to code
    - **Volume normalization** is **NOT applied**
    - pSv * (region volume) / primary particle for prompt radiation; per unit time for residual
    - User needs to divide by region volume in post-processing
- Fluence-to-dose conversion coefficients for DOSE-EQ are based on ICRU spheres or human phantoms
  - **Assumption**: **homogenous radiation field** according to irradiation geometry
  - **Bin sizes** (dimensions **≥ 10cm**) should be used to obtain meaningful results

Fluence-to-dose conversion coefficients

- Several fluence-to-dose conversion coefficients are available (see lecture on Radiation Protection fundamentals)
- **Effective dose E**
  - Based on Monte Carlo simulations of human phantoms in certain radiation fields
  - Conversion coefficients sets depending on different recommendations and weighting factors: e.g. ICRP74, ICRP116, ICRP60, and Pelliccioni
  - Recommended sets: ICRP 116 (ED* in AUXSCORE card)
  - Conversion coefficients sets implemented for different irradiation geometries: Anterior-Posterior (AP), Posterior-Anterior (PA), Left lateral (LLAT), Right lateral (RLAT), Rotational (ROT), Isotropic (ISO), Working Out Radiation Shielding Thicknesses (WORST)
- **Ambient dose equivalent** H*(10)
  - Operational quantity for area monitoring (10mm depth in ICRU sphere)
  - "AMB74" (ICRP74) coefficient set, is the default choice for dose equivalent calculation
  - i.e.: it is possible to score DOSE-EQ without an AUXSCORE card (see later)

Effective Dose E vs Ambient Dose Equivalent H*(10)

- Protection/Operational quantities introduced in the Radiation Protection fundamentals lecture.
- Protection quantities cannot be measured, although legislations are based on these quantities (principle of dose limitation).
- Effective Dose E: "*risk-adjusted dosimetric quantity for the management of protection against stochastic effects (), enabling comparison of planned or received doses with dose limits, dose constraints, and reference levels expressed in the same quantity*" [IRCP].
- Ambient dose equivalent H*(10): operative quantity used in area monitoring.
- In the photon energy range up to 10 MeV, H*(10) provides an overestimate of E (i.e. E/H*(10)<1)
- In many cases limiting H*(10) means limiting E.

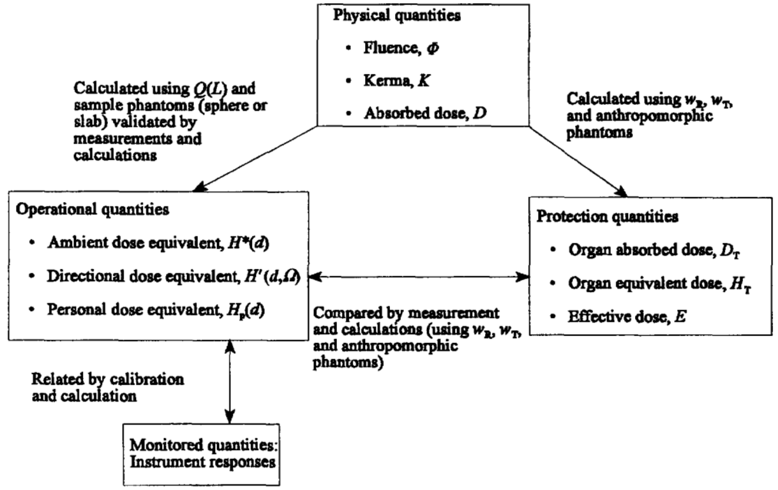


Fig. 1. Relationship of quantities for radiological protection monitoring purposes.

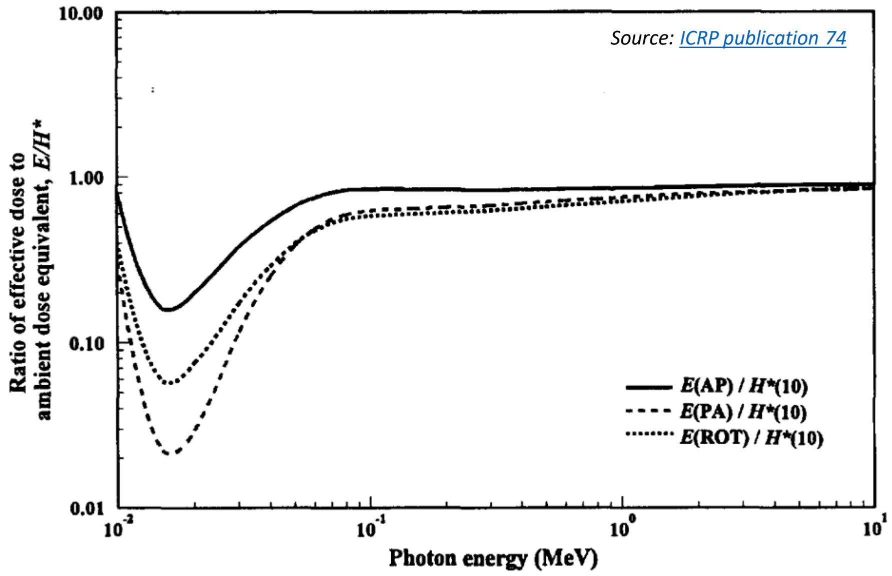
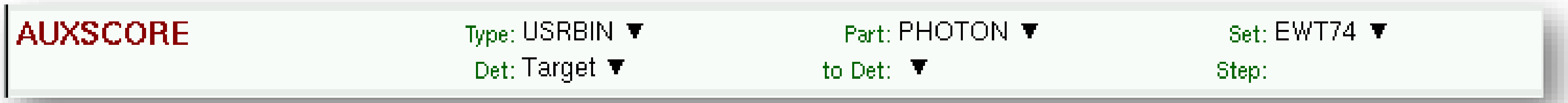


Fig. 55. The ratio of E/H*(10) for various irradiation geometries as a function of photon energy.

Input option: AUXSCORE

- Allows to **associate** scoring estimators with **dose equivalent conversion factors**
- Allows to apply a **filter** within the scoring estimator for a specific generalized particle type



Type — **Type of estimator to associate with**
drop down list of estimator types (`USRBIN`, `USRBDX`…)

Part — **Particle or isotope to filter for scoring**
Particle or particle family list

Det .. to Det — **Detector range**
Drop down list to select detector range of type **Type**

Step — **Step in assigning indices of detector range**

Set — **Conversion factor set for dose equivalent (DOSE-EQ) scoring**
Drop down list of available dose conversion sets

Note: This card can be used for prompt and residual scorings.

Input option: AUXSCORE

- Allows to **associate** scoring estimators with **dose equivalent conversion factors**
- Allows to apply a **filter** within the scoring estimator for a specific nuclide (can be stable or unstable)

```
AUXSCORE                 Type: USRBIN ▾      Part: ▾         Set: ▾
Delta Ray: ▾                Z: 4                A: 7      Isomer: 0
                          Det: Be7 ▾       to Det: ▾        Step:
```

Type — **Type of estimator to associate with**
drop down list of estimator types (`USRBIN`, `USRBDX`…)

Z — **Nuclide filtering**
atomic number Z

A — **Nuclide filtering**
mass number A

Isomer — **Nuclide filtering**
isomeric state

Summary of main input cards

PHYSICS

switch to activate the evaporation of heavy fragments (up to A=24) and the simulation of coalescence

RADDECAY

requests simulation of decay of produced radioactive nuclides and allows to modify biasing and transport thresholds (defined with other cards) for the transport of decay radiation

IRRPROFI

definition of an irradiation profile (irradiation times and beam intensities)

DCYTIMES

definition of decay (cooling) times

DCYSCORE

associates scoring detectors (radio-nuclides, fluence, dose equivalent) with different cooling times

AUXSCORE

allows to associate scoring estimators with dose equivalent conversion factors or/and to filter them according to (generalized) particle identity

Geometry modification - Motivation

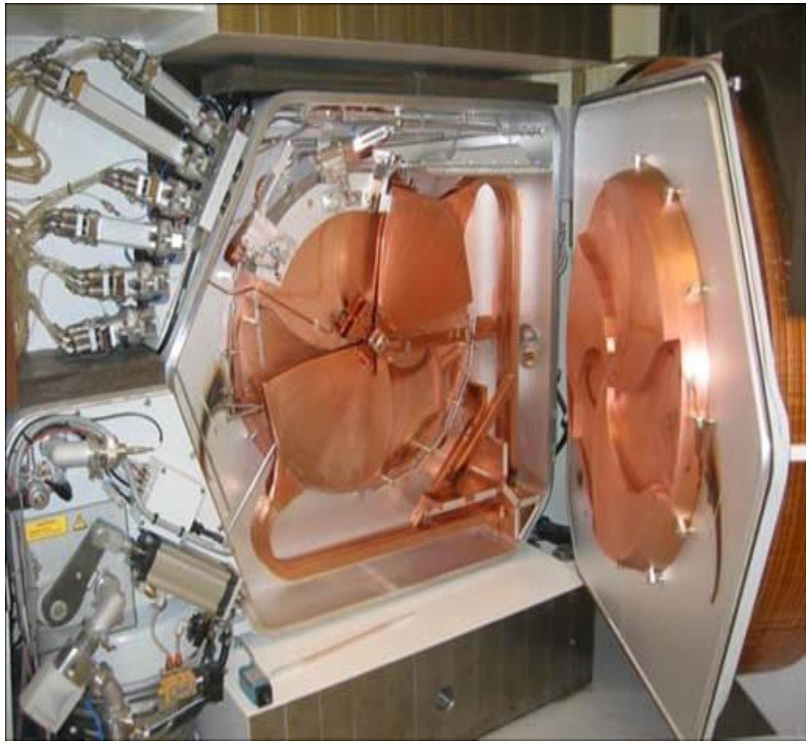
Geometry modification - Motivation

- A key aspect of any accelerator facility operation-cycle is the repetition, over the years, of physics with beam and shutdown periods.
- While the first ones clearly define the prompt source term of any FLUKA-related radiation protection assessment, the second represent a major challenge for the prediction of residual dose rates.
- During scheduled stops, accelerator equipment and/or detectors may change configuration to allow for maintenance, substitution, and subsystems upgrades.
- As a result, the position in which structures and devices might get activated during a run could be different from the one where they are stored, or simply moved, during a shutdown.
- The need of reproducing these different setups can be partially handled within the FLUKA environment requiring, in some cases, additional simulations tools capable of handling much complex situations.

Geometry modification - Motivation

Example (I): Planned maintenance of a PET cyclotron, requiring opening the accelerator vacuum chamber to access the ion source, stripping foils, etc.

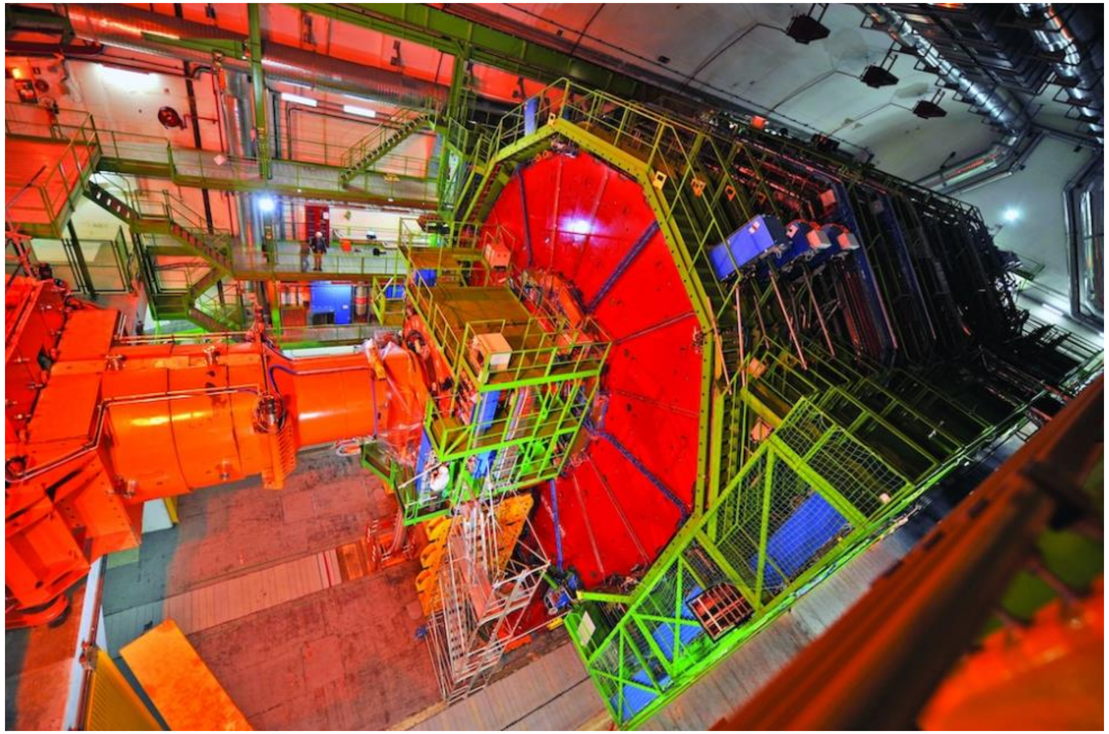
PET cyclotron in its operational configuration



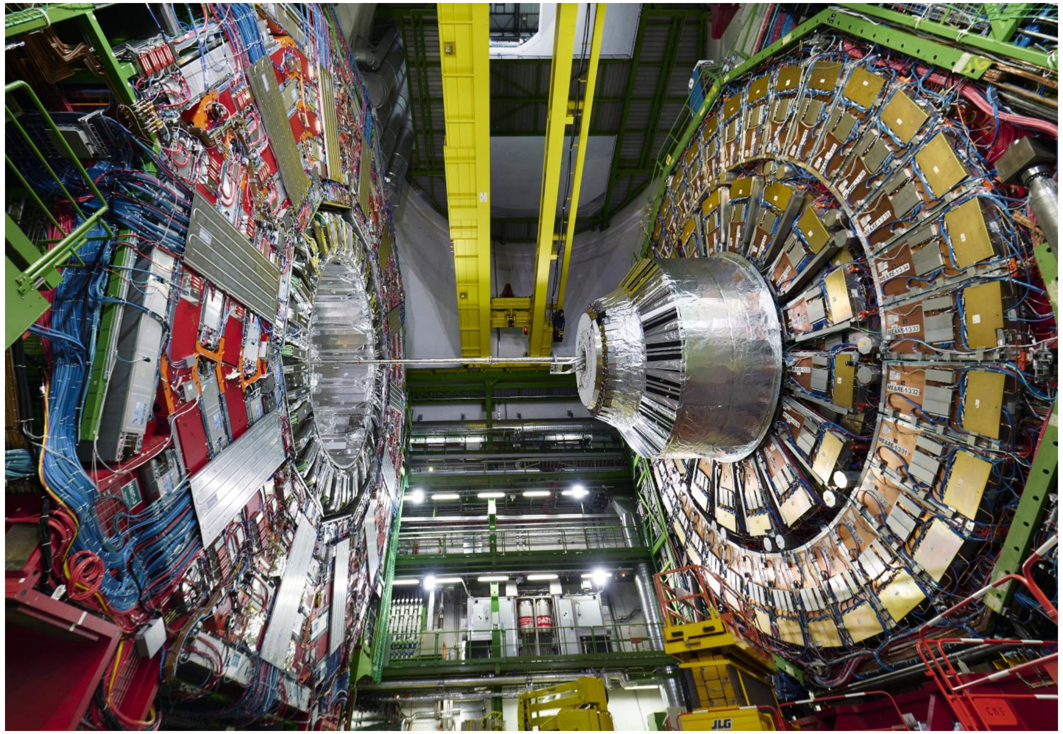
PET cyclotron in its maintenance configuration

Geometry modification - Motivation

Example (II): Maintenance of the CMS detector at the LHC complex.



The CMS experiment in its closed configuration in the underground experimental cavern.

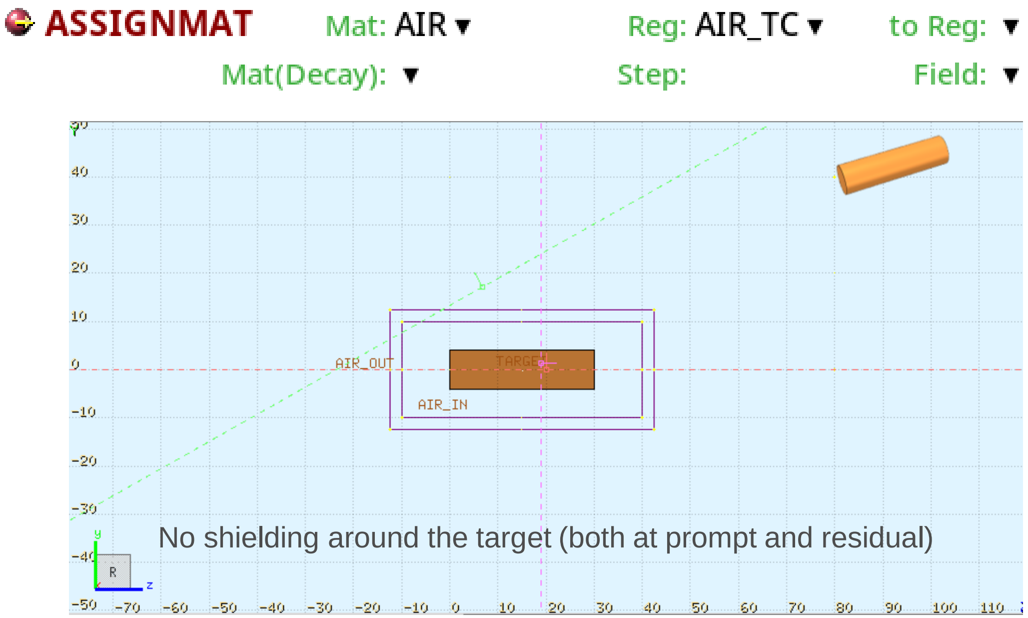


The CMS experiment in its maintenance configuration; the detector endcaps move to access the most inner part of the CMS detector.

