Radiation Protection calculations

Advanced course – ANL, June 2023

Outline

Exposure of persons and **activation of components and materials** are the core considerations for Radiation Protection (RP) related simulations

Topics treated in this lecture:

- **External exposure** to ionizing radiation of persons
- **Activation**
  - Potential internal exposure to ionizing radiation of persons
  - Radiological characterization
    - Clearance
    - Transport
    - Emission/Immission limits
  - Activation of liquids or gases in circuits

External Exposure

External Exposure

- **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**;

  present even when the beam has stopped

- Persons can be exposed to **prompt radiation** and/or **residual radiation**;

  both need to be estimated!

External Exposure

Exposure of persons

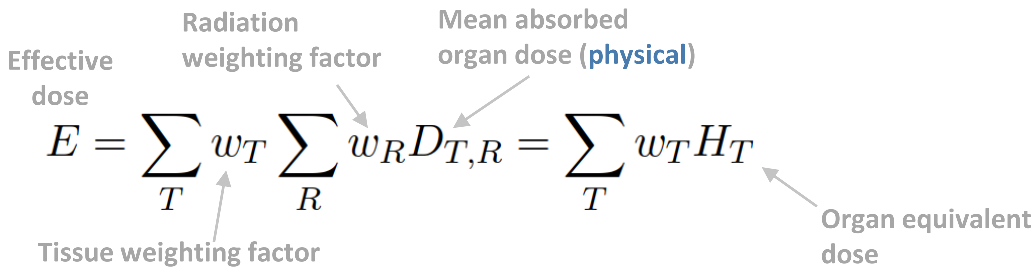
- The **prompt radiation** is related to the **cascade generated by the primary beam**
  - E.g. radiation penetrating a shielding structure when the beam is operating
  - Scored in pSv/primary
  - Normalization with beam intensity (e.g. primaries/h) is needed to get dose rates, e.g. (mSv/h)

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

External Exposure

Exposure of persons due to radiation fields

- RP quantities (ambient dose equivalent or effective dose [pSv]) are **not physical quantities** directly simulated



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

Effective dose

Radiation weighting factor

Mean absorbed organ dose (**physical**)

Tissue weighting factor

Organ equivalent dose

- FLUKA estimates of these quantities are based on particle fluence:

  fluence-to-dose conversion coefficients are applied
  to translate radiation fields into generalized particles -> [pSv cm^2]

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

Fluence-to-dose conversion coefficients

- Several fluence-to-dose conversion coefficients are available

- **Ambient dose equivalent** H*(10)
  - Operational quantity for area monitoring (10mm depth in ICRU sphere)
  - “**`AMB74`**” 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)
  - The “**`AMB74`**” coefficients are based on ICRP74 recommendations and Pelliccioni data
  - M. Pelliccioni, “*Overview of fluence-to-effective dose and fluence-to-ambient dose equivalent conversion coefficients for high energy radiation calculated using the FLUKA code”,* Radiation Protection Dosimetry 88 (2000) 279-297

Fluence-to-dose conversion coefficients

- **Effective dose**
  - 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**):

      It is the (actual) worst of all irradiation geometries

      It is recommended for shielding design

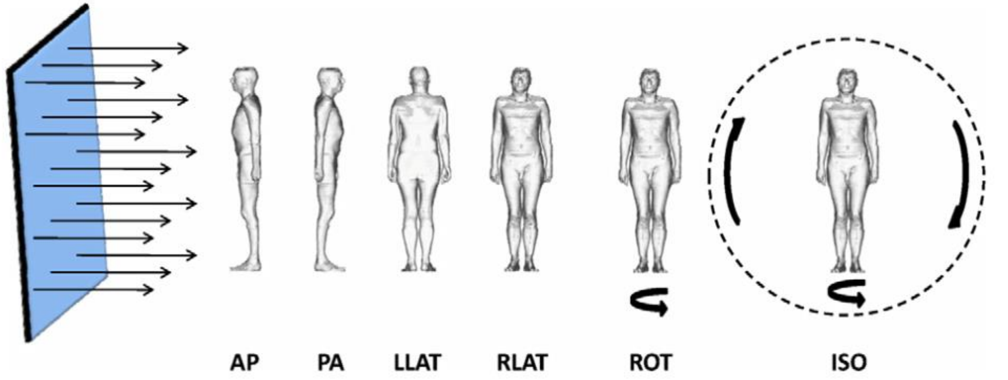
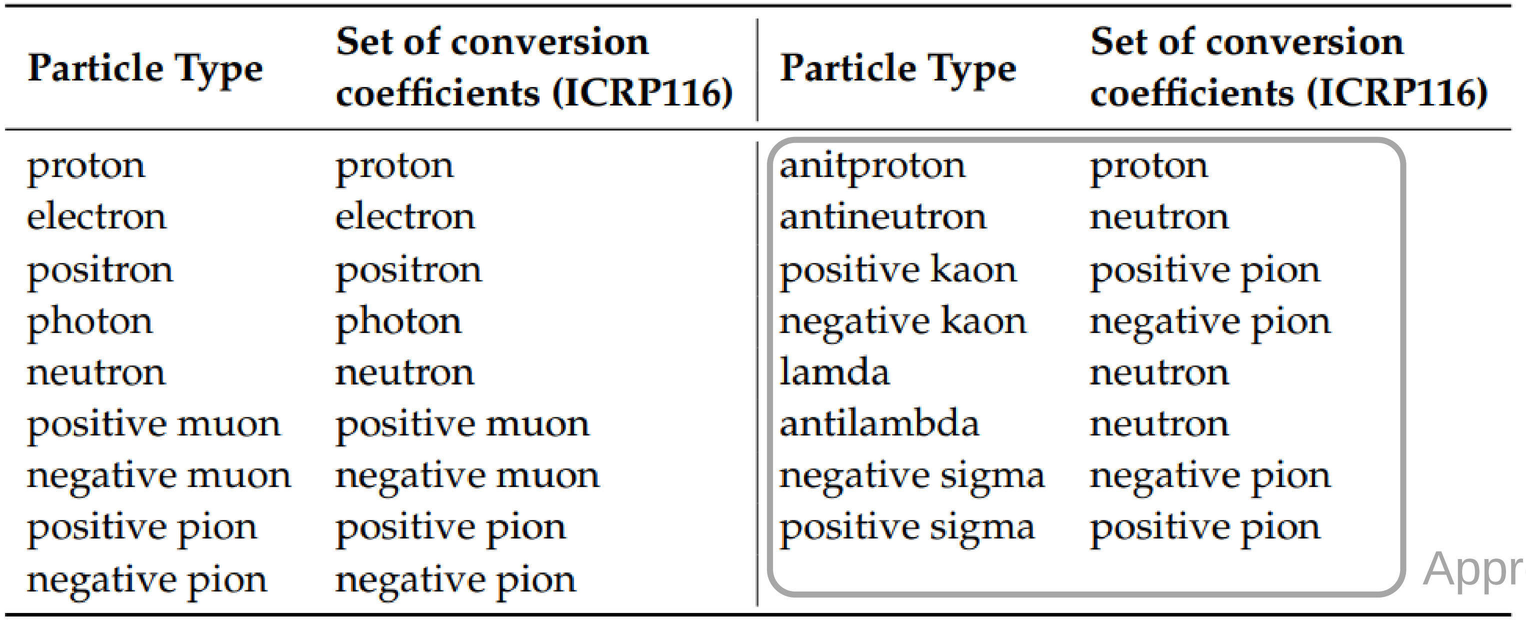


Fig. 3.2. Schematic representation of the idealised geometries considered. AP, antero-posterior; PA, postero-anterior; LLAT, left lateral; RLAT, right lateral; ROT, rotational; ISO, isotropic.