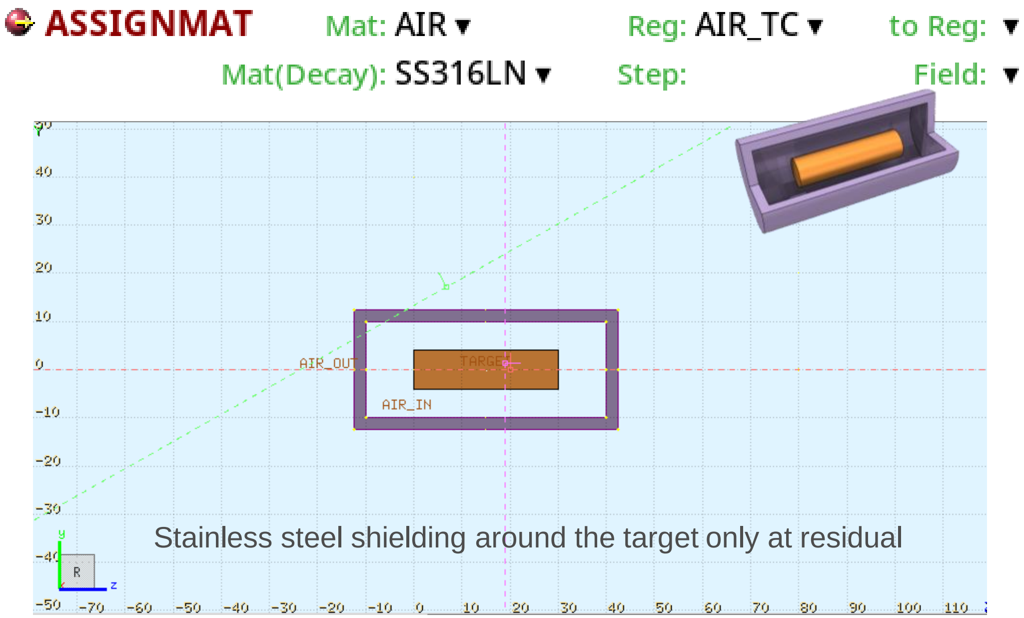
Geometry modification (I) - ASSIGNMAT

Geometry modification

- Exploiting **ASSIGNMAT** card for describing simple changes of geometry configuration in the simulation
- Examples: target irradiated in a facility and
  - *Addition* of a container for simulating a simple transport scenario (see example below)
  - *Removal* of the surrounding structures and shielding for calculating residual dose rate from the target
  - *Removal* of the target for calculating residual dose rates from surrounding structures and shielding
- Note: for regions where Mat *is not* equal to Mat(Decay), radioactive decay radiation originating from that region is ignored.



No shielding around the target (both at prompt and residual)

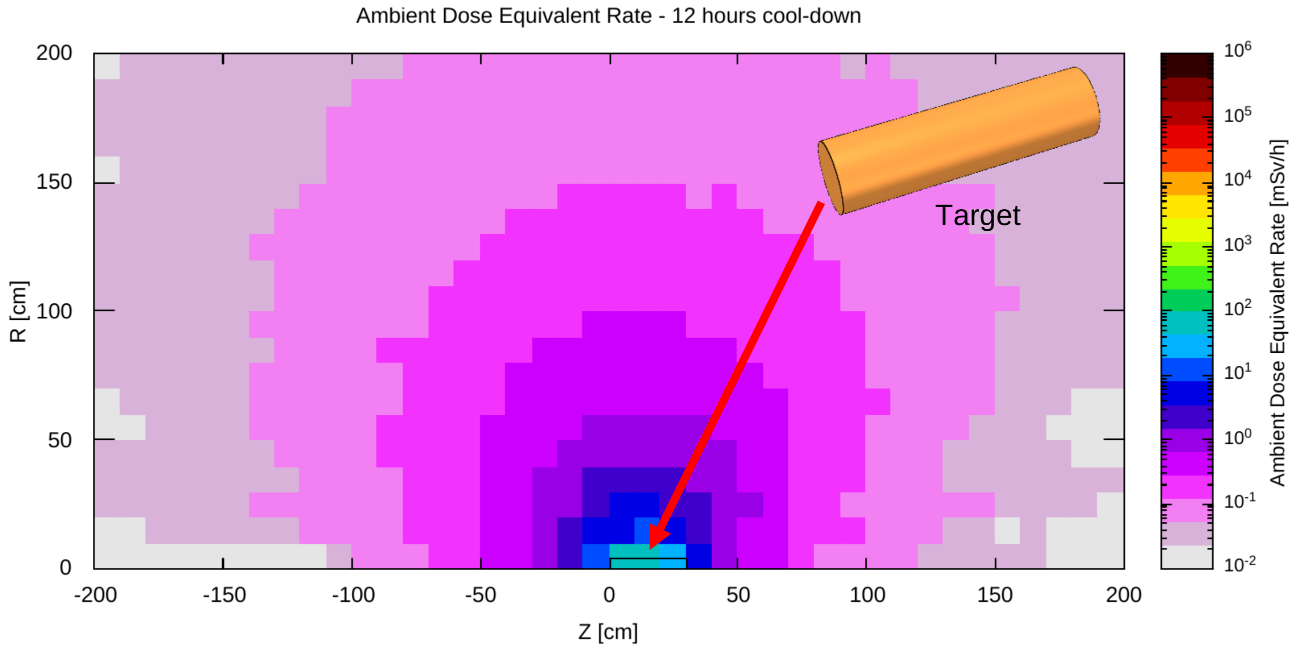


Stainless steel shielding around the target only at residual

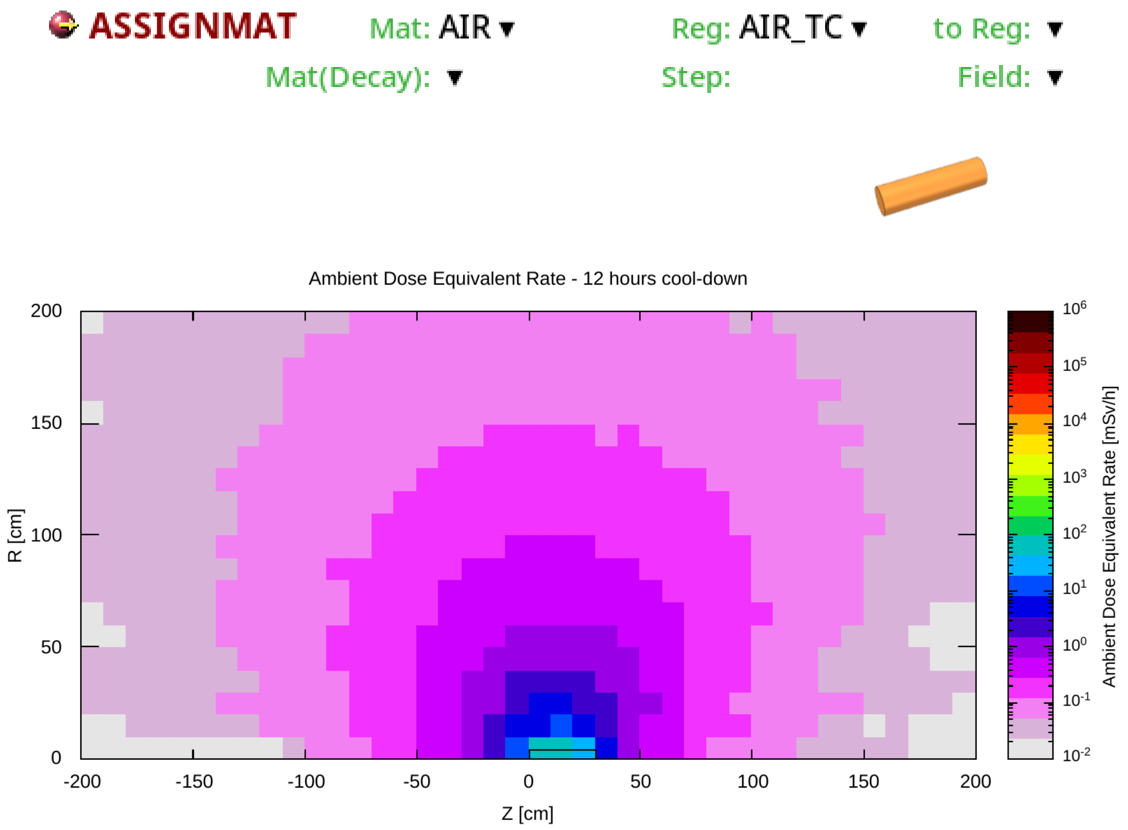
Geometry modification

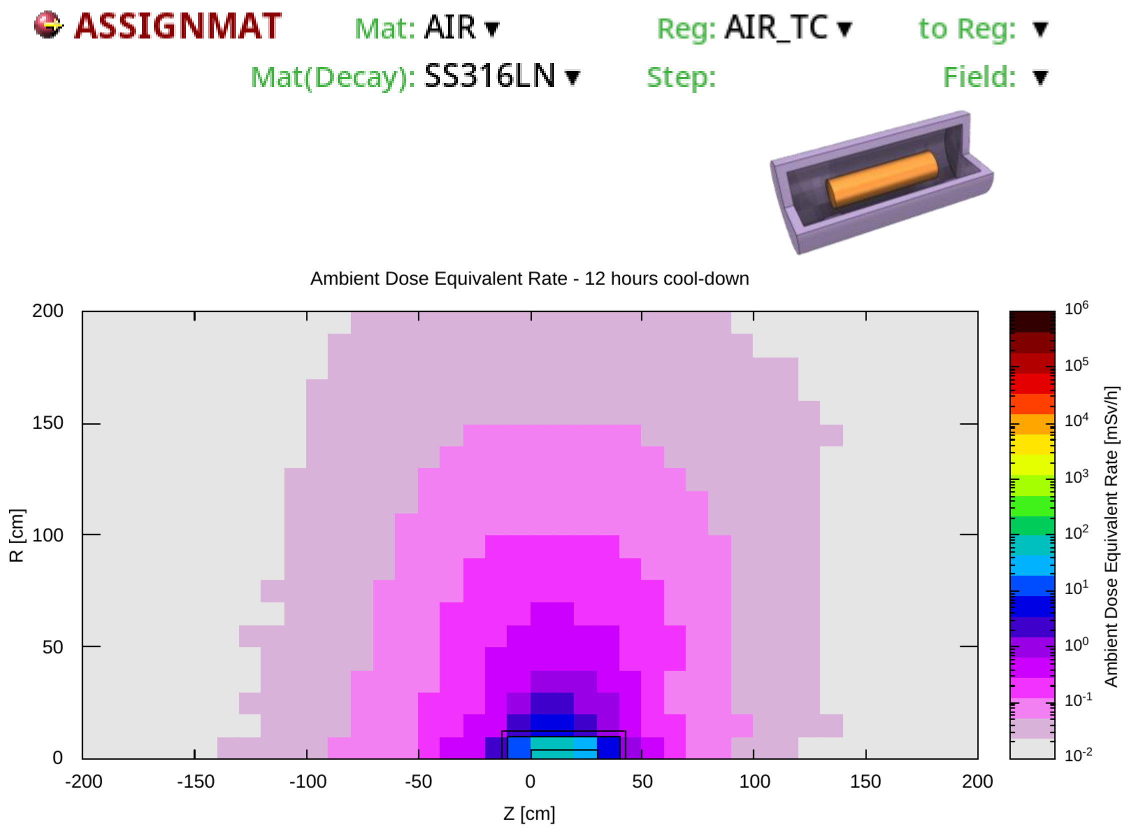
Residual H*(10) dose rate in one-step simulation

- Irradiation profile: 180 days of irradiation at 1e+10 protons/s
- Cool-down time: 12 hours
- USRBIN map normalization: 1e-9 * 3600 (pSv/s to mSv/h)



Geometry modifications





Note: in such shielding scenarios, biasing might be needed for the decay step; it might not be trivial to set it up. More details in the FLUKA Advanced course.

Geometry modification (II) – SESAME & DORIAN

SESAME

- The **SESAME** code, developed at CERN (CMS collaboration) and maintained by the CERN Radiation Protection group, provides the workflow and a set of tools that fulfils the requirement of geometry modification at decay, i.e. to model the geometry changes in a way that is efficient and compatible with FLUKA.
- The code, coupled to FLUKA, allows assessing residual dose rates in a two simulation steps: radionuclide creation events are simulated in the *prompt step*, while their decay and the transport of the decay radiation is performed in the *decay step*.
- Geometry modifications can be introduced between the prompt and the decay steps.
- Overall, SESAME provides the infrastructure to correctly and more easily set up a two-steps FLUKA simulation for advanced activation studies.
- This tool does not pose any limitation on the usage of FLUKA features, because the weight of primary particles is taken into account and autonomously propagated into the second step. As a major consequence, variance reduction techniques can be applied to the radiation transport case under study.
- At present the SESAME code is available only within the FLUKA CERN collaboration.

SESAME

- Prompt step:
  - The primary process of interest, that is the main source of activation, is first simulated in FLUKA during the prompt step.
  - The accurate geometry model of the case study is needed, as well as the correct description of the radiation source (e.g., beam settings for particle collisions at the LHC experiments).
  - A dedicated user routine, linked to the FLUKA libraries to create a custom executable, dumps the information about radionuclide creation events to binary files, including the number of the primary history in which the nuclide was produced, its atomic number and mass number, its isomeric state, its spatial coordinates and statistical weight, and the index of the FLUKA region in which the (possibly recoiling) nuclide was stopped.

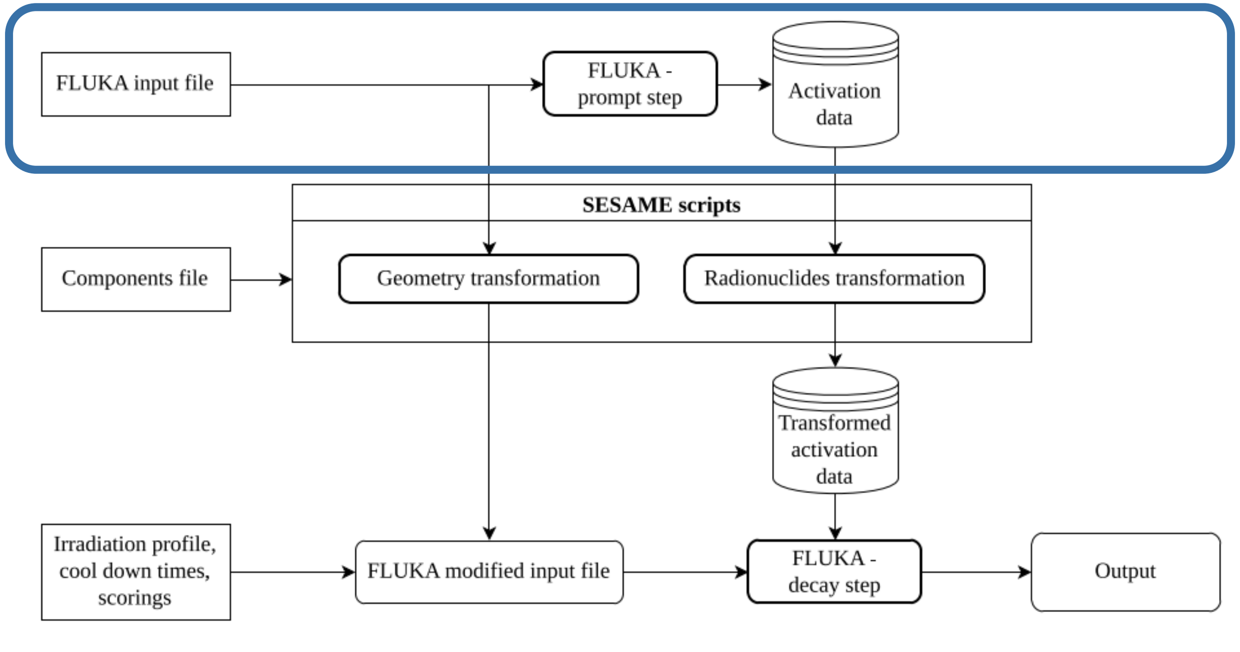


Fig. 3. Schematic representation of the SESAME workflow (Lorenzon et al., 2023).

Ref: D. Bozzato et al. Advanced simulation techniques for Radiation Protection studies at the Large Hadron Collider, Radiation Physics and Chemistry, Volume 218, 2024, 111573

SESAME

➢ Geometry transformation:

- At this stage, complex modification can be implemented in the FLUKA input file to account for geometry changes.
- These can be introduced by defining a list of geometry directives in a plain text file (Components file).
- Directives are applied to components, SESAME objects defined as sets of FLUKA regions that have to be handled all together: intuitively, these components could be regions representing real-life composite objects, such as sub-detectors or shielding elements.
- Currently available directives allow to describe multiple roto-translations, complete removal of items from the geometry, and disabling components.
- As output of this operation, SESAME automatically writes a modified FLUKA input and a transformed radionuclide inventory.

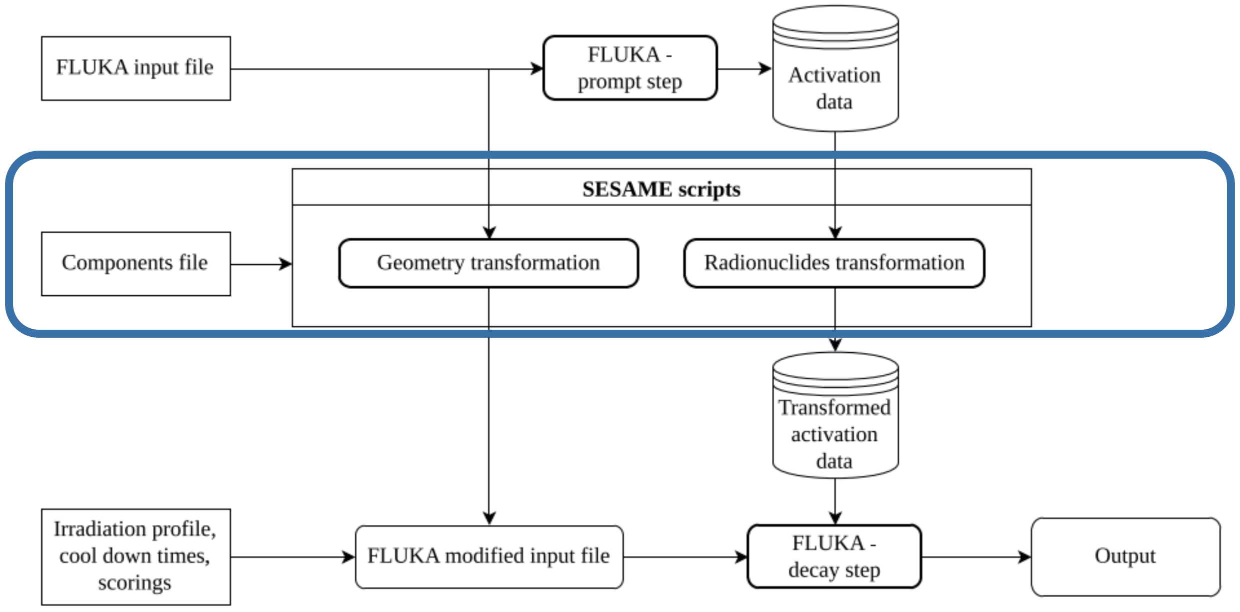


Fig. 3. Schematic representation of the SESAME workflow (Lorenzon et al., 2023).

Ref: D. Bozzato et al. Advanced simulation techniques for Radiation Protection studies at the Large Hadron Collider, Radiation Physics and Chemistry, Volume 218, 2024, 111573

SESAME

- Decay step:
  - Using the transformed radionuclide inventory as radiation source, nuclides are loaded into FLUKA as primary particles via a dedicated source user routine and their decay is simulated in the newly modified geometry.
  - As any other typical FLUKA activation study, this step requires that the radioactive decay is enabled (RADDECAY) and that all the relevant cards for residual studies, such as a suitable irradiation profile, decay times, etc, are provided.