ICRP, 2010. Conversion Coefficients for Radiological Protection Quantities for External Radiation Exposures. ICRP Publication 116, Ann. ICRP 40(2–5). https://journals.sagepub.com/doi/pdf/10.1177/ANIB_40_2-5

Fluence-to-dose conversion coefficients

- Defined for protons, neutrons, charged pions, muons, photons, electrons, alphas; conversion coefficients for other particles are approximated by these



Particle Type	Set of conversion coefficients (ICRP116)	Particle Type	Set of conversion coefficients (ICRP116)
proton	proton	anitproton	proton
electron	electron	antineutron	neutron
positron	positron	positive kaon	positive pion
photon	photon	negative kaon	negative pion
neutron	neutron	lamda	neutron
positive muon	positive muon	antilambda	neutron
negative muon	negative muon	negative sigma	negative pion
positive pion	positive pion	positive sigma	positive pion
negative pion	negative pion		

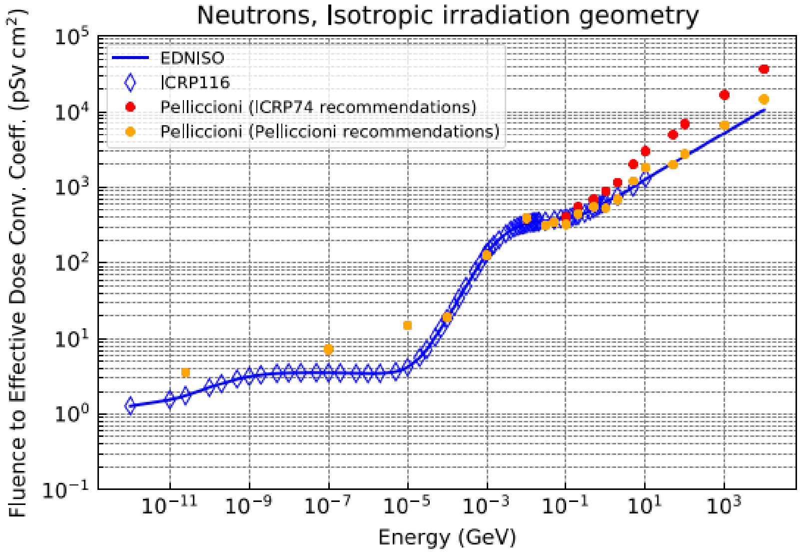
Approximations

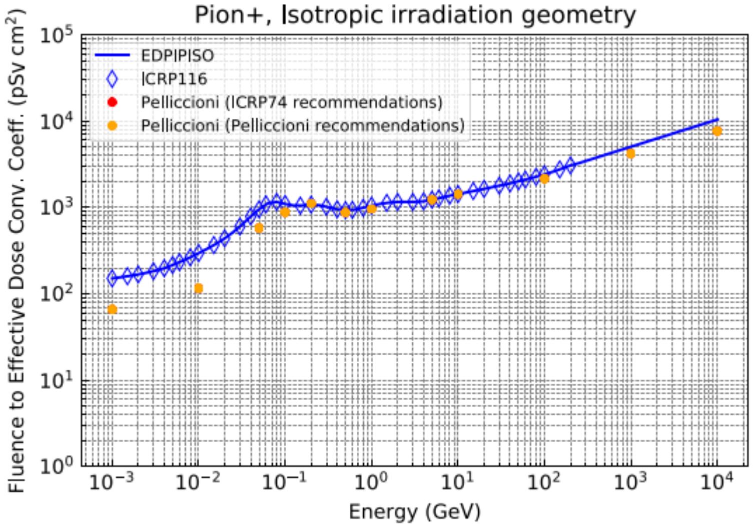
- Zero coefficient is applied to all heavy ions

Fluence-to-dose conversion coefficients – ICRP 116

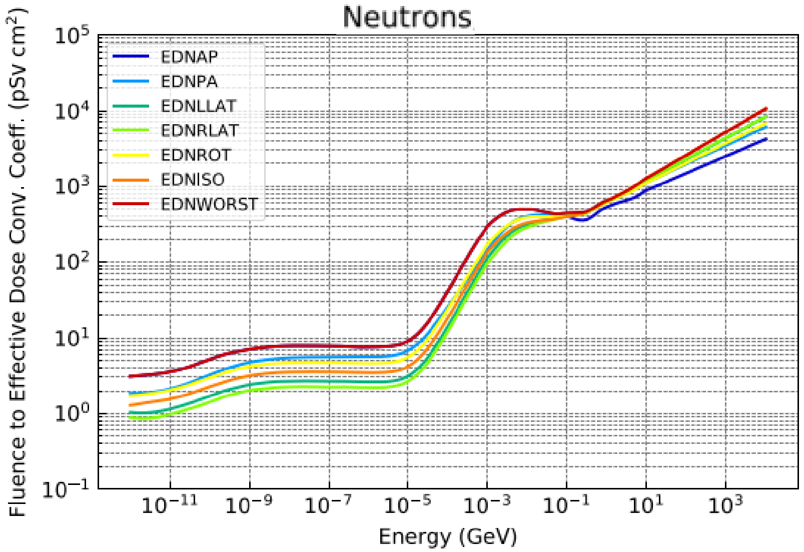
- ICRP Publication 116 fluence-to-effective dose conversion coefficients for external radiation exposure **implemented** in **FLUKA**
    - Data tables for discrete energy values up to 10 GeV.
    - A **linear extrapolation** was implemented **up to 10 TeV.**
    - If the energy is >10 TeV the coefficient corresponding to 10 TeV is assigned.
    - If the energy is below the lowest tabulated value zero weighting is applied (except for neutrons and photons for which the lowest tabulated values is used).
    - The energy points are equally spaced in a logarithmic scale (ten points per each decade).
    - A **cubic spline** was used to **interpolate** between the ICRP tabulated coefficients in a **log-log scale**.
    - Implemented for **AP**, **PA**, **ISO** and **WORST** irradiation geometries (see slide 7)
    - **LLAT**, **RLAT** and **ROT** only for protons, photons and neutrons by default.

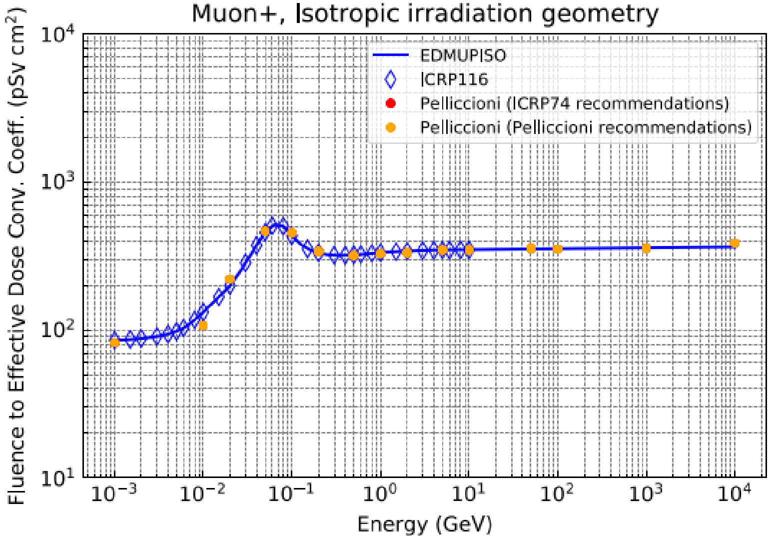
Fluence-to-dose conversion coefficients – ICRP 116





D. Bozzato, R. Froeschl. Implementation of ICRP116 Fluence to Effective Dose Conversion Coefficients in a FLUKA user routine, CERN EDMS 2439884, 2020.





Fluence-to-dose conversion coefficients – ICRU 95

Proposed quantities from **International Commission on Radiation Units and Measurements (ICRU)**;

Not to be confused with the International Commission on Radiological Protection (ICRP)

1. Ambient dose
   - Conversion coefficients from ICRU95
2. Personal dose
   - 12 different conversion coefficients from ICRU95
   - Depending on the irradiation geometry
3. Directional and personal absorbed dose in the lens of the eyes
   - 8 different conversion coefficients from ICRU95
4. Directional and personal absorbed dose in the local skin
   - 6 different conversion coefficients from ICRU95

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 know, **volume normalization** is **automatically applied**
    - pSv / primary particle for prompt radiation
  - USRBIN **Region-based**:
    - Volume of scoring region not know to code
    - **Volume normalization** is **NOT applied**
    - pSv * (region volume) / primary particle for prompt radiation
    - 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

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

AUXSCORE Type: USRBIN ▼ Part: PHOTON ▼ Set: EWT74 ▼

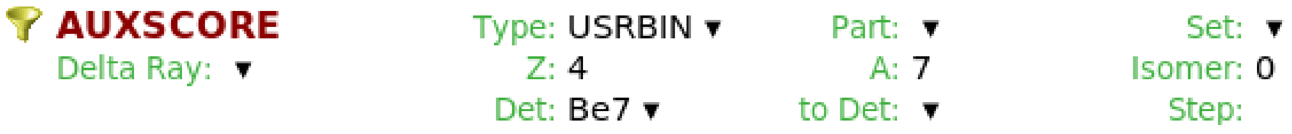
Det: Target ▼ to Det: ▼ Step:

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)

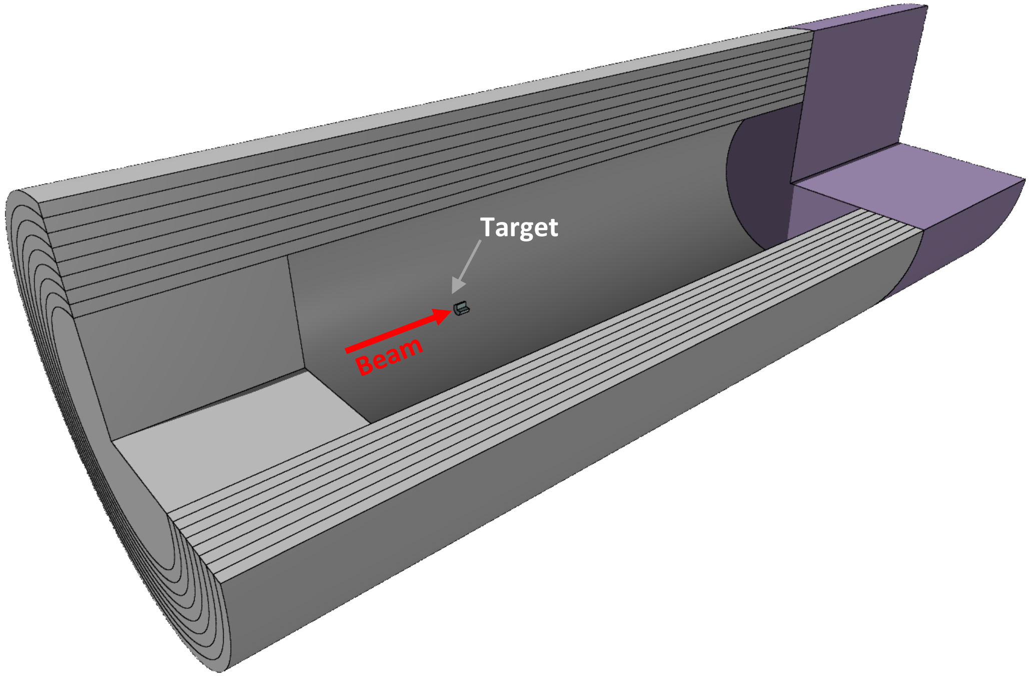


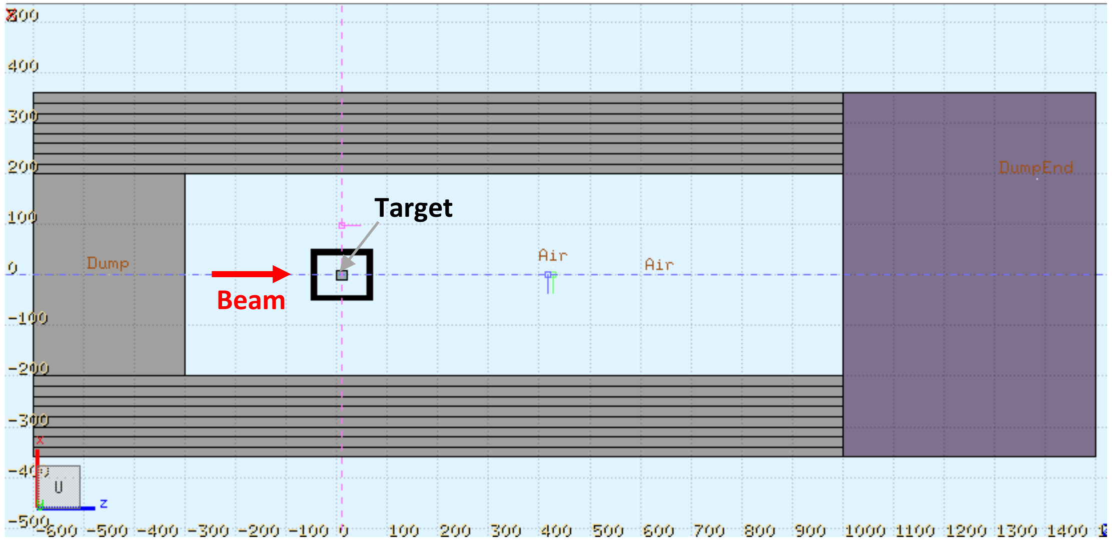
AUXSCORE
Type: USRBIN ▾
Part: ▾
Set: ▾
Delta Ray: ▾
Z: 4
A: 7
Isomer: 0
Det: Be7 ▾
to Det: ▾
Step:

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

External Exposure - Example

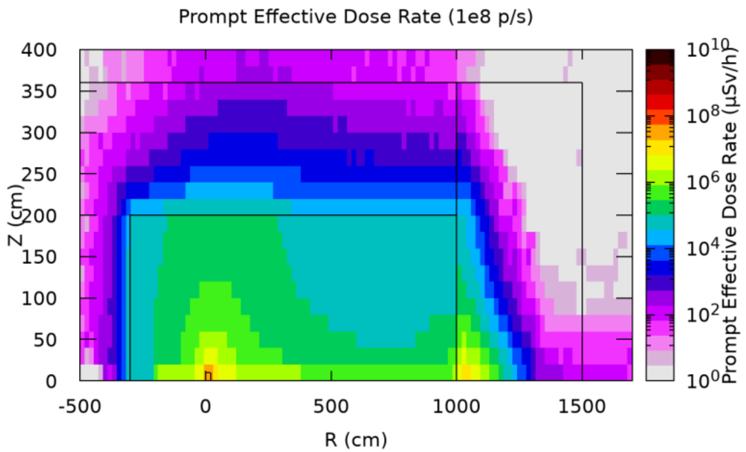
- Proton beam
  - Pencil shape
  - 100 GeV kinetic energy
  - Hitting a Tungsten target
    - Radius 10 cm, Thickness 20 cm
- Target inside shielding structure
  - Concrete
    - Lateral: divided into several layers
    - Upstream of target
  - Cast Iron dump downstream
- Geometry is cylindrical symmetric
  - For fast convergence
- Optional:
  - Stainless steel container around target during residual transport

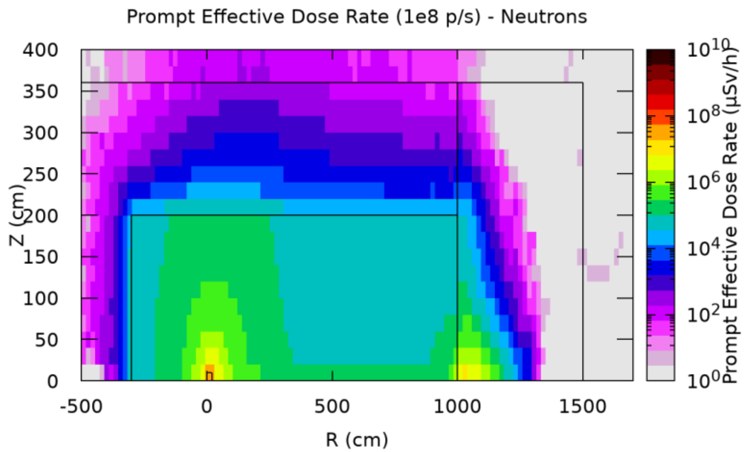




External Exposure - Example

Prompt effective dose rates – Contributions from various particle species



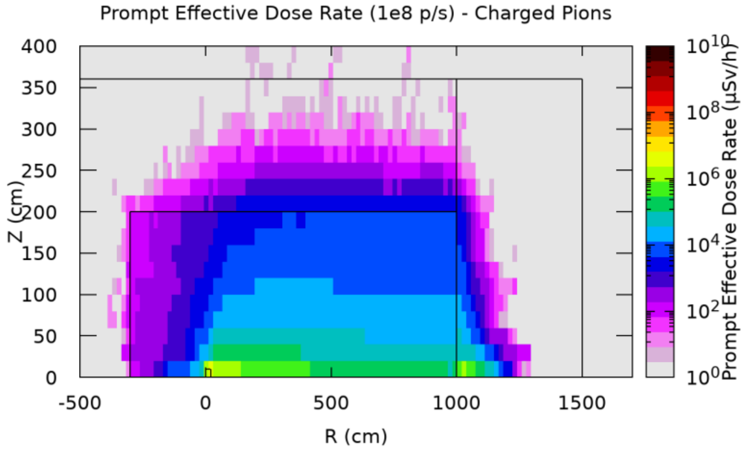


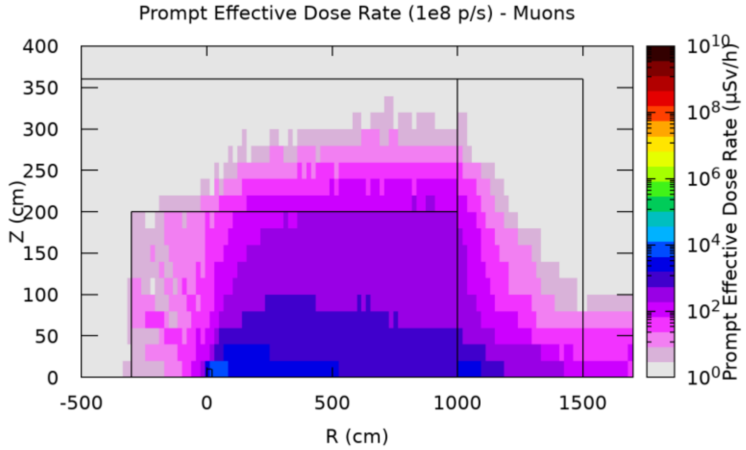
Normalization:
1e-6 * 3600 * 1e8

pSv → µSv

1/primary
→ 1/s

1/s → 1/h



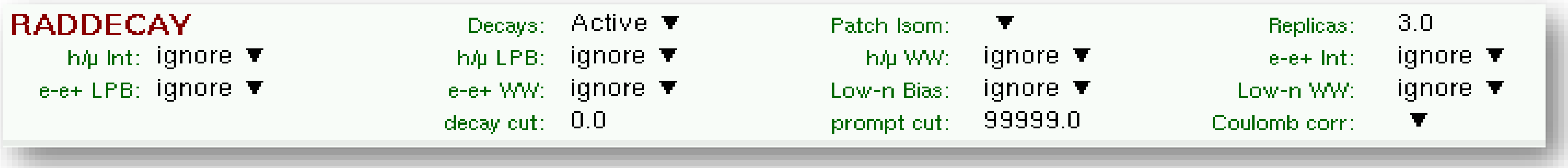


External Exposure - Residual radiation

- **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)