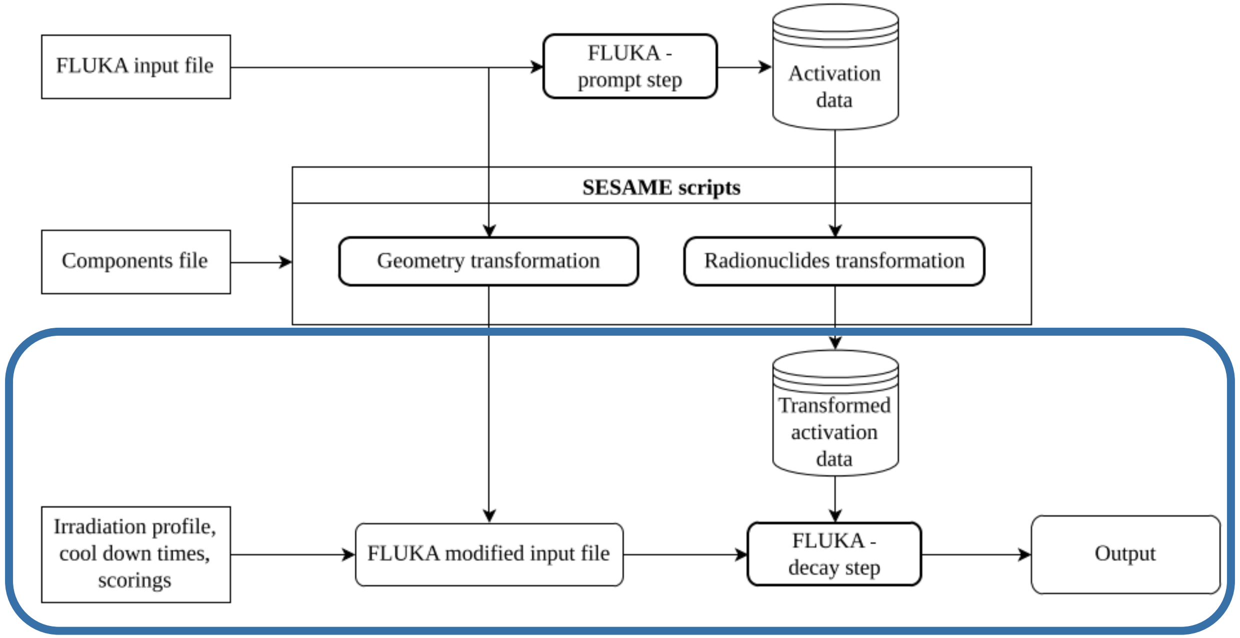


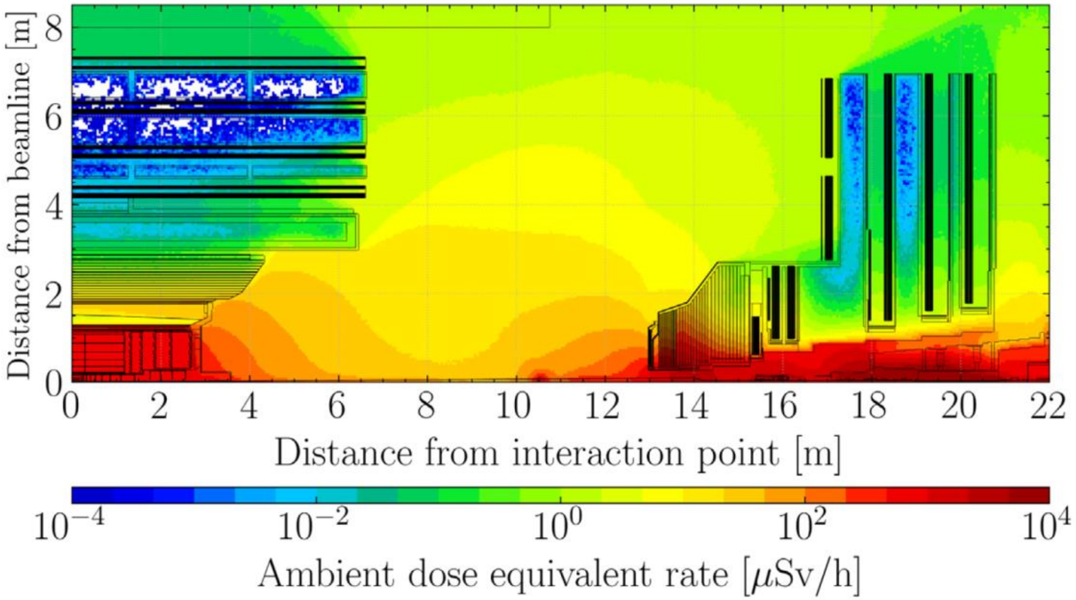
Fig. 3. Schematic representation of the SESAME workflow (Lorenzon et al., 2023).

Ref: D. Bozzato et al. *Advanced simulation techniques for Radiation Protection studies at the Large Hadron Collider, Radiation Physics and Chemistry*, *Volume 218, 2024, 111573*

Ref: D. Bozzato et al. Advanced simulation techniques for Radiation Protection studies at the Large Hadron Collider, Radiation Physics and Chemistry, Volume 218, 2024, 111573

SESAME: example

- Prompt step: simulation of the CMS experiment in its operation configuration (detector closed). Source term: $s = \sqrt{14}$ TeV proton-proton collisions. Scoring of the radionuclide inventory via a dedicated *usrrnc.f*.
- Geometry transformation (SESAME): transformation of the *activation data* and the geometry, accordingly to a series of directives (e.g. translation of the end-caps) provided via a *component* file.
- Decay step: residual study using a suitable irradiation profile. Source term: *transformed activation data* loaded via a dedicated *source*.f Scoring of the residual ambient dose rate via USRBINs (DOSE-EQ).



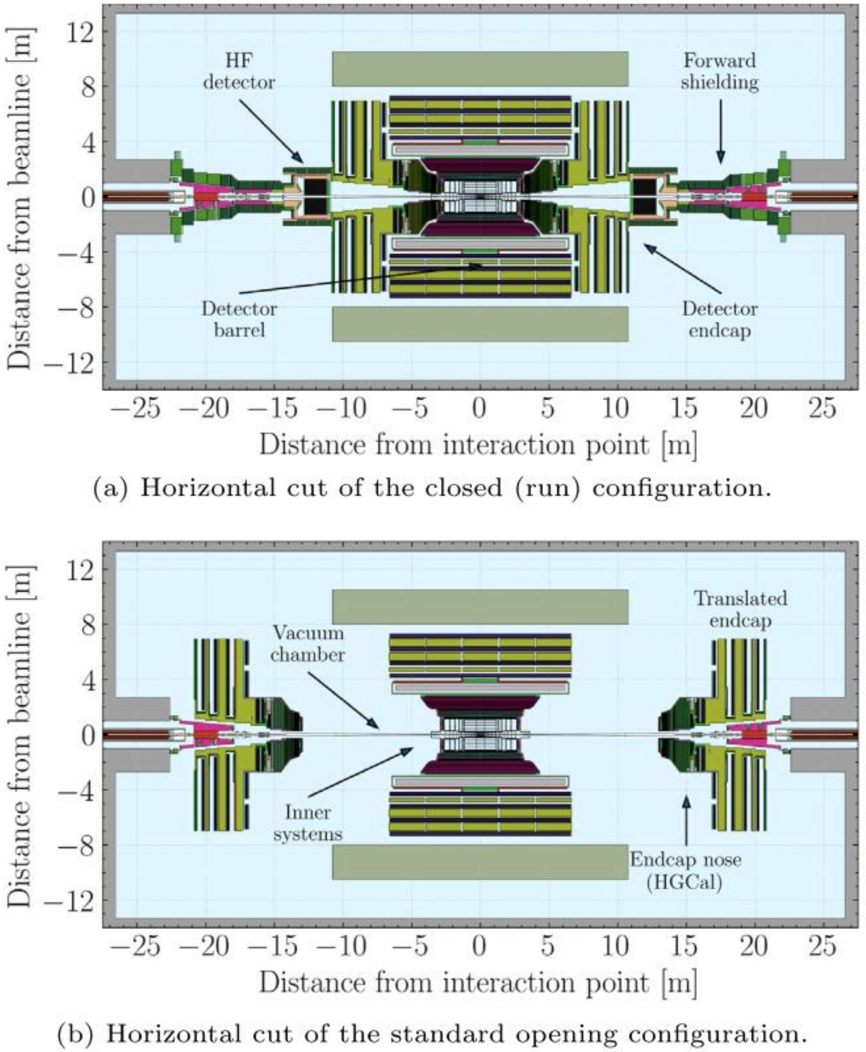


Fig. 5. Example of geometry transformation performed by the SESAME tool on the CMS FLUKA geometry: (a) closed configuration used for the simulation of the prompt step; (b) standard opening configuration with the opening of the forward shielding and translation of the detector endcaps used for the simulation of the decay step.

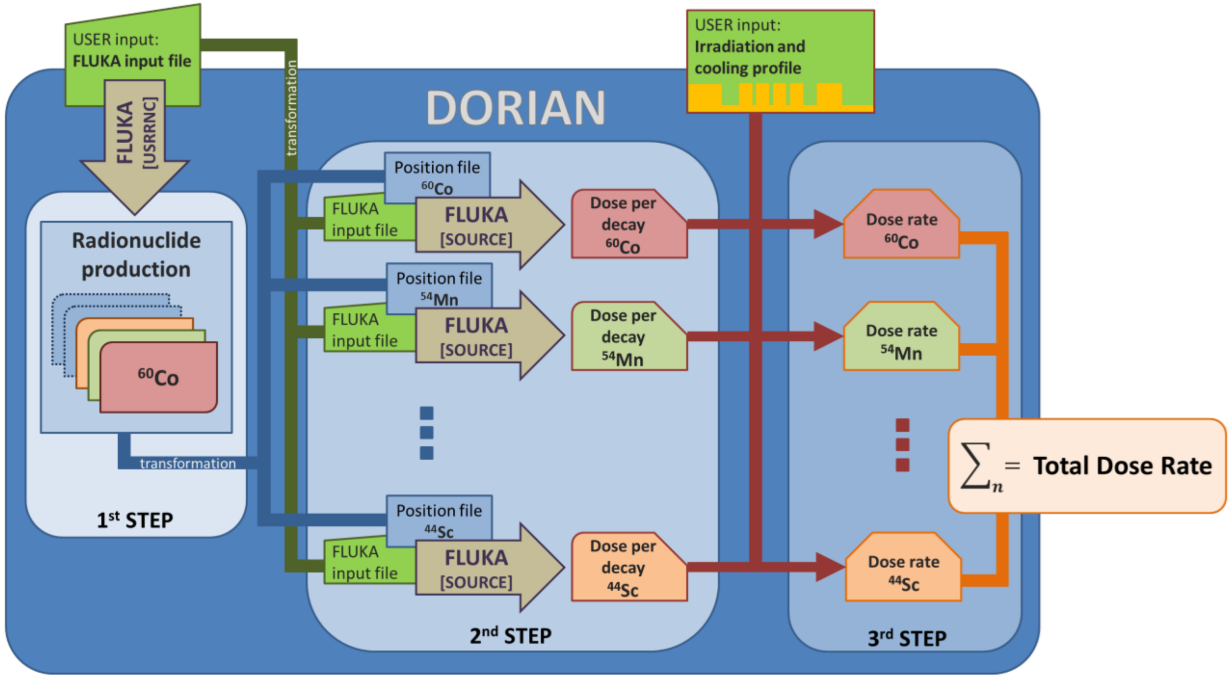
DORIAN

Ref: R. Froeschl, The DORIAN code for the prediction and analysis of residual dose rates due to accelerator radiation induced activation, 2013

- FLUKA can provide estimates for residual dose rates for a given irradiation profile and a set of cooling times.
- However, at present, it is not possible to obtain the dose rate for a different irradiation profile or another set of cooling times without re-running the whole simulation. Furthermore, there is no straightforward method to assess the contribution of the different geometrical regions and different radionuclides to the dose rate.
- The **DORIAN** (DOse Rate Inspector and ANalyzer), written in the Python and based on the FLUKA code, allows to calculate residual dose rates in a three-step process as well as for a comprehensive analysis of the various contributions.
- With the ability to change the geometrical configuration after the irradiation and quickly recalculate the dose rate for any stepwise irradiation profile and cooling time, DORIAN is an effective tool for optimizing residual dose rates in accelerator facilities.
- The DORIAN scripting interface is customizable and allow access to numerical and visualization libraries.
- At present the DORIAN code is available only within the FLUKA CERN collaboration, in the intent to make it available to users in the near future.

DORIAN

- First step:
  - In the first step, the FLUKA simulation of the primary process of interest is performed and information concerning the creation of radionuclides is recorded for the second step.
  - A special *usrrnc.f* is called during the simulations every time a radionuclide is created and writes the *atomic number, the mass number and a flag for an isomeric state of the produced radionuclide, the coordinates of the creation point, the region number, the weight of the creation event and a flag indicating whether nor not the creation was caused by a neutron with an energy below 20 MeV* to a dedicated output file.
  - This last flag also allows the DORIAN to omit calls to the USRRNC user routine by the direct residual dose rate algorithm of FLUKA. Therefore, it is irrelevant for DORIAN whether an irradiation profile and cooling times have been directly specified in the first step.
  - If the simulation of this first step is split over multiple cycles, the output files are merged for the second step.

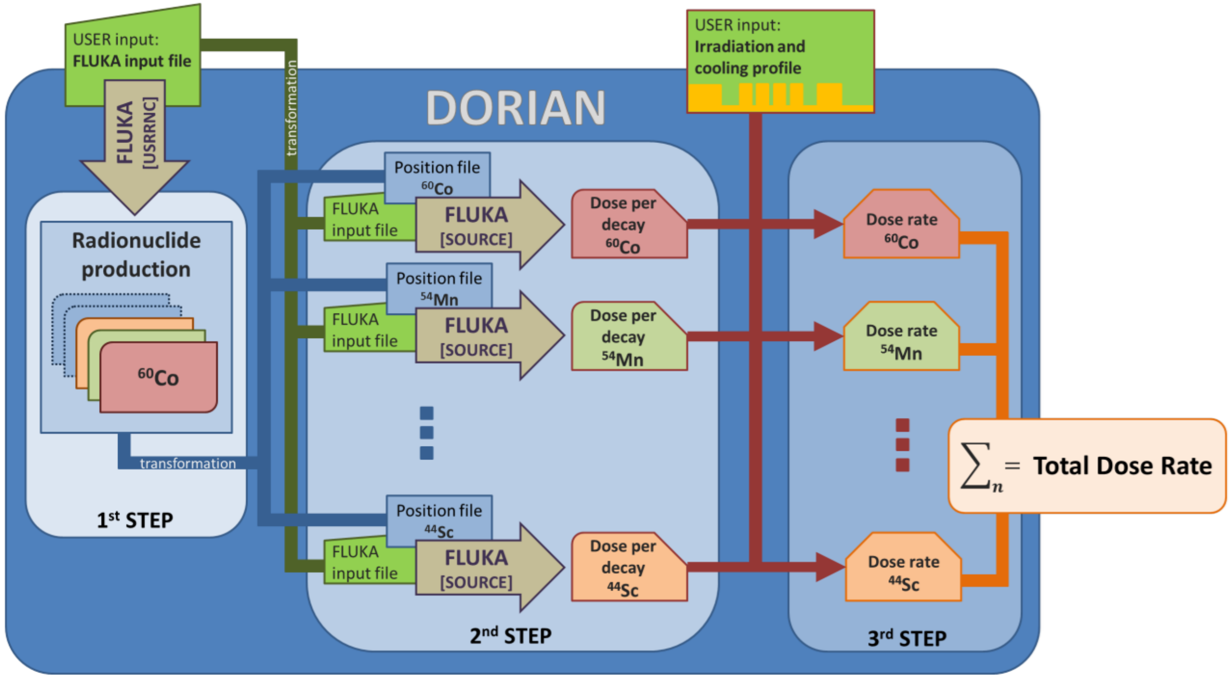


Ref: R. Froeschl, The DORIAN code for the prediction and analysis of residual dose rates due to accelerator radiation induced activation, 2013

DORIAN

➢ Second step:

- In the second step, FLUKA simulations are performed for the decay of the various radionuclides produced in the first step and the resulting dose-per-decay contributions are computed.
- Transformations can be applied to the content of the output file from the first step:
  - Geometrical transformations: The geometrical coordinates of the generation points of radionuclides can be transformed.
  - Branching ratios: A correction can be applied to reflect energy averaged branching ratios found in the JEFF 3.1.1 library.
  - Suppression: The calculation of the contributions for certain radionuclides or for certain regions can be suppressed by the user.
- A DORIAN supplied *source.f* routine handles the decay of each radionuclide produced at 1st step as well as for all radionuclides in all decay chains that originate from it.



Ref: R. Froeschl, The DORIAN code for the prediction and analysis of residual dose rates due to accelerator radiation induced activation, 2013

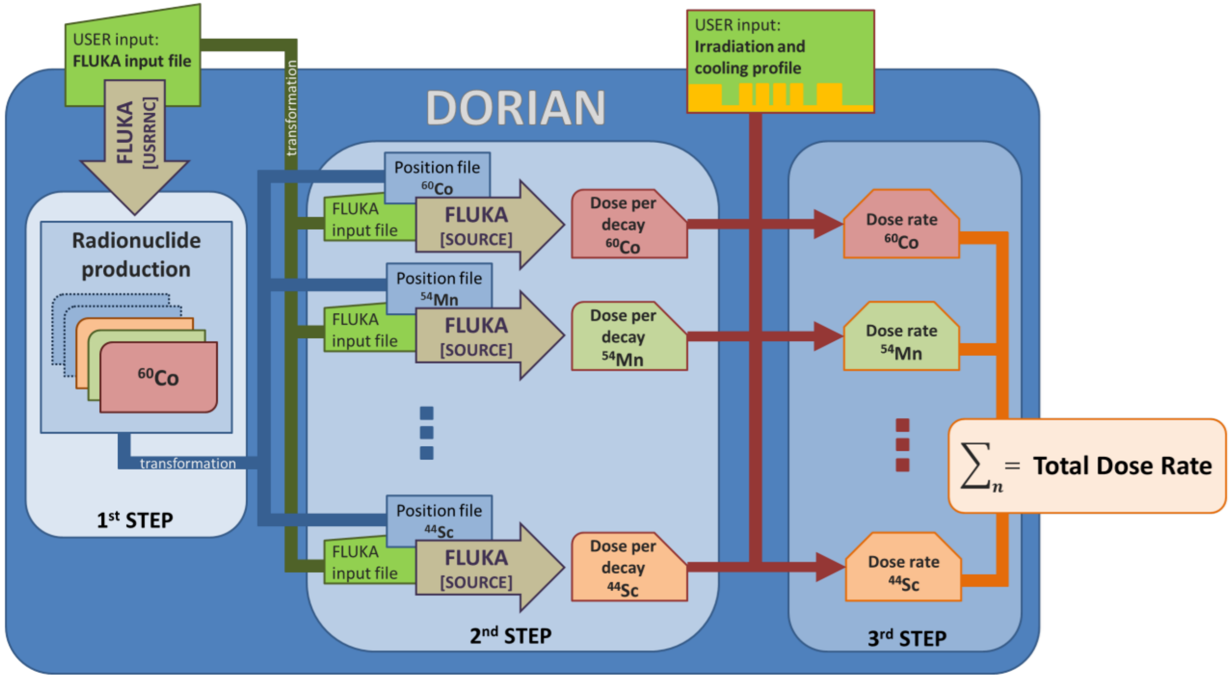
DORIAN

- Third step:
  - The contribution of the various radionuclides computed in the second step are combined according to a specified irradiation profile and cooling time, yielding the residual dose rate.

$$\frac{dD}{dt} = d = \sum_{r} \sum_{b} d^{S2}_{b,r} \frac{N^{S1}_{i_b,r}}{W^{S1}_{tot}} \frac{W^{S2}_{b,r}}{N^{S2}_{b,r}} T(b, i_b, r)$$

  which depends on the dose-per-decay computed in the second step, from the sum of the primary weights at step 1/2, from the number of number of productions/primary leading to radionuclide b, from the time evolution factor which depends on the irradiation profile and the cooling time.