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

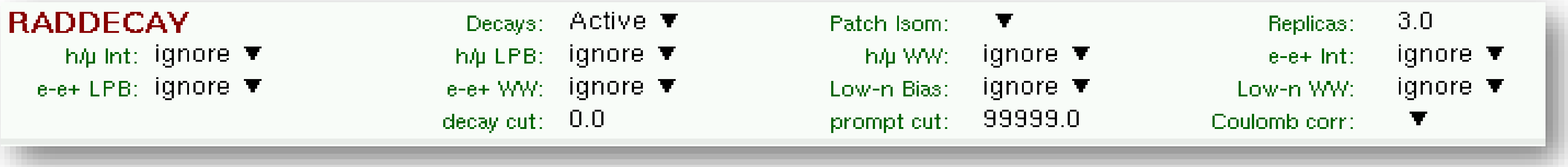


RADDECAY
Decays: Active ▼
Patch Isom: ▼
Replicas: 3.0
h/μ Int: ignore ▼
h/μ LPB: ignore ▼
h/μ WW: ignore ▼
e-e+ Int: ignore ▼
e-e+ LPB: ignore ▼
e-e+ WW: ignore ▼
Low-n Bias: ignore ▼
Low-n WW: ignore ▼
decay cut: 0.0
prompt cut: 99999.0
Coulomb corr: ▼

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**

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 only to prompt radiation or only to particles from radioactive decays – e-e+ WW is an important feature**

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)
-> maximum reduction factor of 10 possible

Examples:

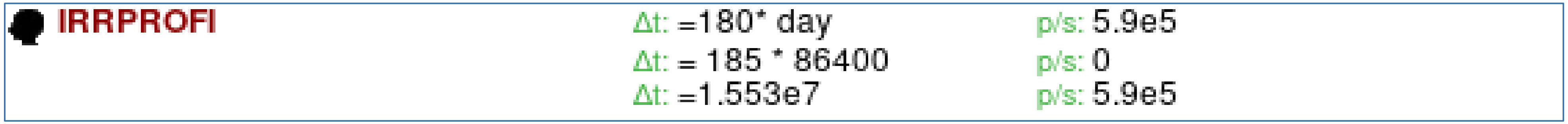
input value for decay cut = 10	decay radiation production and transport thresholds are not modified (0.1 x 10)
input value for prompt cut = 200	prompt radiation threshold increased by factor of 20 (0.1 x 200)

Special cases:

decay cut = 99999	kill EM cascade for residual radiation
prompt cut = 99999	kill EM cascade for prompt radiation (important feature)

Input option: IRRPROFI

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



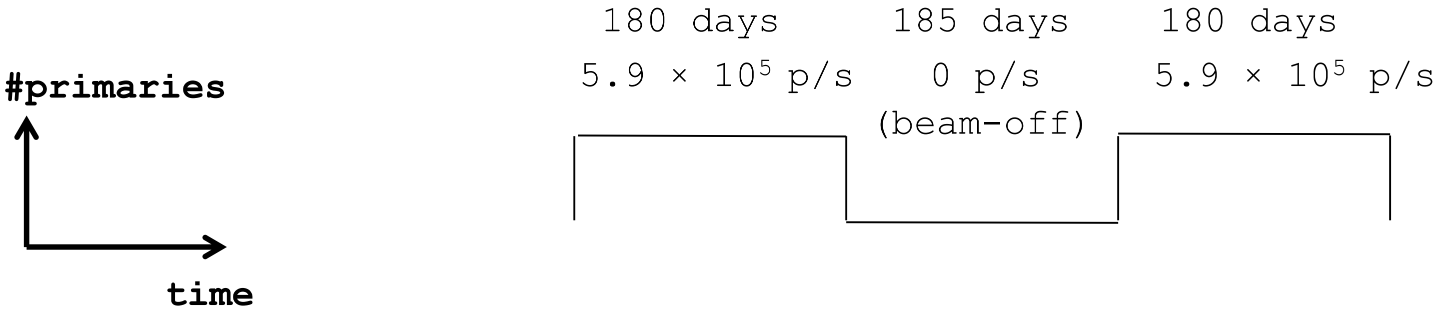
IRRPROFI Δt: =180* day p/s: 5.9e5
Δt: = 185 * 86400 p/s: 0
Δt: =1.553e7 p/s: 5.9e5

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:



180 days
5.9×10^5 p/s

185 days
0 p/s
(beam-off)

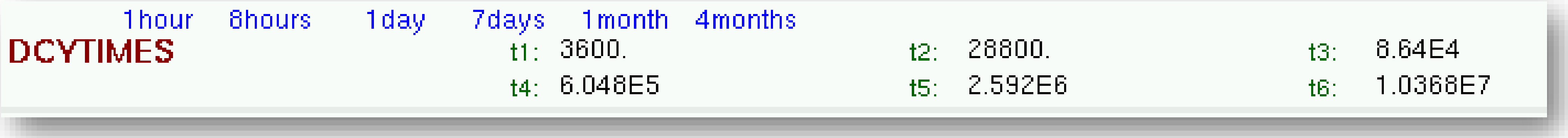
180 days
5.9×10^5 p/s

#primaries

time

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

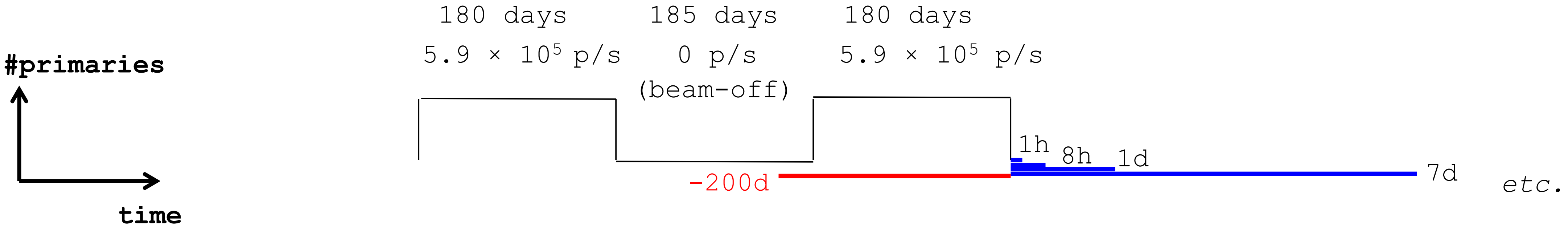
t4: 6.048E5　t5: 2.592E6　t6: 1.0368E7

t1 .. t6 **cooling time (in seconds) after the end of the irradiation**

Note: Several cards can be defined.