  - Each summand in the above equation is available to the user for analysis. Therefore, the relevance of the various contributions to the total dose rate can be assessed.



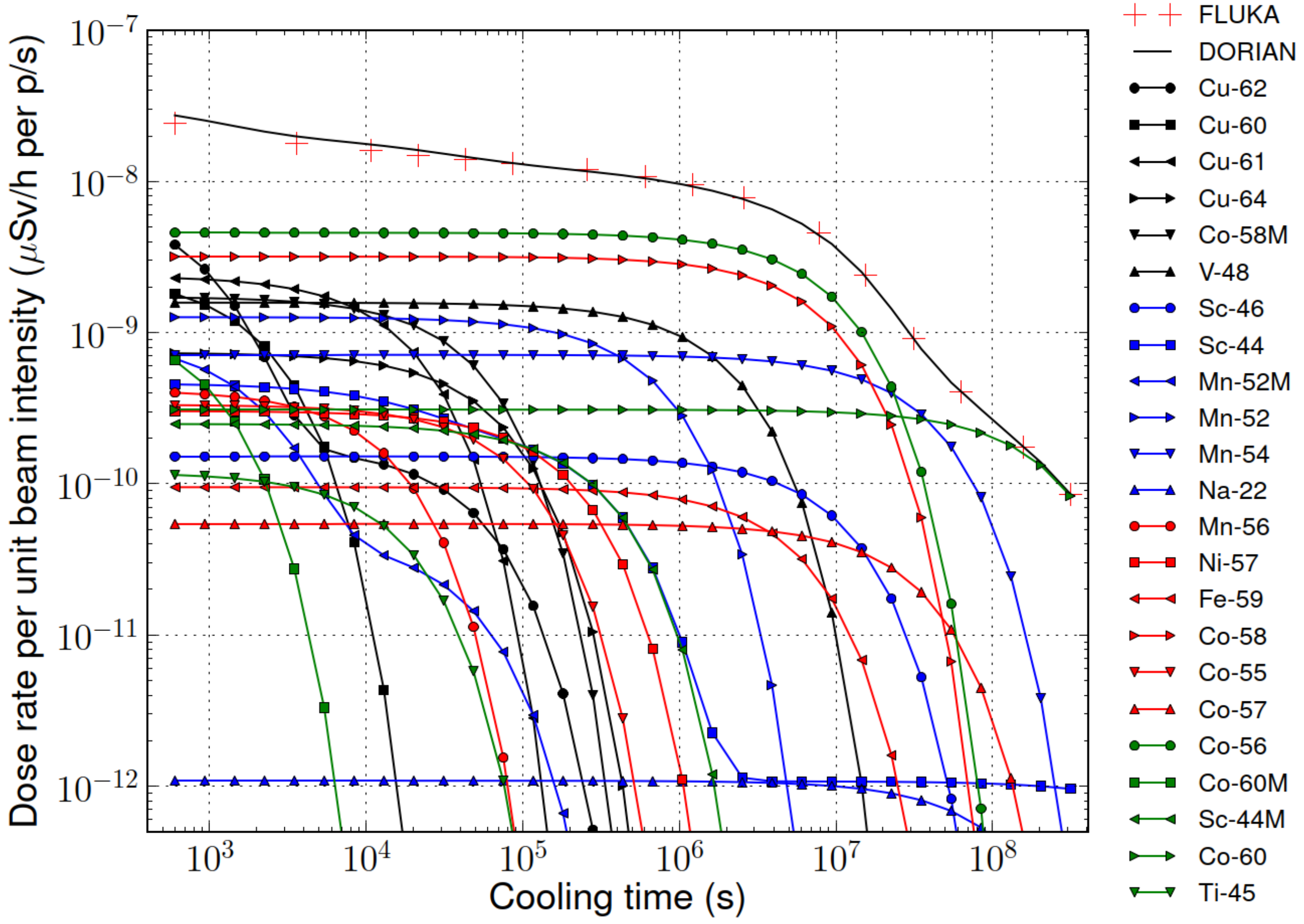
Ref: R. Froeschl, The DORIAN code for the prediction and analysis of residual dose rates due to accelerator radiation induced activation, 2013

DORIAN: validation

Verification of correctness of DORIAN wrt. FLUKA:

- Copper target surrounded by vacuum
- Cylinder, radius 5 cm, length 50 cm
- 1 GeV/c proton beam at the centre of the circular face
- 1 year of irradiation
- Dose rate at 50 cm upstream of the front face

Ref: R. Froeschl, The DORIAN code for the prediction and analysis of residual dose rates due to accelerator radiation induced activation, 2013

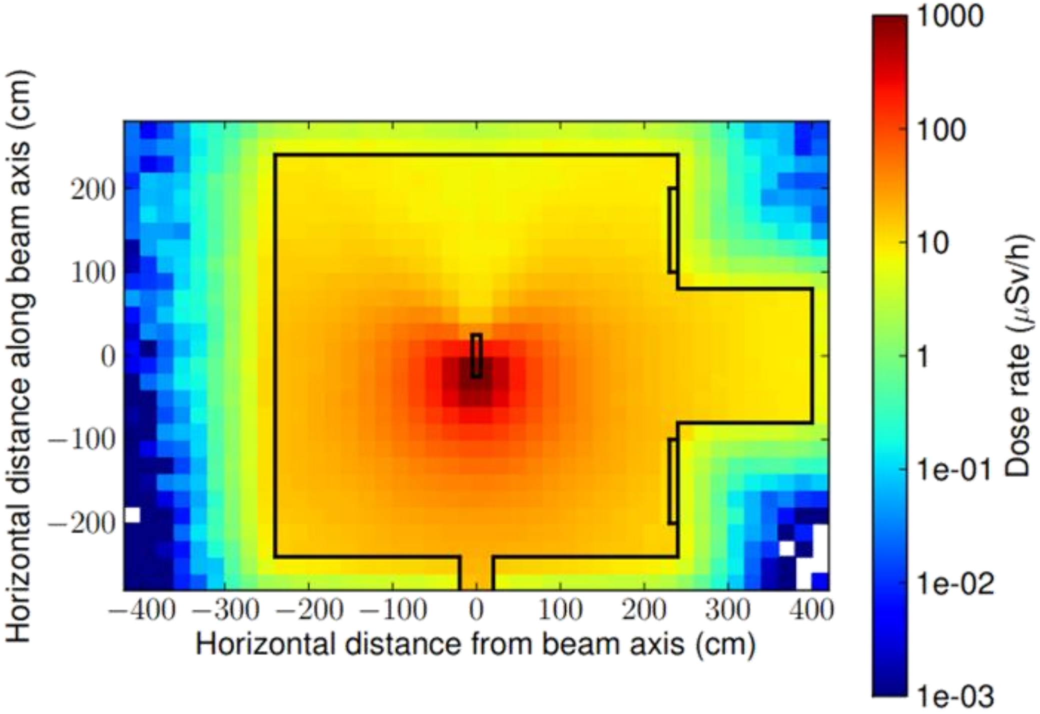


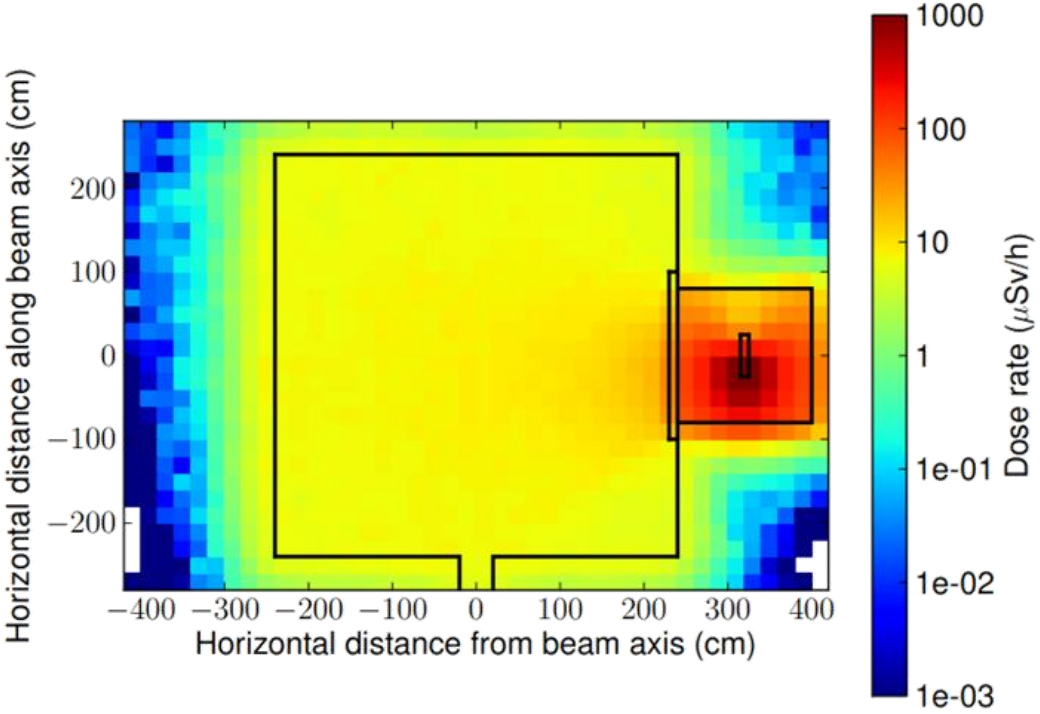
DORIAN: example

Ref: R. Froeschl, The DORIAN code for the prediction and analysis of residual dose rates due to accelerator radiation induced activation, 2013

Copper target irradiated in concrete bunker and then moved to an alcove:

- 1 GeV/c proton beam at the centre of the circular face
- 1 year of irradiation with 10^{10} protons/s
- Dose rate after 1 day of cooling which:
  - Target moved to alcove parking position
  - Movable marble shielding (10 cm thickness) closed at the entry to the alcove



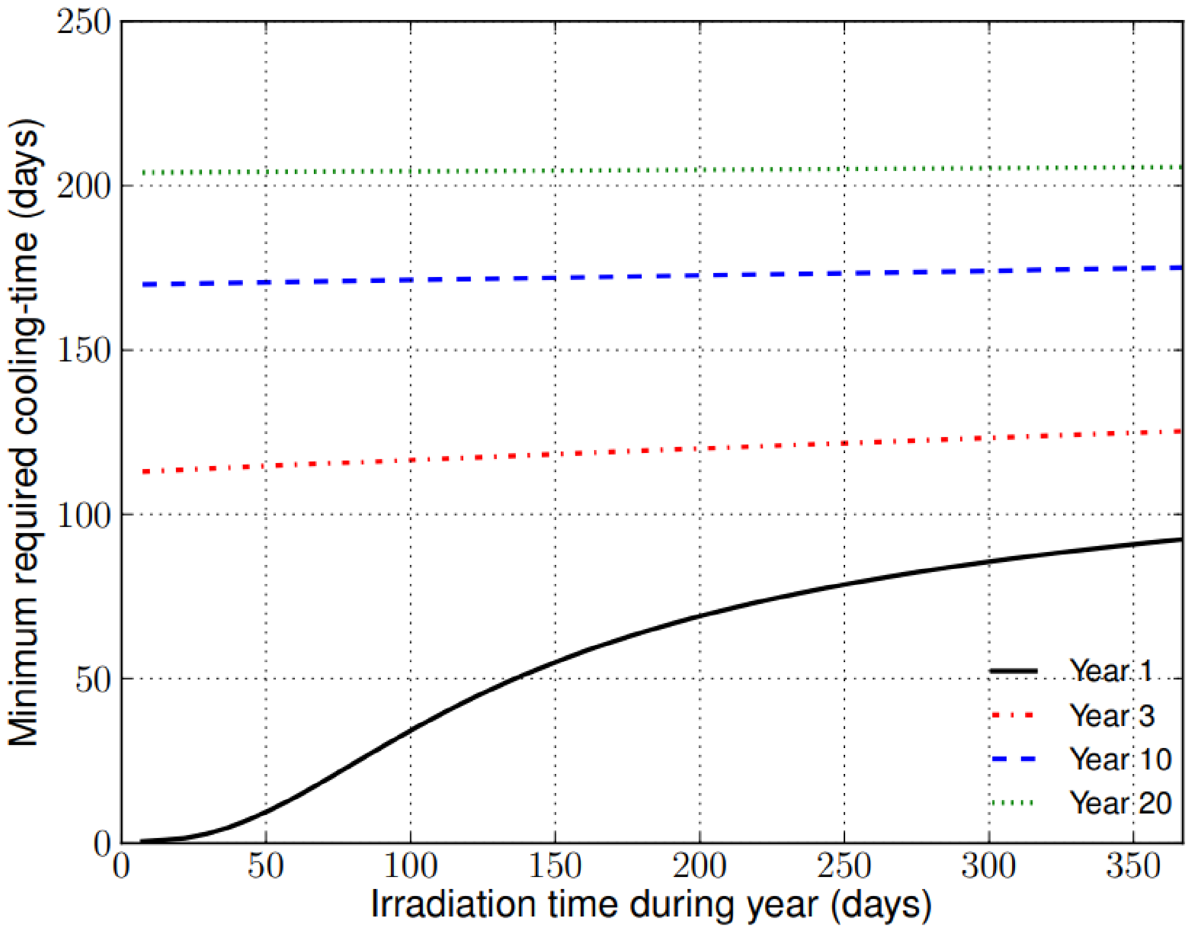


DORIAN: example

Ref: R. Froeschl, The DORIAN code for the prediction and analysis of residual dose rates due to accelerator radiation induced activation, 2013

- WDP for an intervention
- Authorization threshold: 200 µSv/h at 25 cm upstream of the front face of the target at the alcove parking position
- Minimum cooling time for a given irradiation profile by root finding algorithm

$$d(t_{irr}, t_{cool}) = 200\ \mu Sv/h$$



“Validation” of residual studies

Validation of residual studies

**in this sense it would be better to say "validation of the simulation parameters".*

- FLUKA cannot replace your judgement as Radiation Protection Expert.
- "Validation" can be intended also from the more operational point* of view (e.g. comparison with existing radiation measurements and/or analytical methods).
- Information on the radionuclide inventory (e.g. via FLUKA/ActiWiz/DORIAN) can identify the main isotopes contributing to the dose (e.g. Mn-54/Co-60 in steel).
- Analytical methods can, in most of the case, provide you the order of magnitude of the expected residual dose rate at a given time.
- See references/books indicated in the Prompt Radiation Exposure lecture and your national law!.

TABLE 6. RADIONUCLIDES COMMONLY IDENTIFIED IN SOLID MATERIALS IRRADIATED AROUND ACCELERATORS
(reproduced from Ref. [7])

Irradiated material	Radionuclides
Plastics, oils	^{3}H, ^{7}Be, ^{11}C
Concrete and aluminium	^{3}H, ^{7}Be, ^{11}C, ^{22}Na, ^{24}Na, ^{32}P, ^{42}K, ^{45}Ca, ^{152}Eu
Iron and steel	^{3}H, ^{7}Be, ^{11}C, ^{22}Na, ^{24}Na, ^{32}P, ^{42}K, ^{45}Ca, ^{44}Sc, ^{44m}Sc, ^{46}Sc, ^{47}Sc, ^{48}Sc, ^{48}V, ^{51}Cr, ^{52}Mn, ^{52m}Mn, ^{54}Mn, ^{56}Mn, ^{57}Co, ^{58}Co, ^{60}Co, ^{57}Ni, ^{55}Fe, ^{59}Fe, ^{63}Ni
Copper	^{3}H, ^{7}Be, ^{11}C, ^{22}Na, ^{24}Na, ^{32}P, ^{42}K, ^{45}Ca, ^{44}Sc, ^{44m}Sc, ^{46}Sc, ^{47}Sc, ^{48}Sc, ^{48}V, ^{51}Cr, ^{52}Mn, ^{52m}Mn, ^{54}Mn, ^{56}Mn, ^{57}Co, ^{58}Co, ^{60}Co, ^{57}Ni, ^{63}Ni, ^{65}Ni, ^{55}Fe, ^{59}Fe, ^{61}Cu, ^{64}Cu, ^{63}Zn, ^{65}Zn

Source: IAEA

Radionuclide	Half-life	Type of decay/ radiation	Assessment quantities				
			e_{inh} Sv/Bq	e_{ing} Sv/Bq	h_{10} (mSv/h)/ GBq at 1 m distance	0,07 mSv/h)/ GBq at 0 cm istance	$h_{c,0,07}$ (mSv/h)/ (kBq/cm^2)
1	2	3	4	5	6		8
Sc-48	43.67 h	β⁻ / ph	1.60E-09	1.70E-09	0.495	000	1.7
Sc-49	57.2 min	β⁻ / ph	6.10E-11	8.20E-11	0.001	000	1.6
Ti-44	60.0 a	ec / ph	7.20E-08	5.80E-09	0.026	[illegible]	<0.1
Ti-45	184.8 min	ec, β⁺ / ph	1.50E-10	1.50E-10	0.136	000	1.5
V-47	32.6 min	ec, β⁺ / ph	5.00E-11	6.30E-11	0.156	000	1.7
V-48	15.9735 d	ec, β⁺ / ph	2.70E-09	2.00E-09	0.432	00	1
V-49	330 d	ec / ph	2.60E-11	1.80E-11	<0.001	1	<0.1
Cr-48	21.56 h	ec, β⁺ / ph	2.50E-10	2.00E-10	0.071	0	0.1
Cr-49	42.3 min	ec, β⁺ / ph	5.90E-11	6.10E-11	0.166	000	1.7
Cr-51	27.7025 d	ec / ph	3.60E-11	3.80E-11	0.005	[illegible]	<0.1
Mn-51	46.2 min	ec, β⁺ / ph	6.80E-11	9.30E-11	0.159	000	1.7
Mn-52	5.591 d	ec, β⁺ / ph	1.80E-09	1.80E-09	0.510	00	0.7
Mn-52m	21.1 min	ec, β⁺, it / ph	5.00E-11	6.90E-11	0.389	000	1.7
Mn-53	3.7 E6 a	ec / ph	3.60E-11	3.00E-11	<0.001	0	<0.1
Mn-54	312.12 d	ec, β⁺, β⁻ / ph	1.20E-09	7.10E-10	0.126	0	0.1
Mn-56	2.5789 h	β⁻ / ph	2.00E-10	2.50E-10	0.275	000	1.7
Fe-52	8.275 h	ec, β⁺ / ph	9.50E-10	1.40E-09	0.116	00	1
Fe-55	2.737 a	ec / ph	9.20E-10	3.30E-10	<0.001	0	<0.1
Fe-59	44.495 d	β⁻ / ph	3.20E-09	1.80E-09	0.175	000	1.1
Fe-60	1.5 E6 a	β⁻	3.30E-07	1.10E-07	<0.001	0	0.3
Co-55	17.53 h	ec, β⁺ / ph	8.30E-10	1.10E-09	0.302	000	1.4
Co-56	77.23 d	ec, β⁺ / ph	4.90E-09	2.50E-09	0.485	00	0.6
Co-57	271.74 d	ec / ph	6.00E-10	2.10E-10	0.021	00	0.1
Co-58	70.86 d	ec, β⁺ / ph	1.70E-09	7.40E-10	0.147	00	0.3
Co-58m	9.04 h	it / ph	1.70E-11	2.40E-11	<0.001	0	<0.1
Co-60	5.2713 a	β⁻ / ph	1.70E-08	3.40E-09	0.366	000	1.1

Source: Swiss Federal Law on Radiation Protection

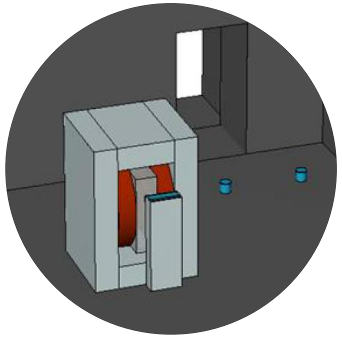
$$\dot{D}(t) = \frac{h_{10} \times A(t)}{d^2}$$

For a point-source

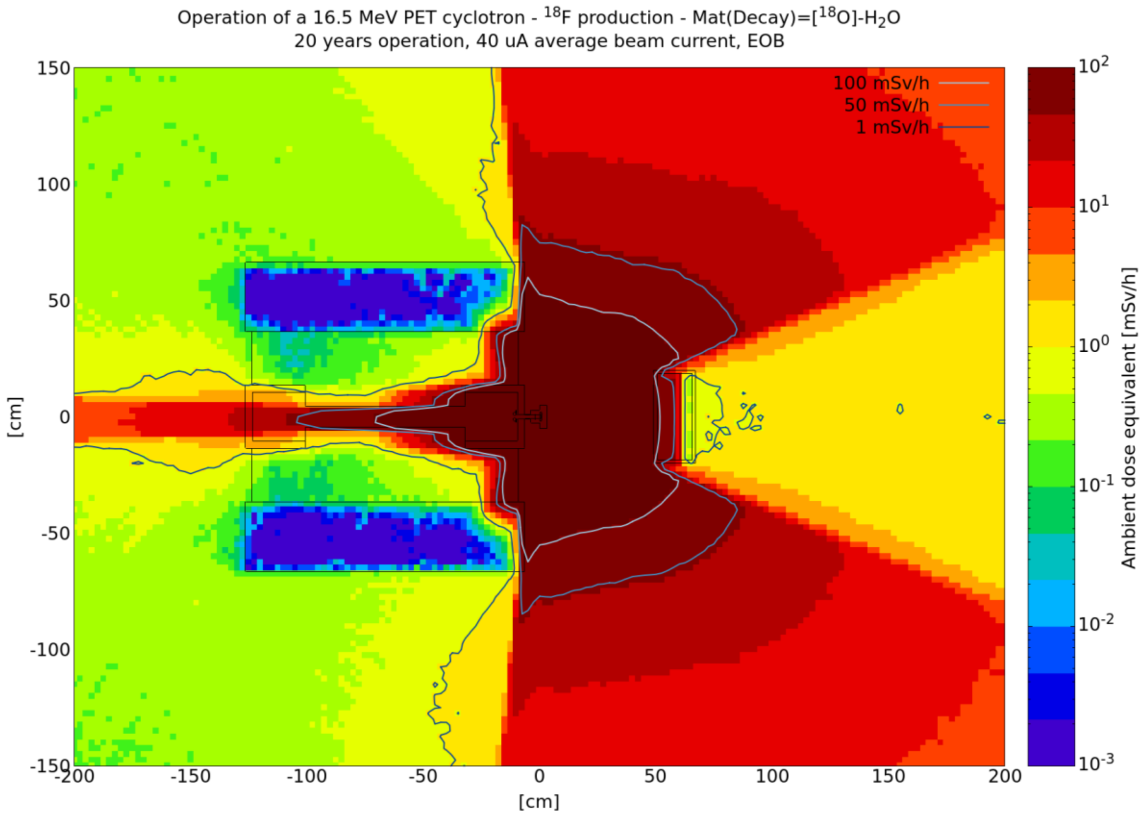
Application examples

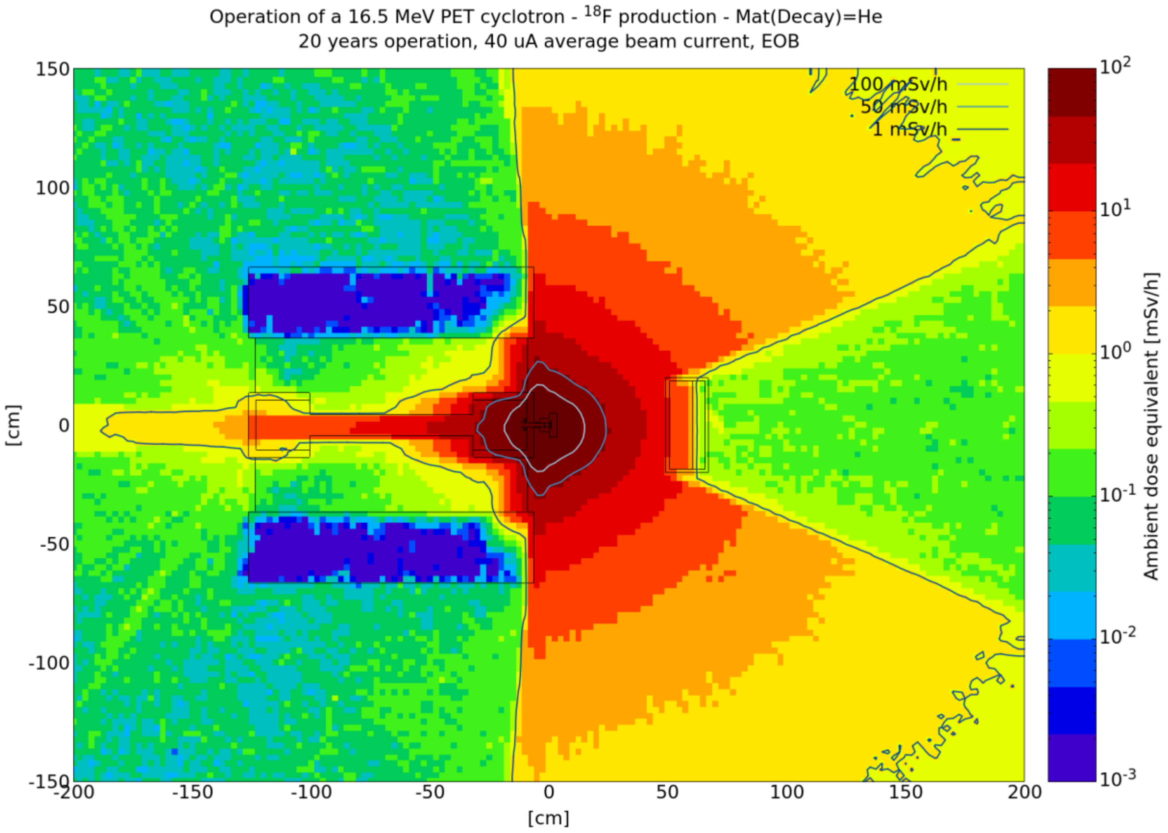
PET cyclotron

A. Infantino et al., Accurate Monte Carlo modeling of cyclotrons for optimization of shielding and activation calculations in the biomedical field. Radiation Physics and Chemistry 116 (2015) 231–236

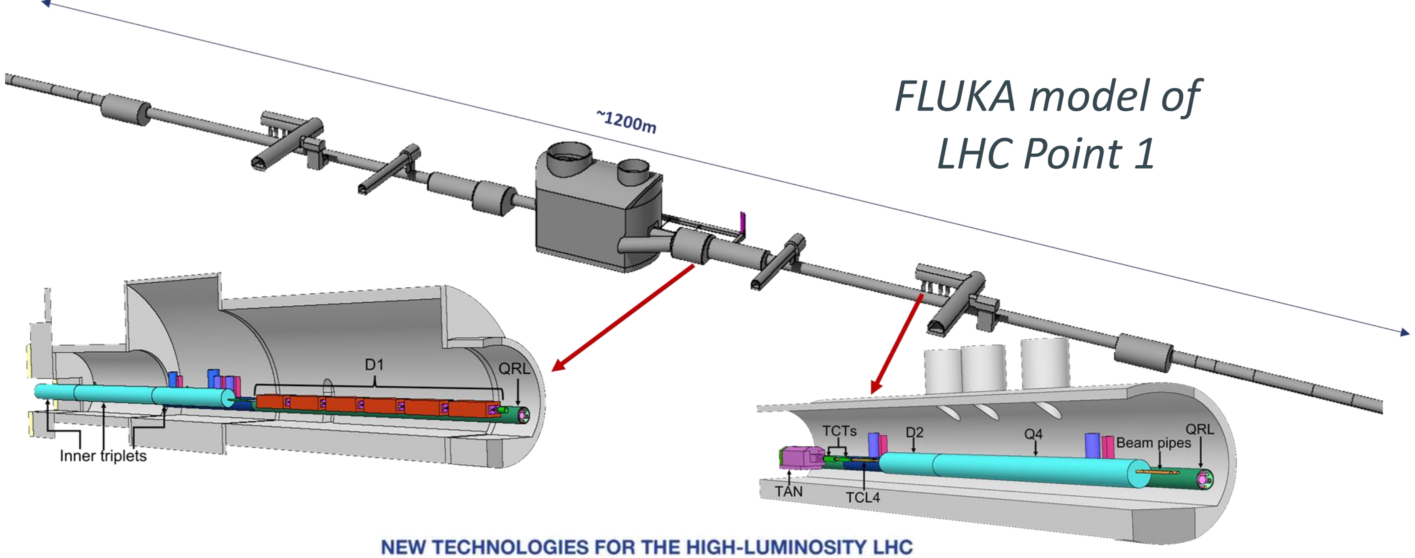


- ^{18}F produced in cyclotron via $^{18}O(p,n)^{18}F$ reaction (enriched O-18 water target).
- Produced activity sent to the radiopharmacy laboratory by flushing the target with Helium.
- FLUKA model of 16.5 MeV proton PET cyclotron.
- 20 years of operation, F-18 production, 40 μA beam current.
- Residual dose rate maps at End-Of-Bombardment (EOB).
- Target material (decay): enriched O-18 water vs He.





LHC upgrade

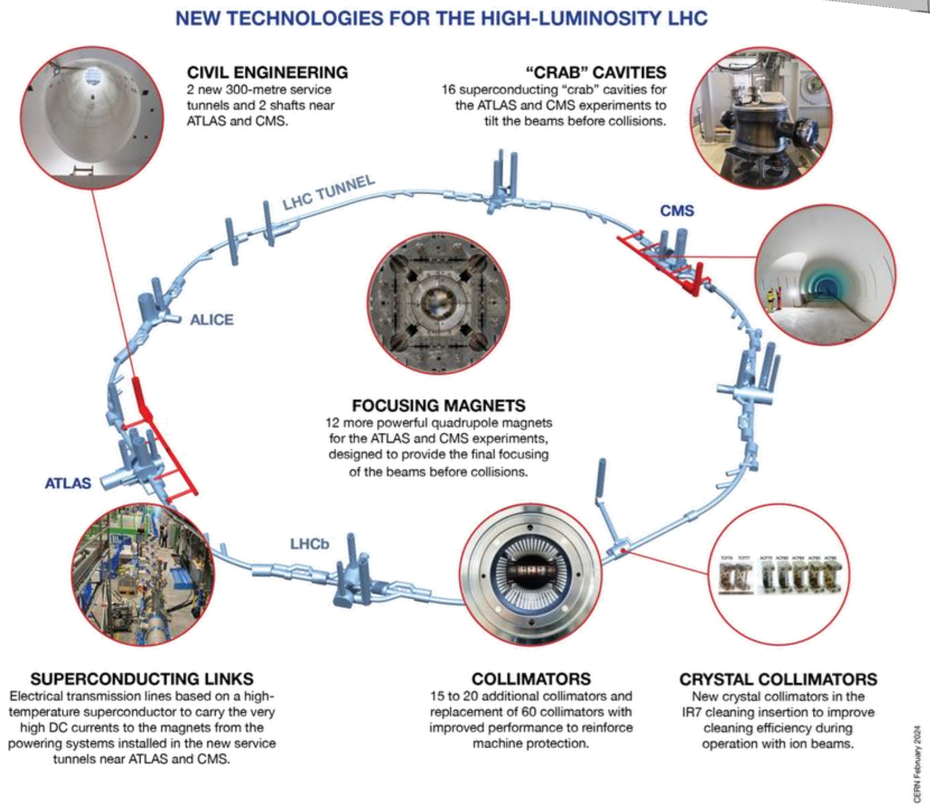


What's new?

- $\dot{\mathcal{L}} = 7.5 \times 10^{34}$ cm^{-2} s^{-1} & $\mathcal{L}_{int} = 4000$ fb^{-1}
- New optics → new magnets in Pt.1/5
- New "*crab-cavities*" in Pt.1/5
- New cryogenic distribution line in Pt.1/5
- New underground infrastructure
- New beam dump
- HEL, crystal collimation, 11T dipoles, and more

What to do? (main activities)
Long Shutdown 3 (LS3) (2026-2028)

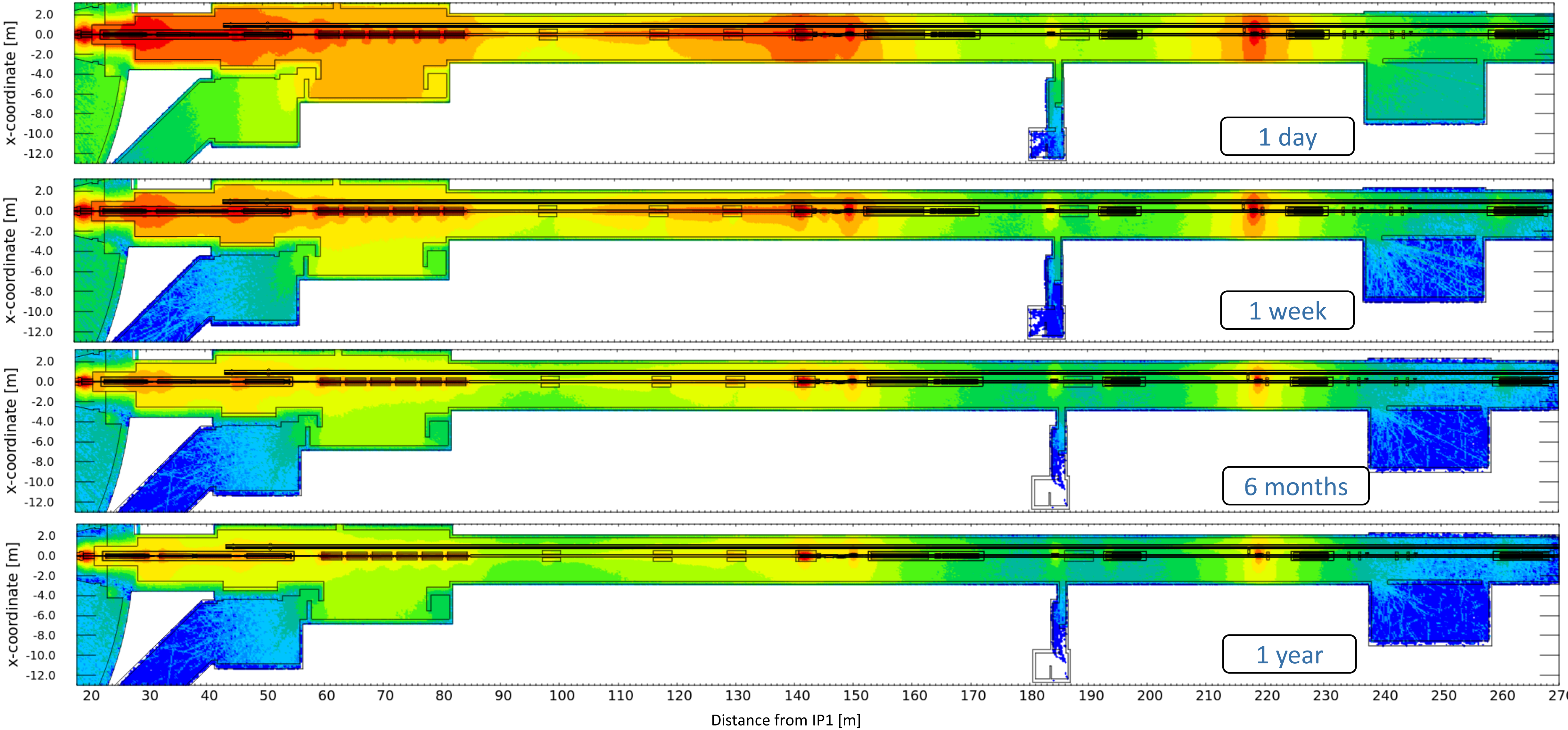
- Dismantling of 800+ m of beam lines in Pt.1/5
- Dismantling old cryo-line in Pt.1/5
- Dismantling Run 3 operational beam dumps (Pt.6)
- CE works for finalizing new underground infrastructure
- Installation of HL-LHC equipment
- Hard deadline: 3 years including beam commissioning