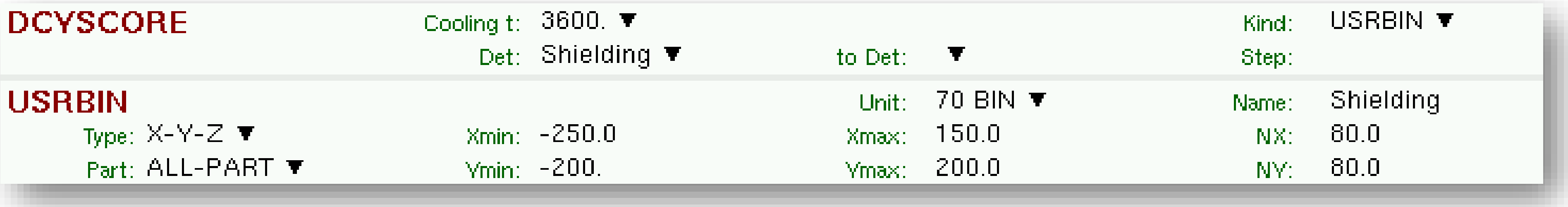
Each cooling time is assigned an index, following the order in which it has been input.
This index can be used in option `DCYSCORE` to assign that cooling time to one or more scoring detectors.
A negative decay time is admitted: scoring is performed at the chosen time "during irradiation"

Example:



Input option: DCYSCORE [1/2]

- associates scoring detectors (radio-nuclides, 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)

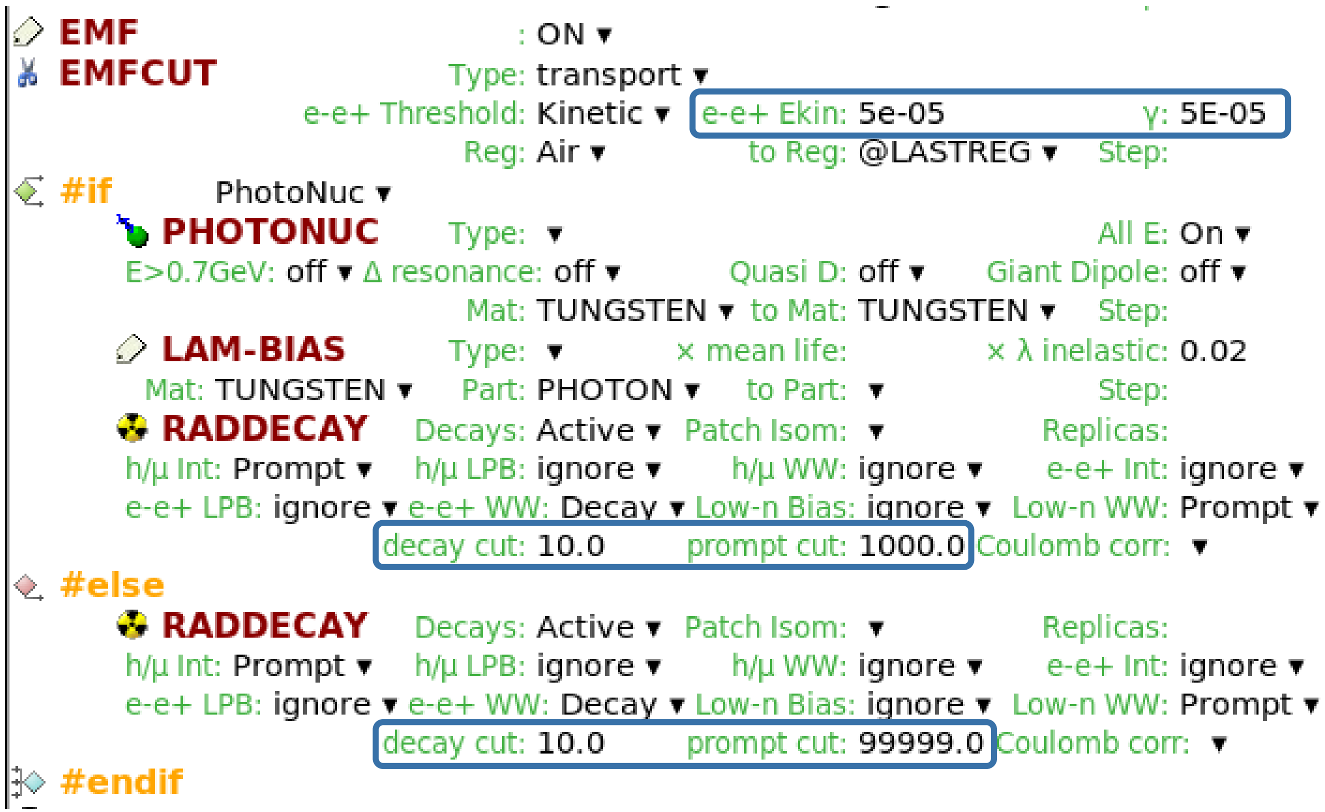
In the semi-analogue decay mode, estimators can include the decay contribution (on top of the prompt one) if associated to **DCYSCORE** with a cooling time index -1.0

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

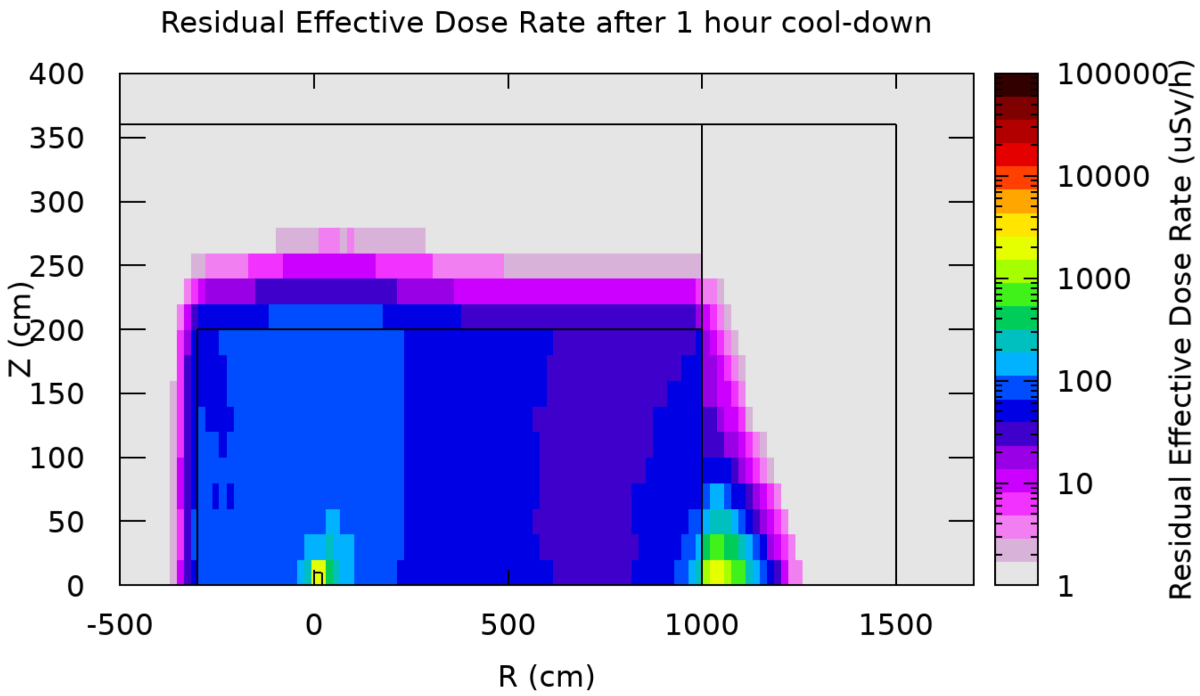
- Two practical examples:
  1. EMF ON; switch from 50 keV (residual) to 5 MeV (prompt) for photons
  2. EMF killed during prompt transport with RADDECAY



```
EMF                                 : ON ▾
EMFCUT                          Type: transport ▾
                   e-e+ Threshold: Kinetic ▾  e-e+ Ekin: 5e-05                γ: 5E-05
                                Reg: Air ▾          to Reg: @LASTREG ▾      Step:
#if          PhotoNuc ▾
     PHOTONUC                   Type:  ▾                                  All E: On ▾
     E>0.7GeV: off ▾ Δ resonance: off ▾      Quasi D: off ▾     Giant Dipole: off ▾
                                 Mat: TUNGSTEN ▾ to Mat: TUNGSTEN ▾         Step:
     LAM-BIAS                   Type:  ▾        × mean life:          × λ inelastic: 0.02
      Mat: TUNGSTEN ▾         Part: PHOTON ▾   to Part:  ▾                  Step:
     RADDECAY              Decays: Active ▾ Patch Isom:  ▾              Replicas:
     h/µ Int: Prompt ▾     h/µ LPB: ignore ▾      h/µ WW: ignore ▾      e-e+ Int: ignore ▾
     e-e+ LPB: ignore ▾ e-e+ WW: Decay ▾ Low-n Bias: ignore ▾ Low-n WW: Prompt ▾
                       decay cut: 10.0        prompt cut: 1000.0 Coulomb corr:  ▾
#else
     RADDECAY              Decays: Active ▾ Patch Isom:  ▾              Replicas:
     h/µ Int: Prompt ▾     h/µ LPB: ignore ▾      h/µ WW: ignore ▾      e-e+ Int: ignore ▾
     e-e+ LPB: ignore ▾ e-e+ WW: Decay ▾ Low-n Bias: ignore ▾ Low-n WW: Prompt ▾
                       decay cut: 10.0        prompt cut: 99999.0 Coulomb corr:  ▾
#endif
```

External Exposure – Residual radiation

- Residual effective dose rate in one-step simulation
- Example:



Geometry modifications

ASSIGNMA

Mat: AIR ▾

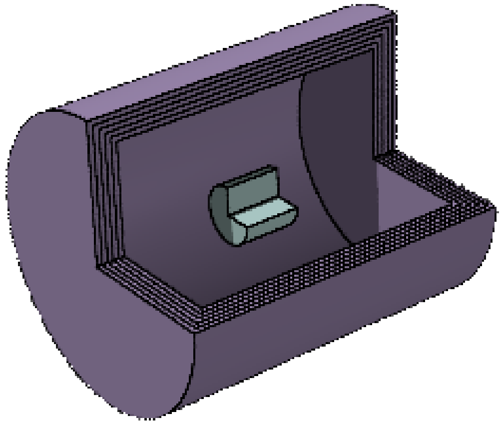
Mat(Decay): LEAD ▾

Reg: ResShield ▾

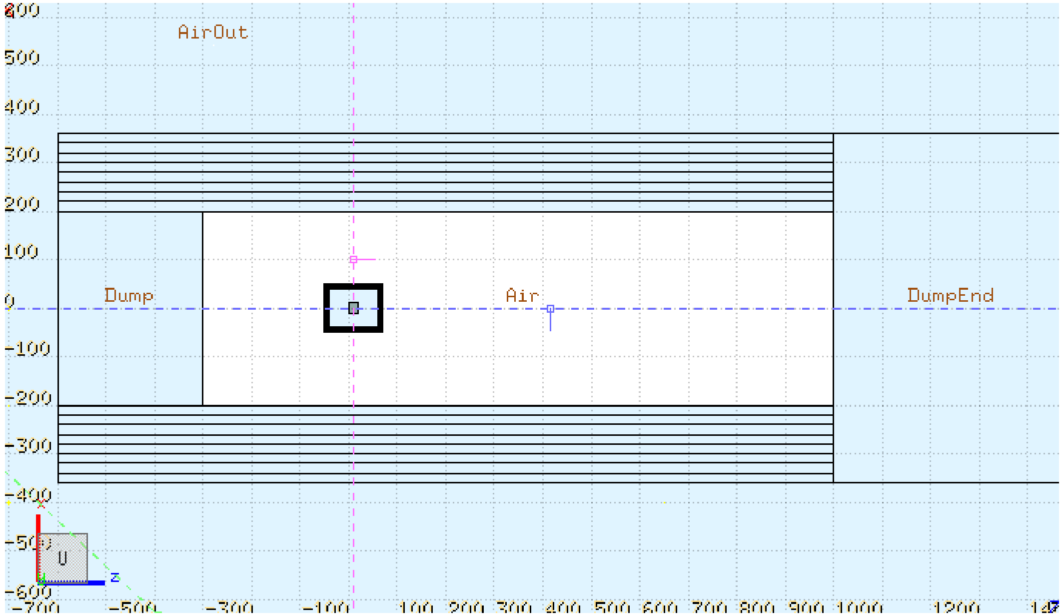
Step:

to Reg: ▾

Field: ▾



Put **lead** during **residual transport**
instead of **Air** during **prompt transport** in Region ResShield
[simulation of transport container]

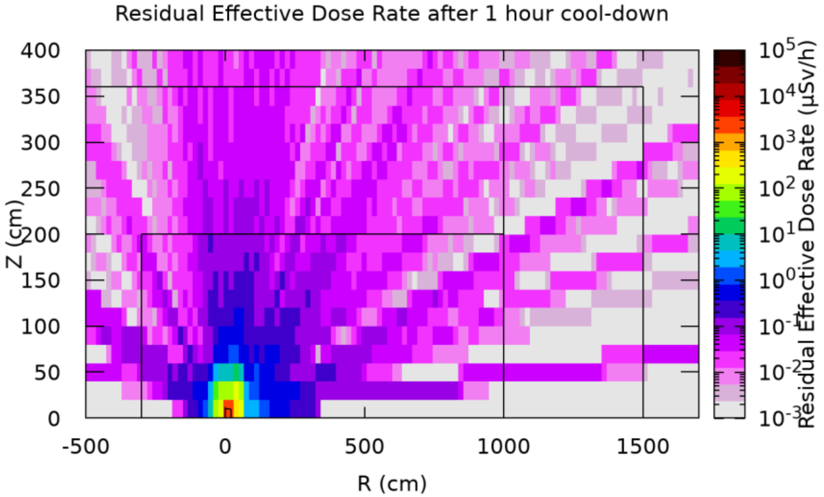


Region where **Mat** is **not equal** to **Mat(Decay)**

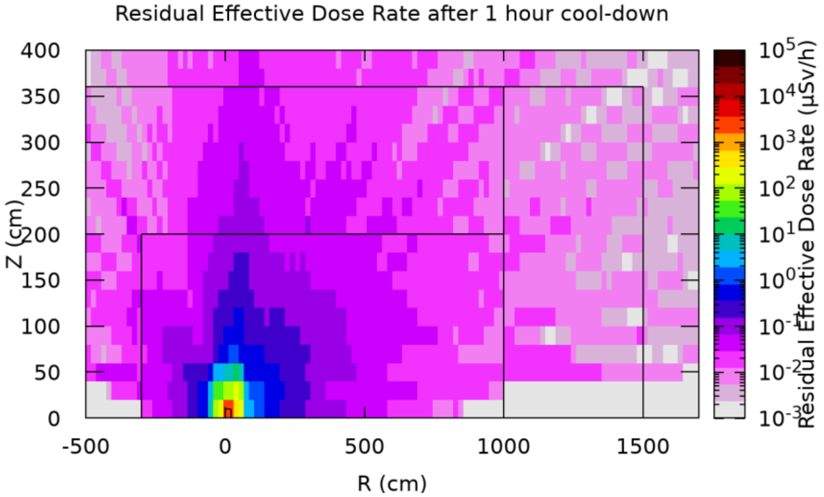
- Radioactive decay radiation originating from that region is ignored.
- Radioactive decays in that region are not scored, e.g. in ACTOMASS.

Geometry modifications – Biasing residual transport

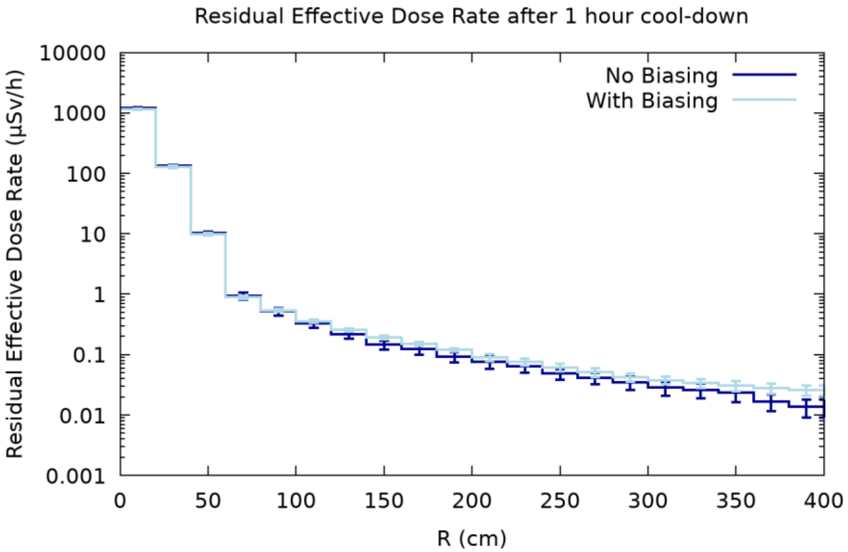
No biasing



Region importance biasing of shielding container layers



1. Shielding container (stainless steel) during residual transport
2. Shielding regions set to AIR



Same number of primaries

Activation

Activation

- **Induced radioactivity** is an integral part of many RP assessments
  - Total and/or specific (mass) activity for all the various radionuclides
- Examples of **use cases**
  - Dose due to inhalation or ingestion (dose conversion coefficients needed)
  - Comparison to regulatory limits
    - Clearance, transport, radioactive waste pathways, …
- **Scoring options** in FLUKA
  - RESNUCLE → **Region based**
    - Gives **access** to **full inventory** information (radionuclide specific incl. isomeric states)
    - Weighting possible with custom **`COMSCW`** routine
    - Access to all production events via **`USRRNC`** routine
  - USRBIN → **Generalized particles**: ACTOMASS and ACTIVITY
    - **Only single value per bin** reported
    - Typically selection and/or weighting needed
      - AUXSCORE or
      - Custom COMSCW with ISCRNG == 5 (Activity binning)

Scoring: `RESNUCLE` [1/3]

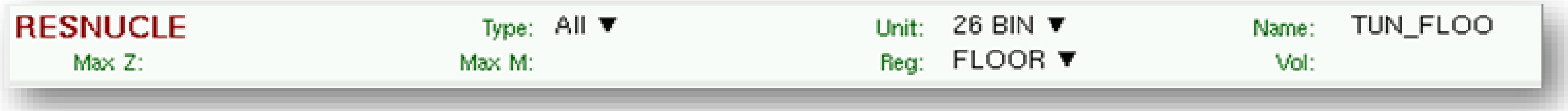
- Scoring of nuclei stopped in a given region.
  - Exception:
    - Stable nuclei that
      - are **created** in a region that **already contains these nuclei** in the material description of the region **and**
      - **do not leave** the region.
    - Note: One has to pay attention when interested in H or He production.
  - Results are expressed in **[#nuclei/g/primary]**
    (if the **mass of the region** is **specified** in the card!)