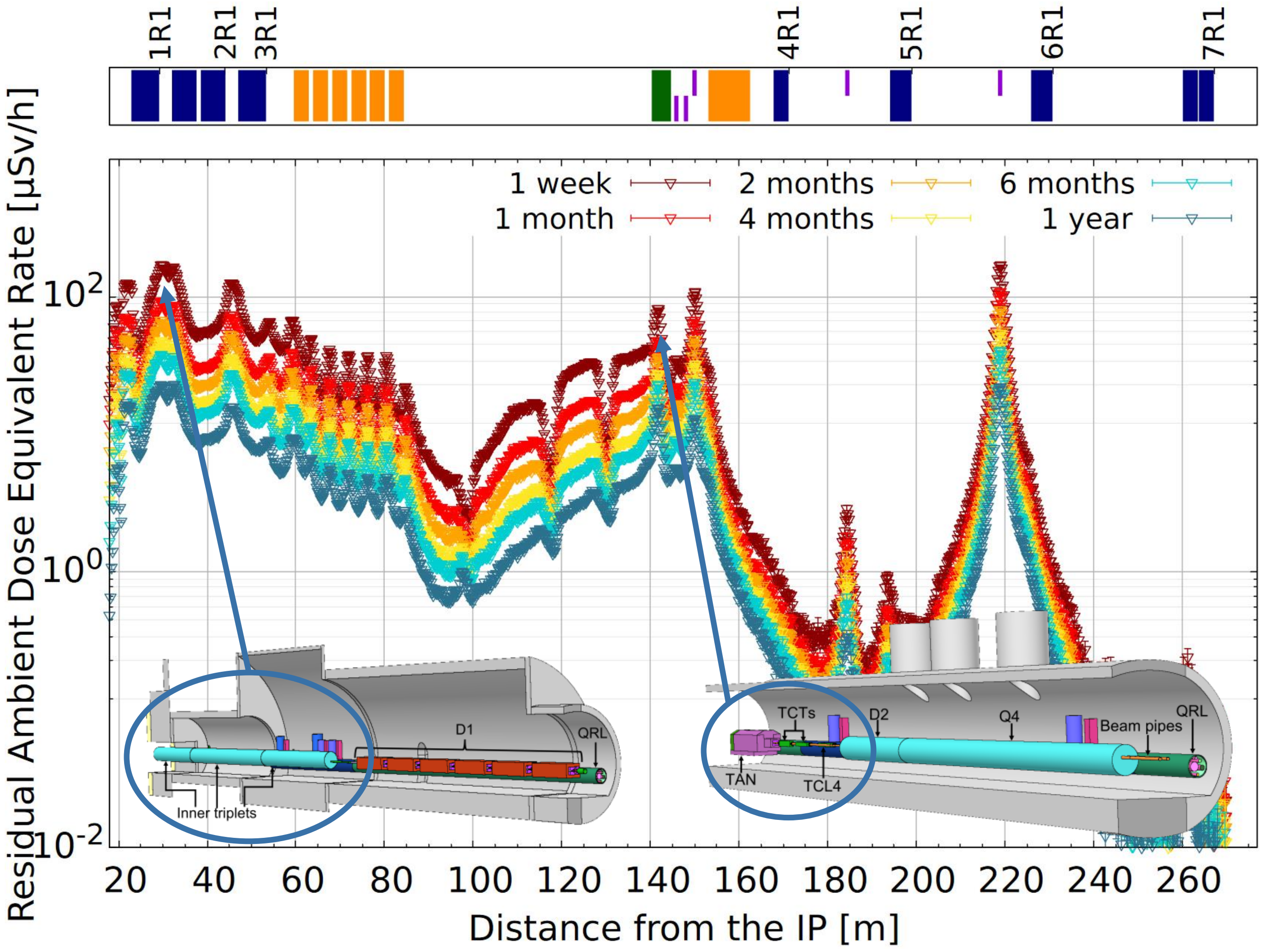
LHC upgrade

A. Infantino et al., [Radiation Protection at the Large Hadron Collider: Problematics, Challenges and Advanced Monte Carlo Simulation Techniques](). Environments 2022, 9(5), 54.
L. Elie et al., [Radiation protection challenges for the Large Hadron Collider upgrade](). Radiation Protection Dosimetry, 2023, 199(8–9), 900–910

Projected residual radiation levels in LHC Point 1 after the end of Run 3 proton physics operation.



LHC upgrade

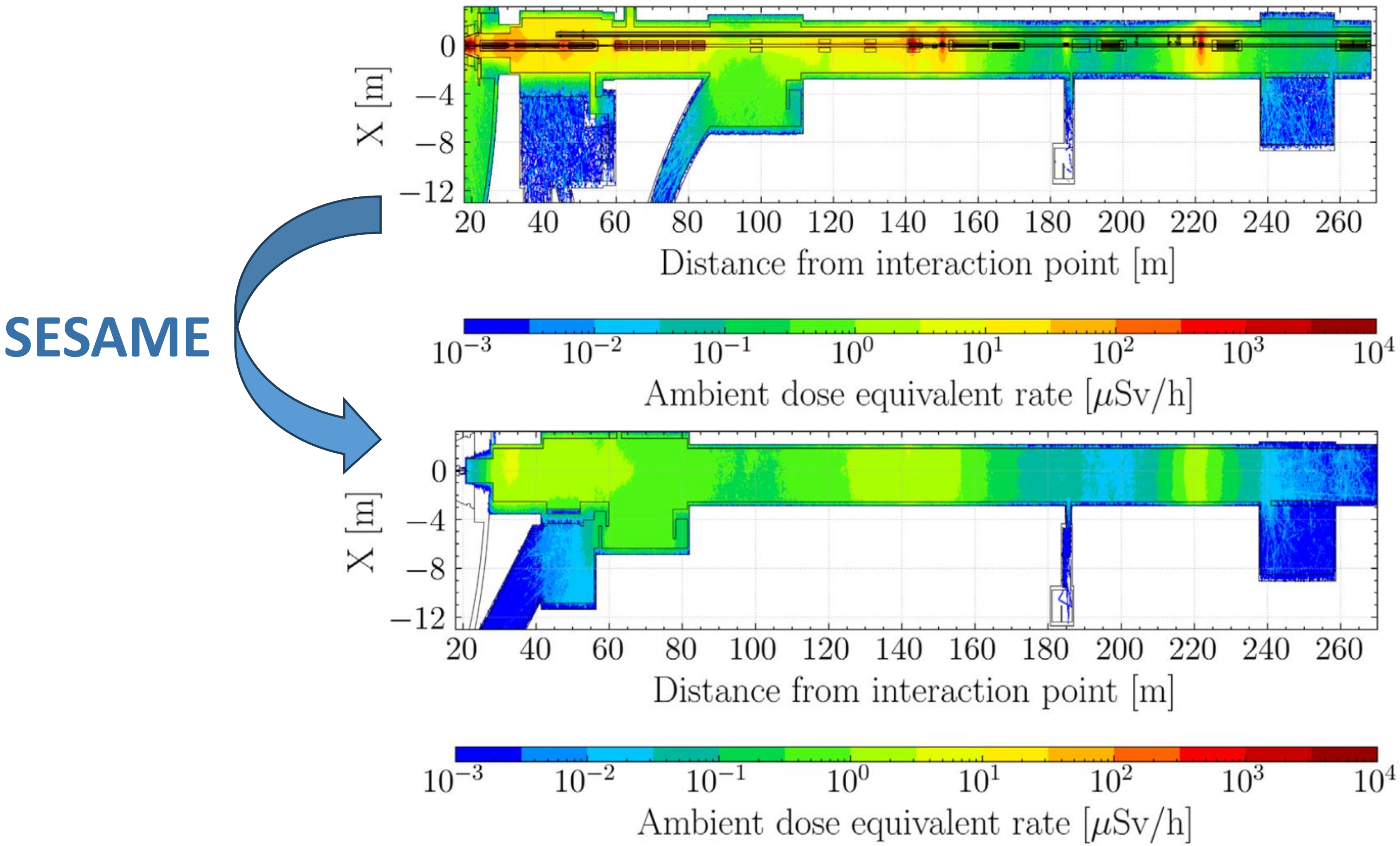


- ✓ FLUKA simulations & measurements used for planning interventions and to prepare "Work-Dose Plan (WDP)" → radiological risk associated to the intervention.
- ✓ Projected residual levels kept updated based on the evolution of the LHC operation and changes in the long-term schedule → i.e. changes in the irradiation profile.
- ✓ Projected levels compared with operational RP surveys and activation samples → agreement, for most locations, better than 30%.

A. Infantino et al., Radiation Protection at the Large Hadron Collider: Problematics, Challenges and Advanced Monte Carlo Simulation Techniques. Environments 2022, 9(5), 54.
L. Elie et al., Radiation protection challenges for the Large Hadron Collider upgrade. Radiation Protection Dosimetry, 2023, 199(8–9), 900–910

LHC upgrade

D. Bozzato et al., [Advanced simulation techniques for Radiation Protection studies at the Large Hadron Collider, Radiat. Phys. Chem. 2024]



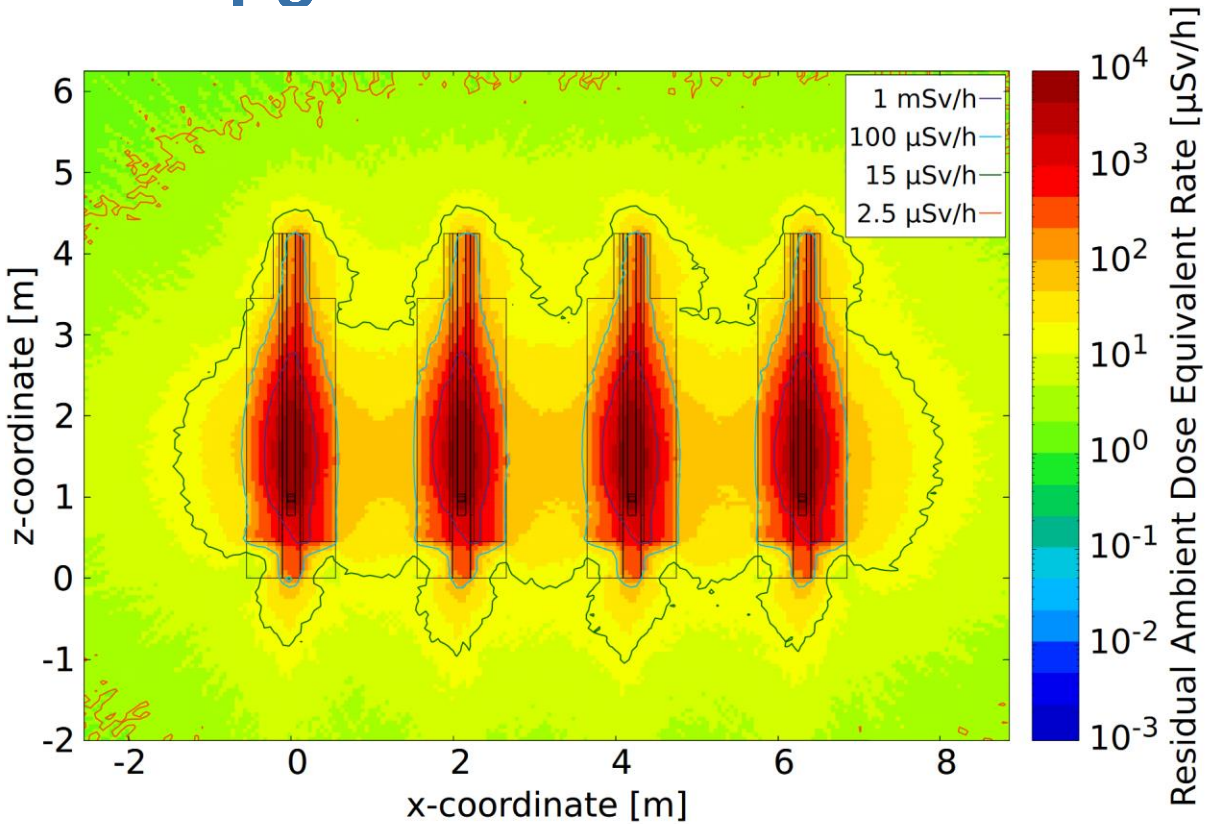
Residual radiation field with no geometry transformation applied.

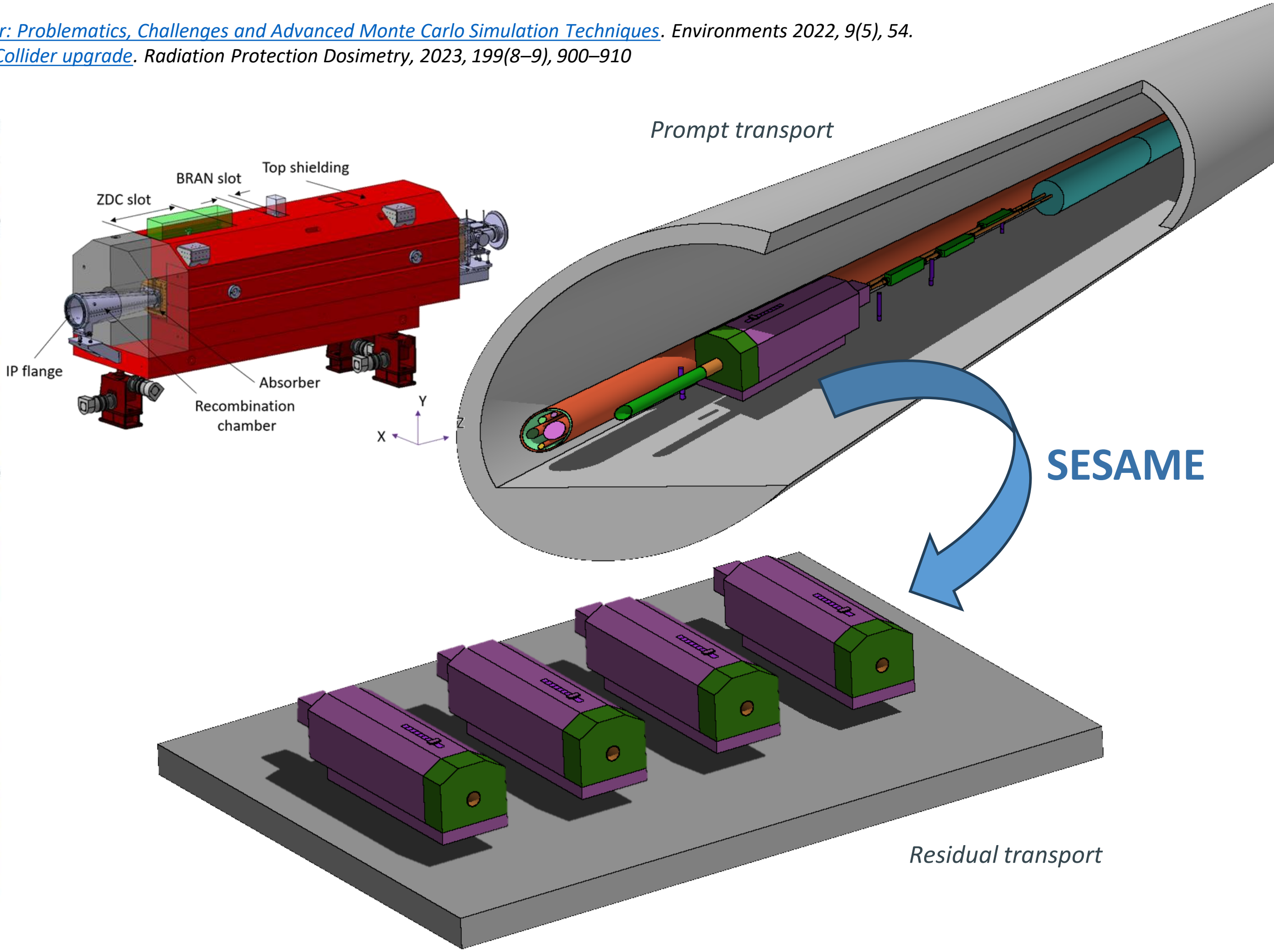
Residual radiation field with geometry transformation applied (machine "virtually" dismantled). Configuration relevant for the installation of the new HL-LHC beam line.

Fig. 9. Estimated radiation levels after removal of the accelerator elements from LSS 1. Residual ambient dose equivalent rate after 1 year from the end of Run 3 proton–proton physics (average over y = ±110 cm).

LHC upgrade

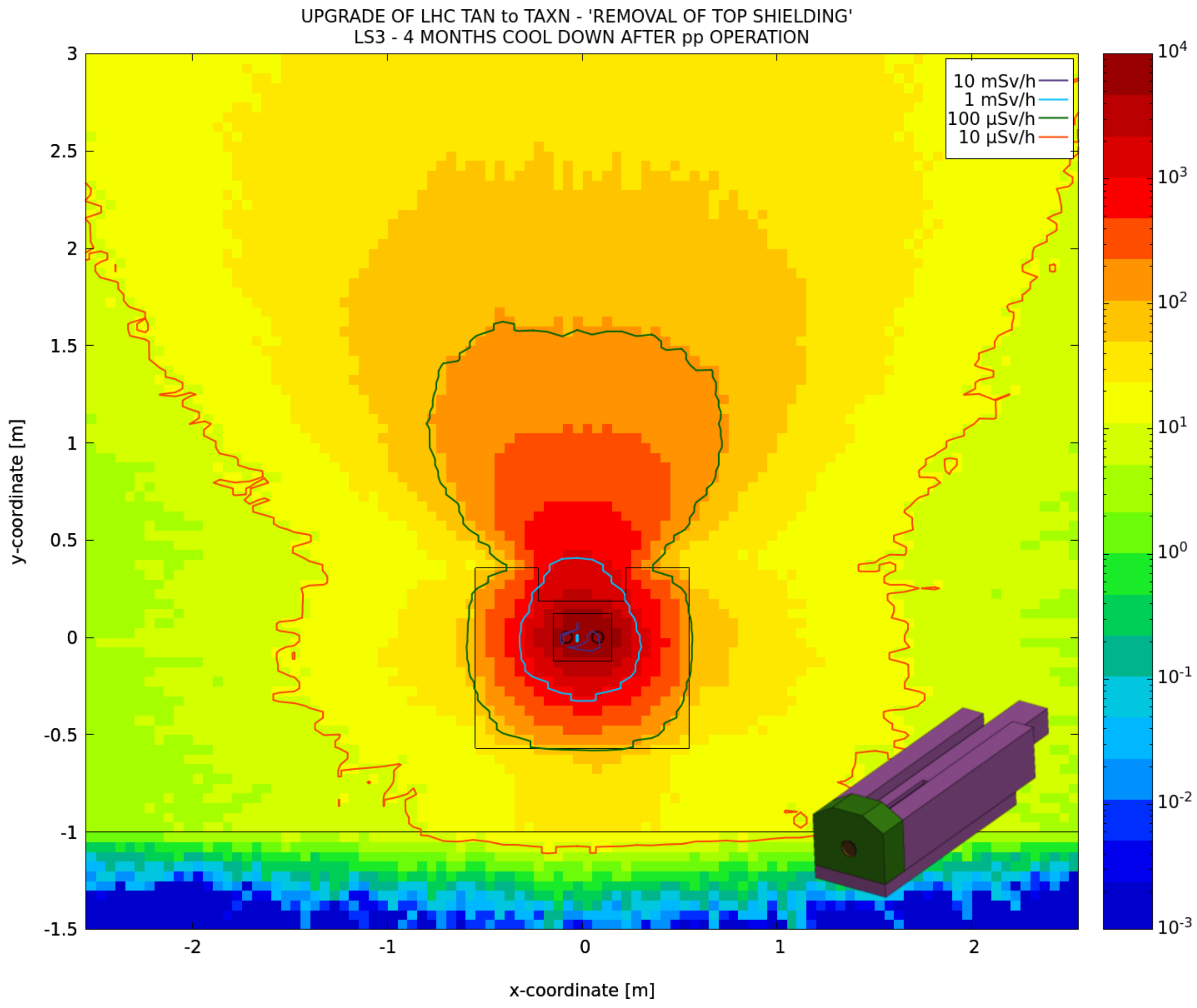
A. Infantino et al., Radiation Protection at the Large Hadron Collider: Problematics, Challenges and Advanced Monte Carlo Simulation Techniques. Environments 2022, 9(5), 54.
L. Elie et al., Radiation protection challenges for the Large Hadron Collider upgrade. Radiation Protection Dosimetry, 2023, 199(8–9), 900–910