- All residual nuclei are scored when they have been fully de-excited down to their ground or isomeric state.

- **Radioactive decay** of residual nuclei over time can be simulated:
  - in combination with RADDECAY, DCYSCORE, DCYTIMES and IRRPROFIle)
  - via a user-written code (i.e, USRSUWEV).
  - results are expressed in [Bq] at the given (DCYSCORE) cool-down time

Scoring: RESNUCLE [2/3]

Scoring of residual nuclei or activity on a region basis

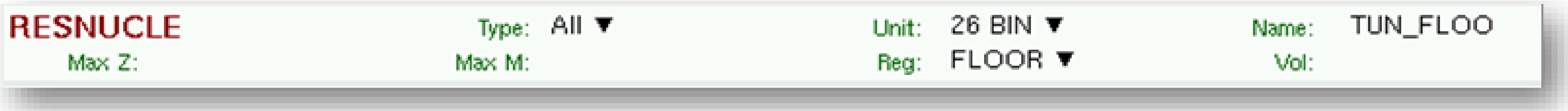


RESNUCLE Type: All ▼ Unit: 26 BIN ▼ Name: TUN_FLOO
Max Z: Max M: Reg: FLOOR ▼ Vol:

Type	**Type of products to be scored**
	1.0 spallation products (all inelastic interactions except for low-energy neutron interactions, i.e. with multigroup treatment)
	2.0 products from low-energy neutron interactions (provided the information is available)
	3.0 all residual nuclei are scored (if available, see above)
	<= 0.0 resets the default (= 1.0)
Unit	**Logical output unit** (Default = 11.0)
Max Z	**Maximum atomic number Z** of the residual nuclei distribution Default: according to the Z of the element(s) of the material assigned to the scoring region
Max M	**Maximum $M = N - Z - NMZ_{min}$** of the residual nuclei distribution (NMZ_{min} = -5) Default: maximum value according to the A, Z of the element(s) of the material assigned to the scoring region.

Scoring: RESNUCLE [3/3]

Scoring of residual nuclei or activity on a region basis



Type: All ▼
Unit: 26 BIN ▼
Name: TUN_FLOO
Reg: FLOOR ▼

Reg	**Scoring region name** Default = 1.0; if set to -1.0 or @ALLREGS scoring will include all regions)
Vol	**Volume of the region** in cm^3 Default = 1.0 cm^3 The scored quantity is normalized by this number. In case **mass specific quantity** is needed, i.e. [Bq/g], the **mass shall be entered**.
Name	**Character string identifying the detector** (max. 10 characters !!!!)

Notes:

1. In the case of heavy ion projectiles, the default **Max M**, based on the region material, is not necessarily sufficient to score all the residual nuclei, which could include possible ion fragments
2. Residual nuclei from low-energy neutron interactions are only scored if that information is available in the low-energy neutron data set (see Manual)
3. Also, protons are scored (at the end of their path)

Input option: PHYSICS

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

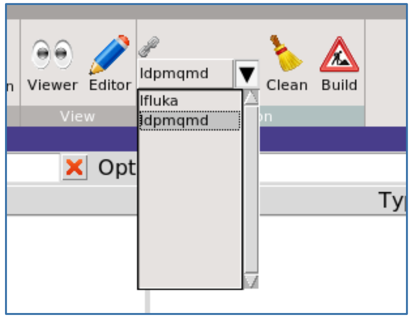
Evaporation of heavy fragments

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

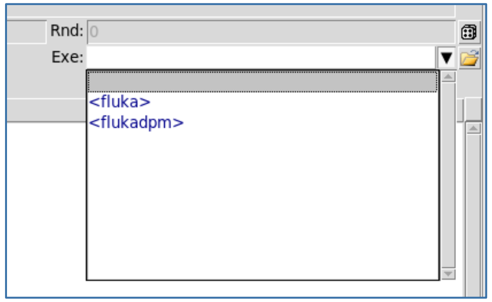
Activation of coalescence treatment

PHYSICS Type: COALESCE ▼ Activate On ▼

Please activate the RQMD and DPMJET packages to enable transport of light fragments produced in COALESCE.



Compile tab

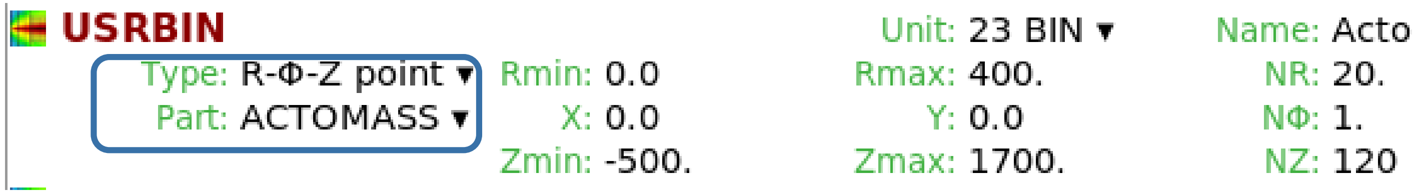


Run tab

Generalized Particle: `ACTOMASS`

- **Specific activity** (per unit mass)

- Typically used within a `USRBIN` estimator associated by means of the `DCYSCORE` option.
  - **Point mesh scoring**!



```
USRBIN                                      Unit: 23 BIN ▾      Name: Acto
        Type: R-Φ-Z point ▾  Rmin: 0.0      Rmax: 400.           NR: 20.
        Part: ACTOMASS ▾        X: 0.0         Y: 0.0            NΦ: 1.
                             Zmin: -500.    Zmax: 1700.          NZ: 120
```

- Results are expressed in:
  - [**Bq/g**] -with a **Cartesian** or **cylindrical binning**
  - [Bq cm3/g] - region or a special binning is requested

- Can be used in **association** with `AUXSCORE`.
  - **Filter** a specific particle or particle family list & **radionuclides**

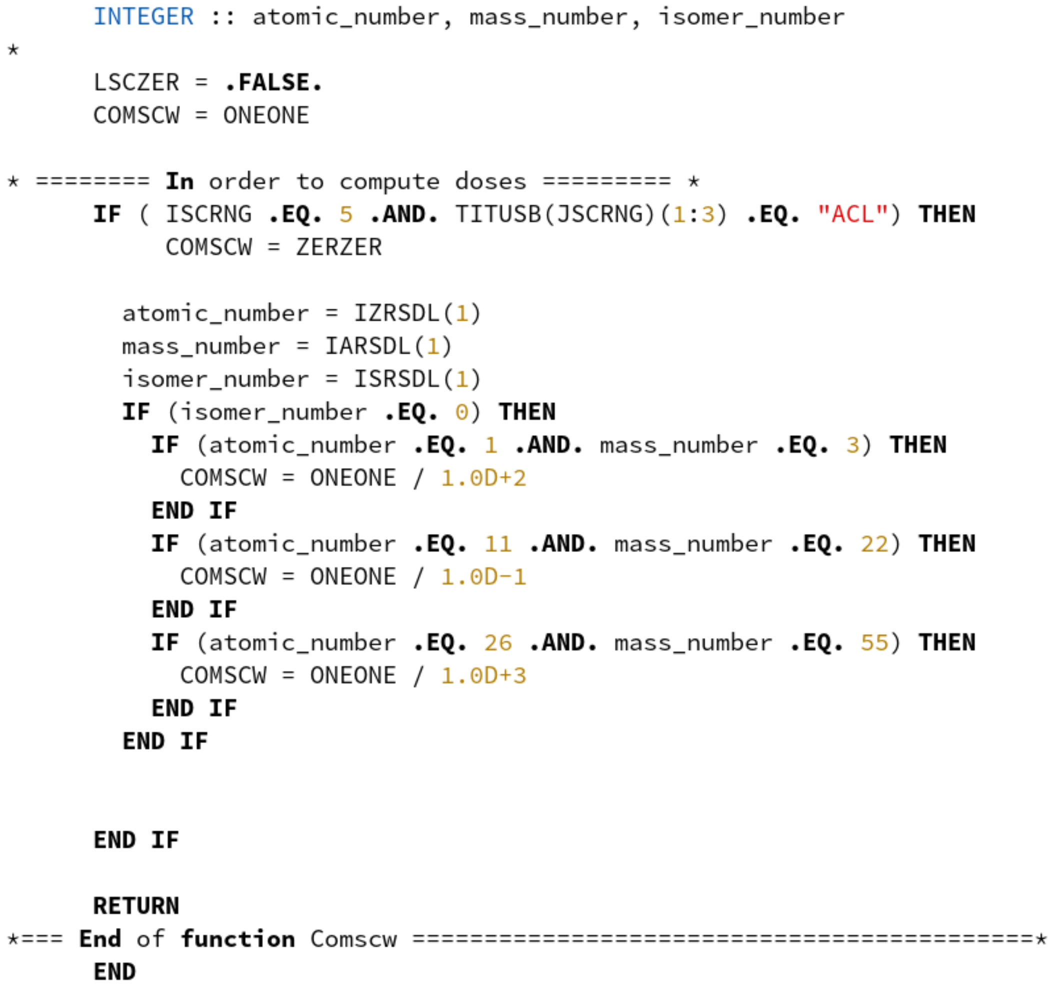
Activation – ACTOMASS applications

1. **Filter contributions** with AUXSCORE (exercise)