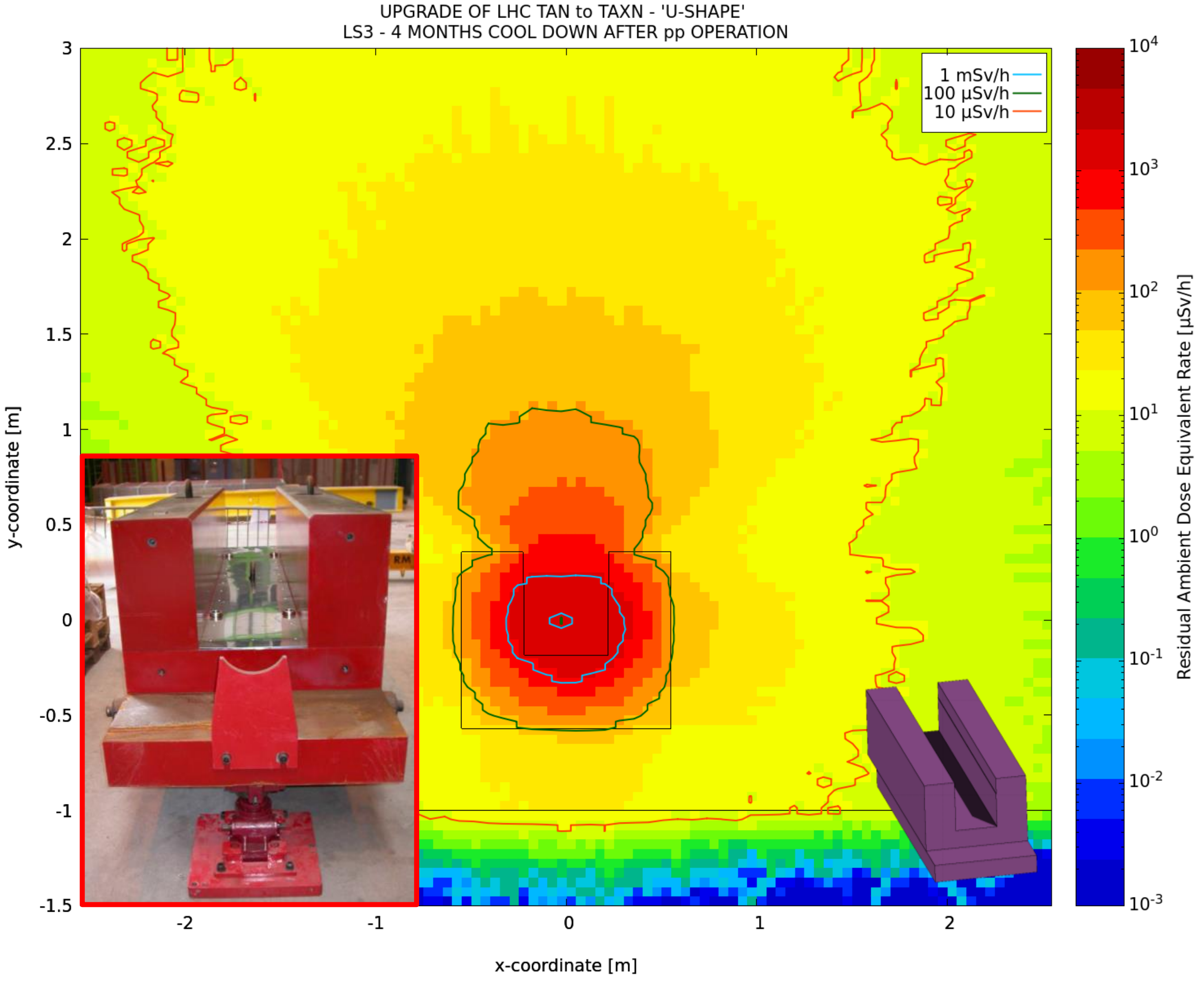




- TAN: 4 units in the LHC layout (2x ATLAS/CMS, ~140m from IP) to **absorb neutral particles from collision** debris and to protect downstream superconducting magnets from quenching → highly activated equipment!
- LS3: upgrade existing units to withstand with HL-LHC beam conditions
- **FLUKA-SESAME** simulations allow to estimate the residual radiation environment at different stages of the upgrade activities and in different configuration/geometries.
- Estimates used for area classification and **worksite requirements (e.g. shielding)**; Work-Dose Plan, i.e. optimization of the intervention and minimization of the radiological risk; pre-characterization of **radioactive waste**.

LHC upgrade



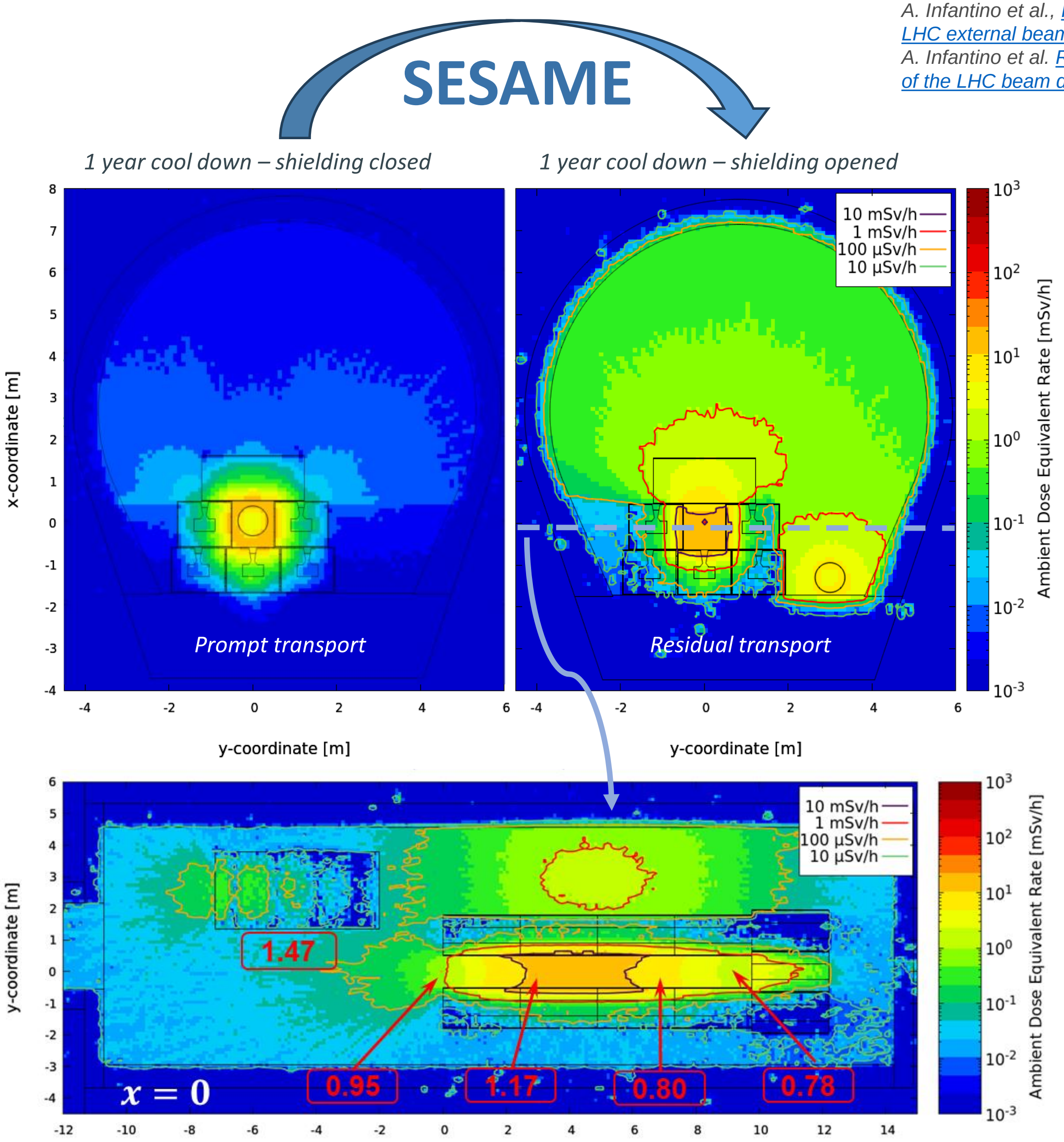


A. Infantino et al., Radiation Protection at the Large Hadron Collider: Problematics, Challenges and Advanced Monte Carlo Simulation Techniques. Environments 2022, 9(5), 54.
L. Elie et al., Radiation protection challenges for the Large Hadron Collider upgrade. Radiation Protection Dosimetry, 2023, 199(8–9), 900–910

LHC beam dump

A. Infantino et al., [Radiological characterization for the disposal of a decommissioned LHC external beam dump at CERN, EPJP 2023]
A. Infantino et al. [Radiation protection challenges in the upgrade, autopsy and disposal of the LHC beam dump]. Radiation Protection Dosimetry, 2023, 199(8–9), 891–899

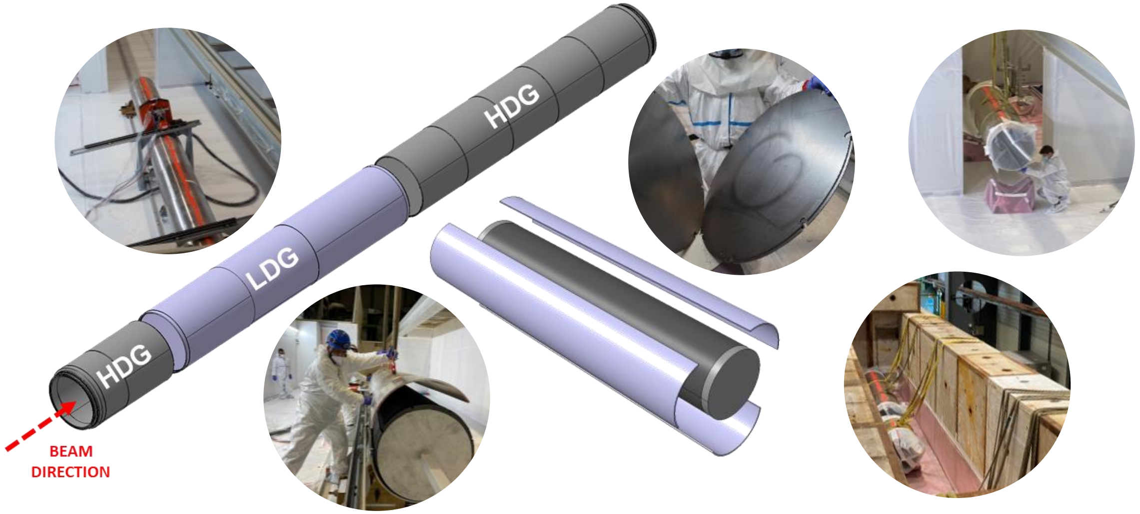
February 2020
opening of the TDE shielding and RP surveys.



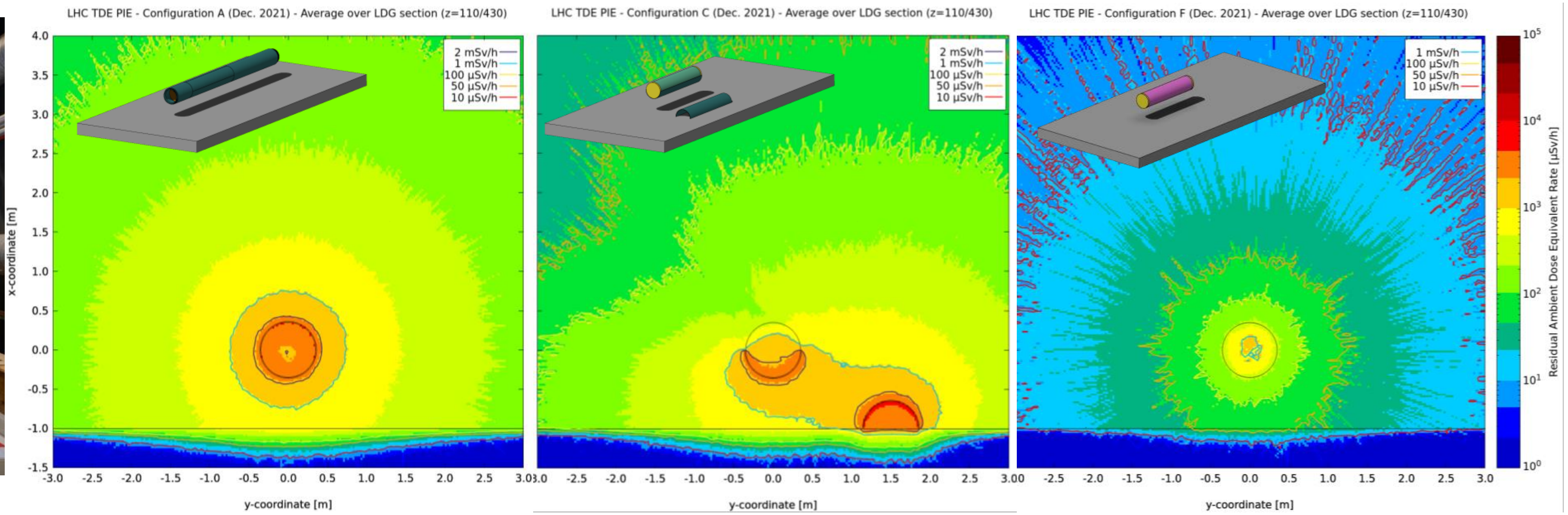
- LHC beam dump (TDE): 0.7x8.5m 318 stainless steel vessel filled with blocks of graphite.
- It safely absorb the 7 TeV proton beam both in normal and abnormal operation.
- TDE surrounded by ~900 tons of iron shielding
- Opening of the TDE shielding: **complex problem** (geometry + residual transport) which cannot be handled directly in FLUKA.
- **FLUKA-SESAME** coupling allows to simulate the opening of the shielding blocks and the manipulation of the TDE for transport.
- Overall **good agreement** between simulations and measurements.

LHC beam dump

A. Infantino et al., Radiological characterization for the disposal of a decommissioned LHC external beam dump at CERN, EPJP 2023
A. Infantino et al. Radiation protection challenges in the upgrade, autopsy and disposal of the LHC beam dump. Radiation Protection Dosimetry, 2023, 199(8–9), 891–899

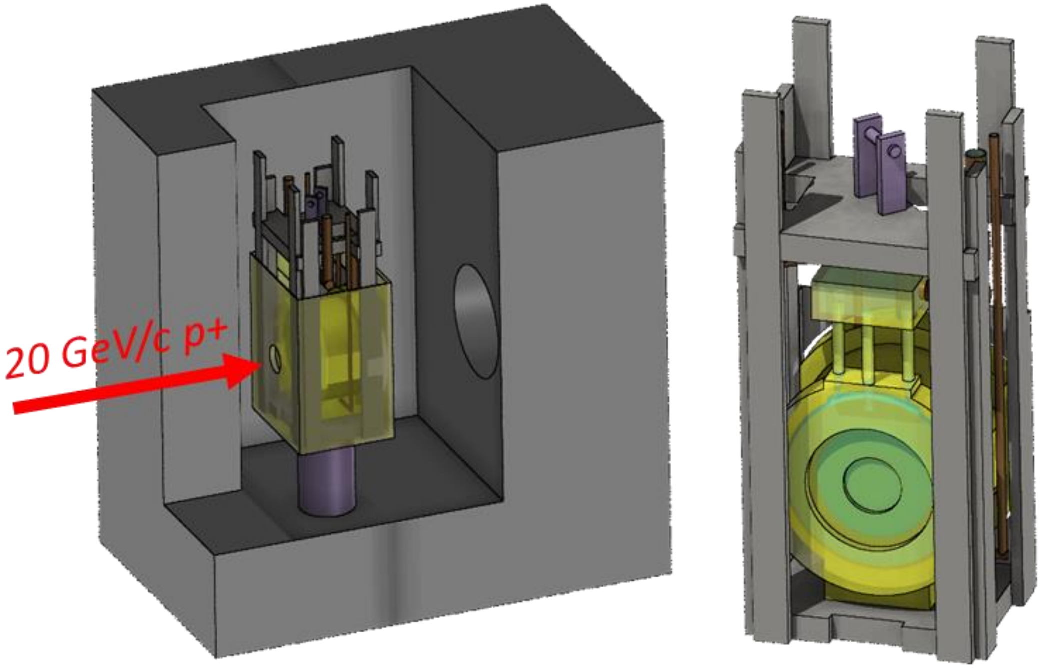


- ✓ **TDE "Autopsy"**: complex cutting sequence with several steps to be optimized due to high residual dose rates even after 3 years cool down.
- ✓ **Waste pre-conditioning** at the same time of the autopsy to optimize (ALARA) the intervention → Final disposal in France (ANDRA's CSA).
- ✓ **Work-Dose Plan** based on cross-validated FLUKA simulations & RP surveys (+ safety margin).
- ✓ Initial estimate ALARA II: **4800 person.µSv collective dose & 558 µSv max individual dose**.
- ✓ After intervention: **2900 person.µSv & 316 µSv**.

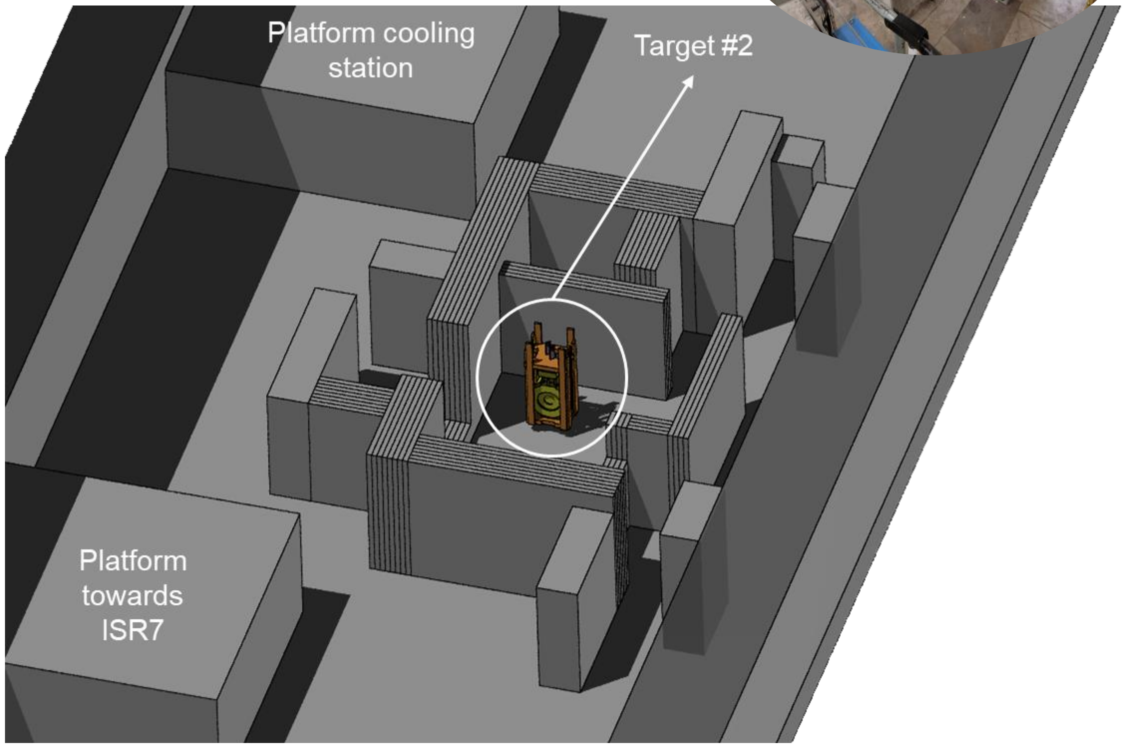


nTOF target #2

- **Goal**: evaluate **residual dose rate** in the **bunker** and surrounding areas of **ISR8** to properly **design the bunker shielding**
  - **ISR8** classified as **Supervised Radiation Area**
  - **SESAME used for residual simulation**

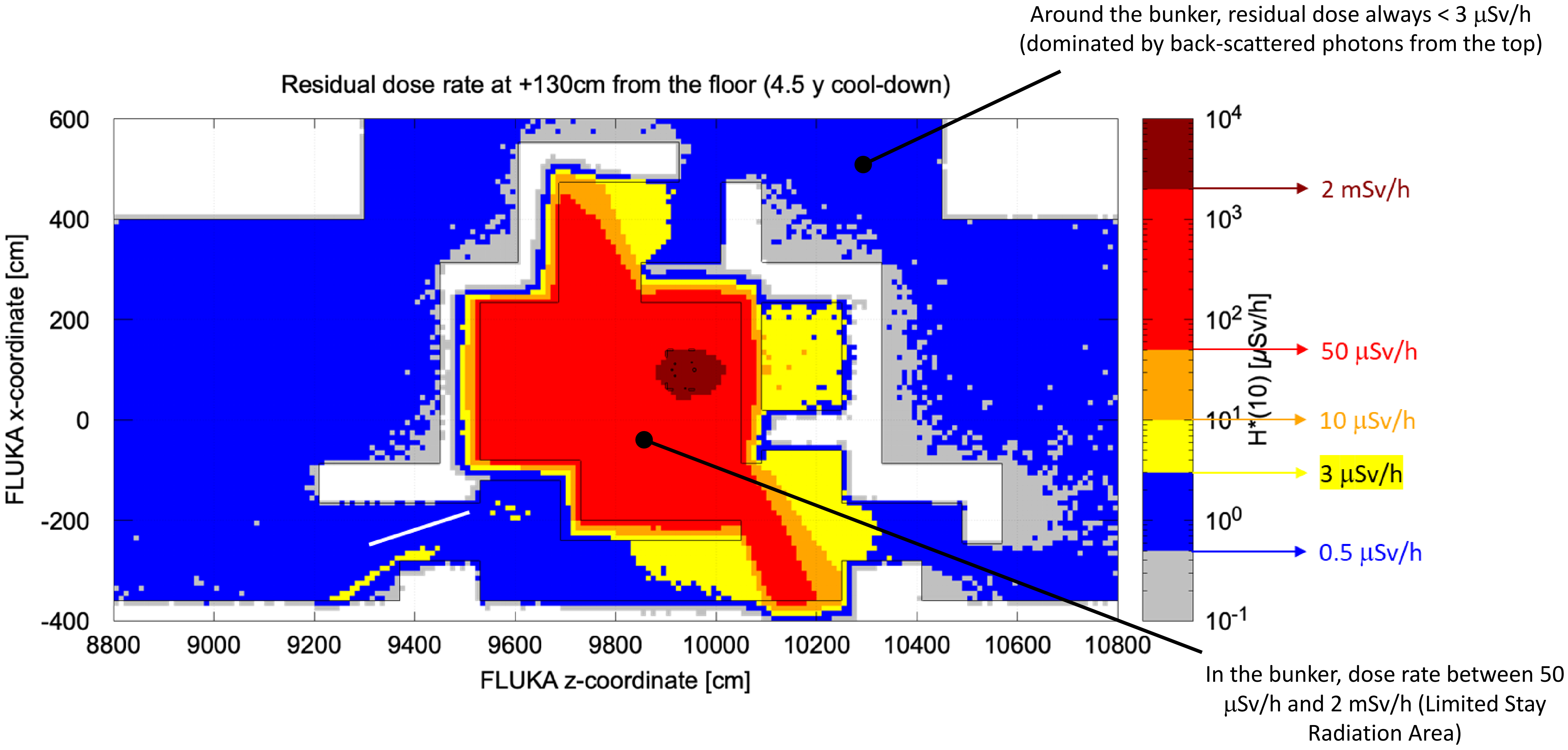


__Target #2__ sitting in a simplifed model of the __target cavern (prompt simulation)__



__Target #2__ installed in the bunker of __ISR8__ (__residual simulation__)

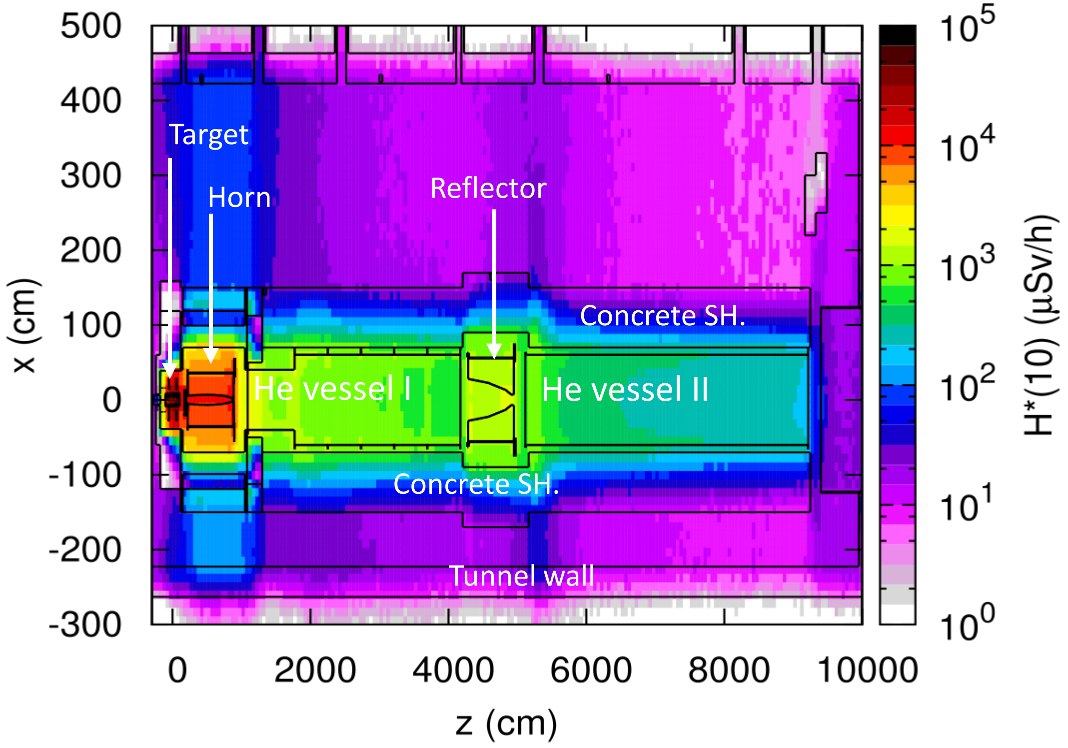
nTOF target #2



CNGS dismantling

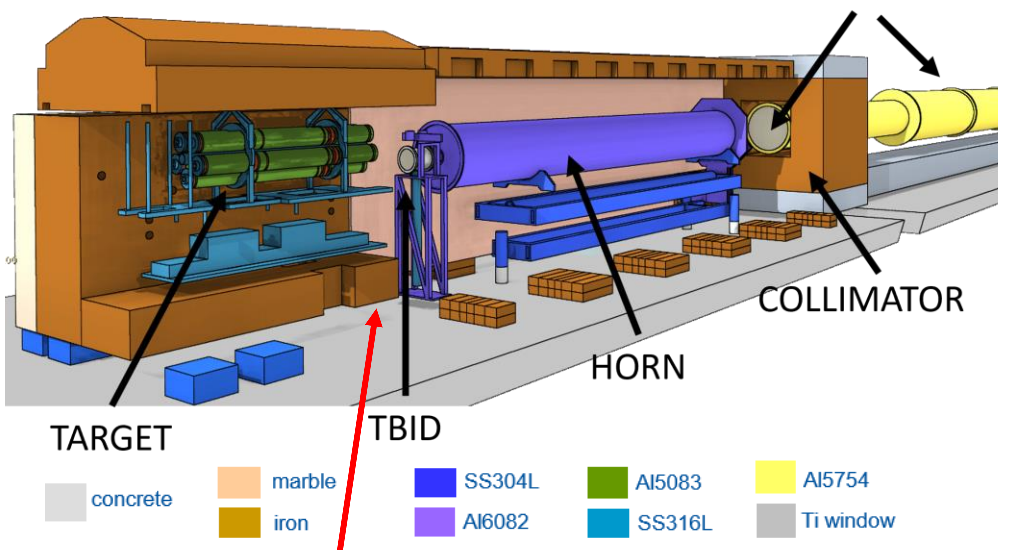
Motivations for the dismantling:

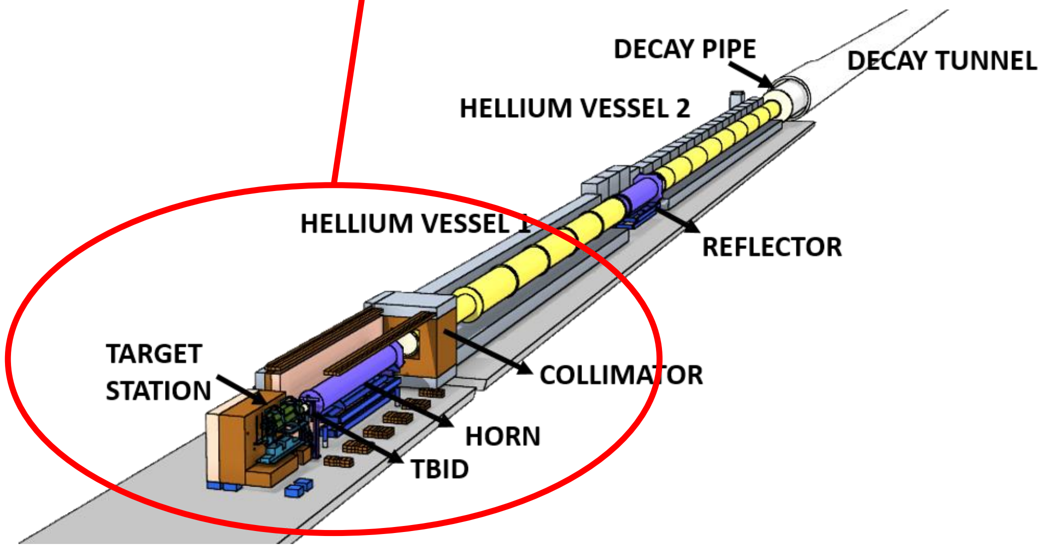
- Dose rates have sufficiently decreased (9.5 y cooling by now)
- Expert knowledge decrease with time
- Equipment's integrity deteriorates
- Re-use of the target cavern, extraction line and beam dump ready



Residual H*(10) ambient dose equivalent rate of the overall area, depicted in a horizontal cut vertically averaged over 40 cm around the beam axis

Detailed model of 100 m long beam line





C. Ahdida et al., Radiological Characterization Studies for the CNGS Dismantling, Nucl. Sci. Eng. 198 (2024) 175-184

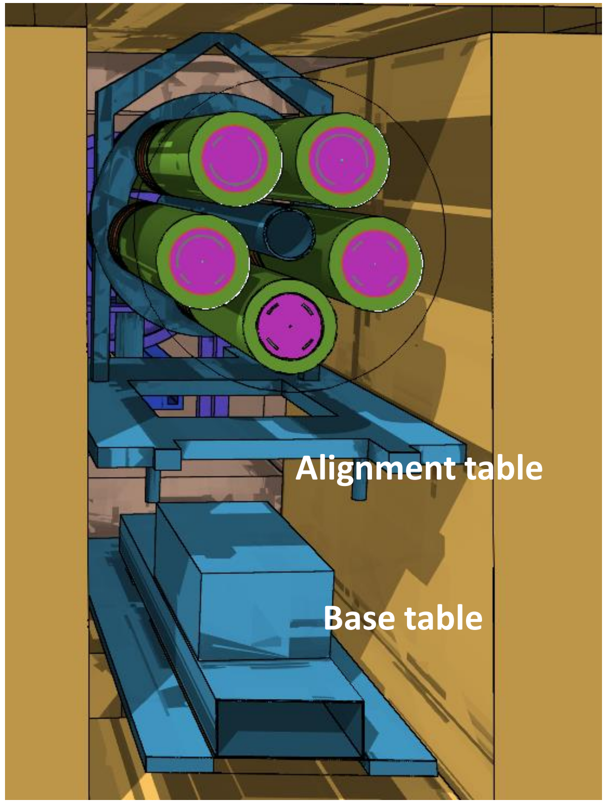
CNGS dismantling

C. Ahdida et al., Radiological Characterization Studies for the CNGS Dismantling, Nucl. Sci. Eng. 198 (2024) 175-184

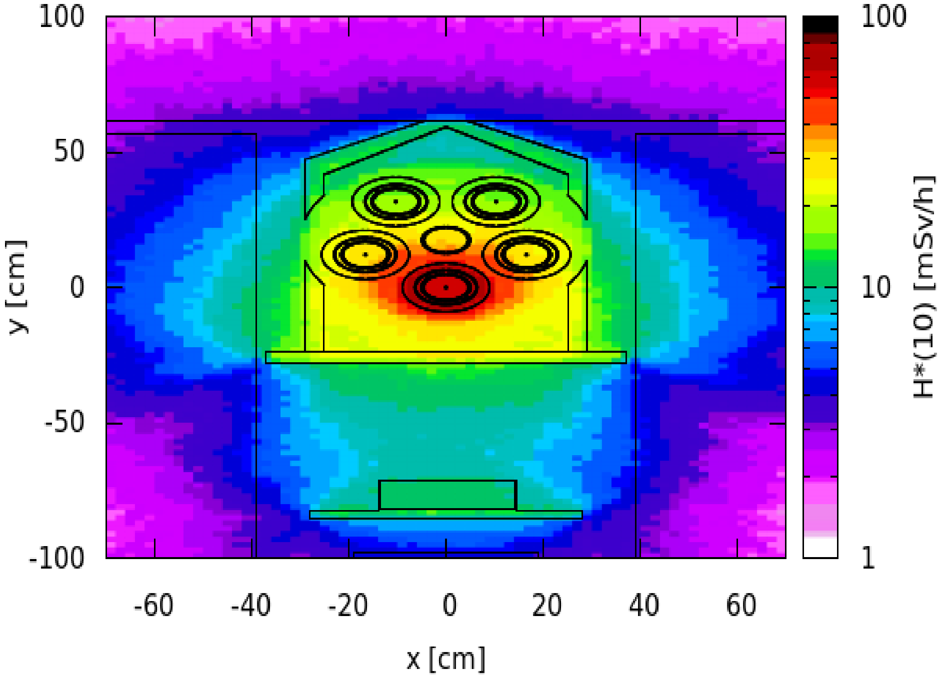
Co-60 (5.27y)
Tables/supports

Na-22 (2.6y)
Al target tube

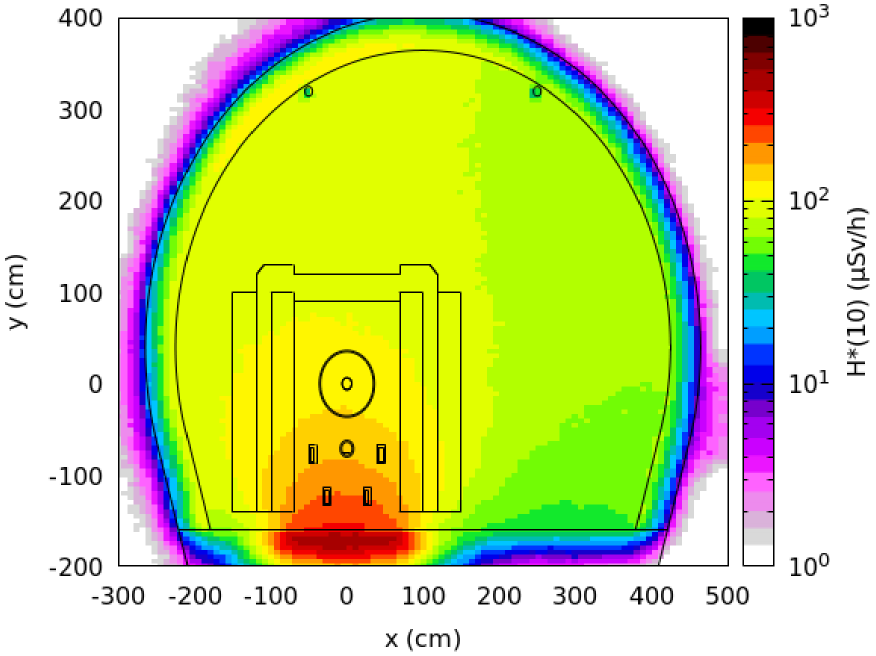
ASSIGNMAT card (Mat-Decay) used such that activation of materials and equipment different than walls and floor concrete is ignored.



FLUKA model of the target station: supporting tables, rotation mechanism and target tubes (Al tube, He gas, carbon support and graphite rods)



Residual dose equivalent rate of the target station standalone depicted in a transversal cut in the most activated location averaged over 10 cm in z



H*(10) ambient dose equivalent rate in the empty tunnel depicted in a transversal cut averaged over 10m in the target and horn area

- MC FLUKA based estimates of the residual dose equivalent rates of the empty cavern important for re-use of the area
- Contribution to ambient dose rate of different isotopes change depending on the location (different spectra of particles): Eu-152 (13.53y), Co-60 (5.27y), Na-22 (2.6y), Eu-154 (8.6y)

Summary

Summary of the lecture

- We have recalled the difference between prompt and residual dose, as well as the motivation behind residual studies.
- We have seen the main cards which need to be used in residual studies, such as **RADDECAY**, **IRRPROFI**, **DCYTIME**, and **DCYSCORE**.
- We have also revised the most important **PHYSICS** and transport settings for residual simulations.
- We have seen the possible alternatives to handle residual simulations which involve geometry modifications between prompt and decay step such as **ASSIGNMAT** and the codes **SESAME** and **DORIAN**.
- We have discussed relevant real-life examples.

FLUKA