2. Simple `COMSCW` user routine with **activity limits**
   - H-3, Na-22, Fe-55 in concrete (without Eu)

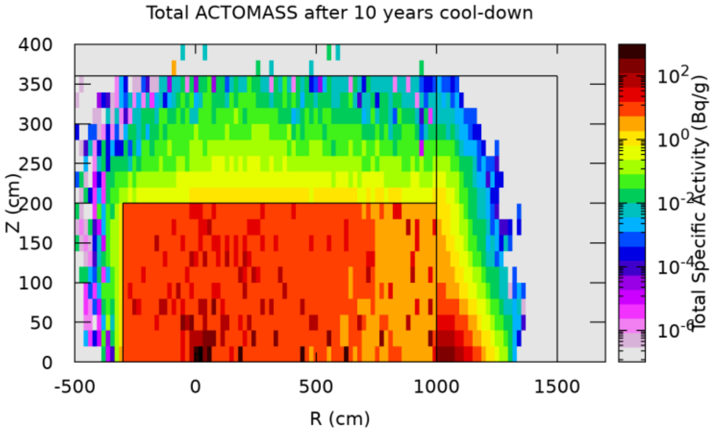
USERWEIG ϕ Weight: FLUSCW+ ▾ Resnuclei: No weight ▾ Density Weight: COMSCW+ ▾

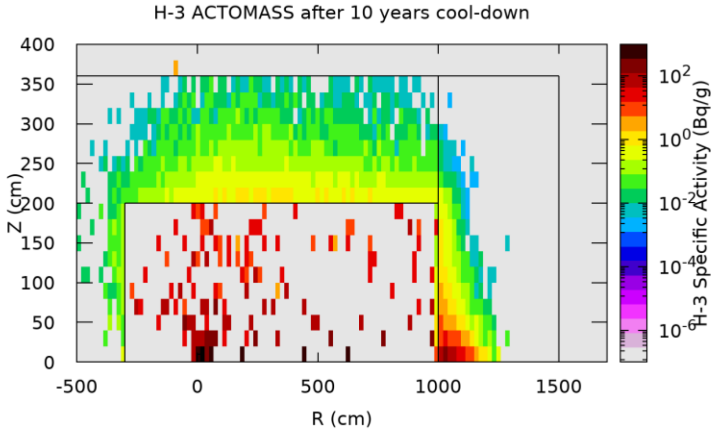
   - **Results** on next slide

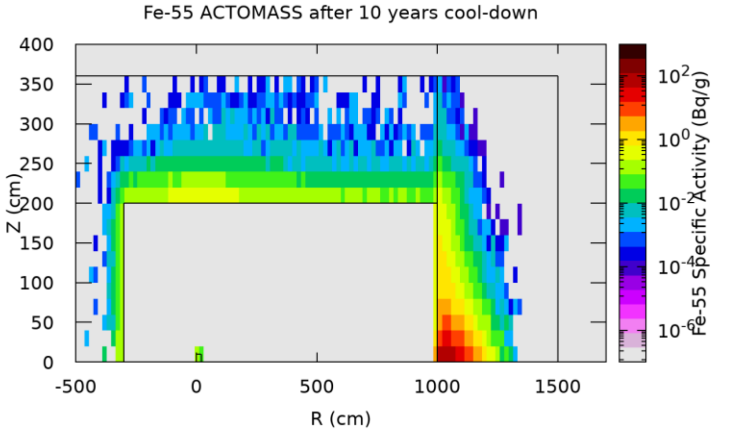


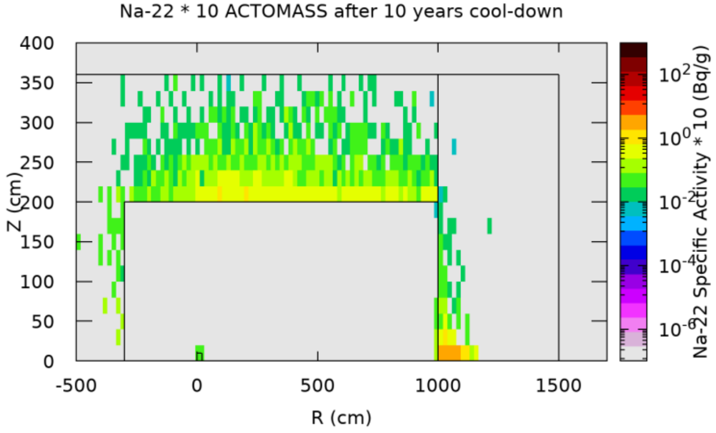
```
      INTEGER :: atomic_number, mass_number, isomer_number
*
      LSCZER = .FALSE.
      COMSCW = ONEONE

* ======== In order to compute doses ========= *
      IF ( ISCRNG .EQ. 5 .AND. TITUSB(JSCRNG)(1:3) .EQ. "ACL") THEN
           COMSCW = ZERZER

        atomic_number = IZRSDL(1)
        mass_number = IARSDL(1)
        isomer_number = ISRSDL(1)
        IF (isomer_number .EQ. 0) THEN
          IF (atomic_number .EQ. 1 .AND. mass_number .EQ. 3) THEN
            COMSCW = ONEONE / 1.0D+2
          END IF
          IF (atomic_number .EQ. 11 .AND. mass_number .EQ. 22) THEN
            COMSCW = ONEONE / 1.0D-1
          END IF
          IF (atomic_number .EQ. 26 .AND. mass_number .EQ. 55) THEN
            COMSCW = ONEONE / 1.0D+3
          END IF
        END IF


      END IF

      RETURN
*=== End of function Comscw ===========================================*
      END
```

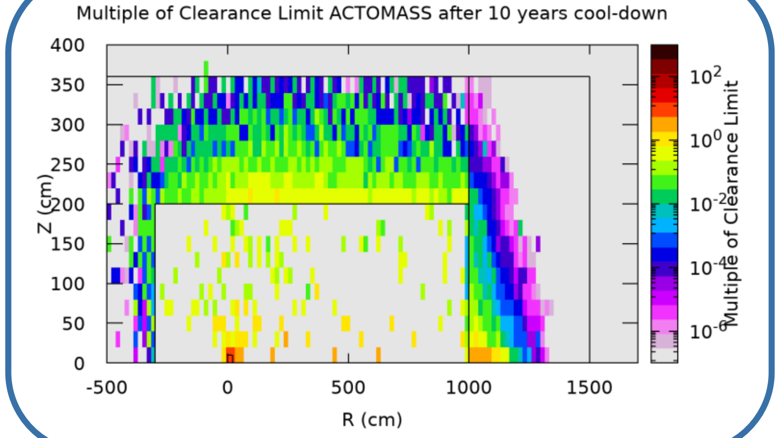
Activation – `ACTOMASS` applications

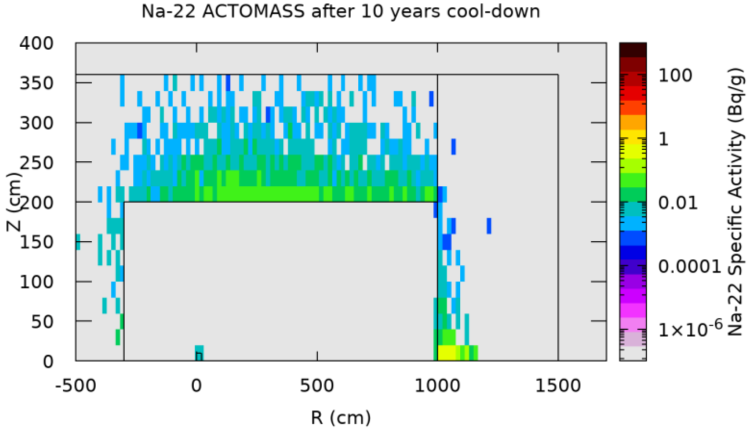

Total ACTOMASS after 10 years cool-down


H-3 ACTOMASS after 10 years cool-down


Fe-55 ACTOMASS after 10 years cool-down

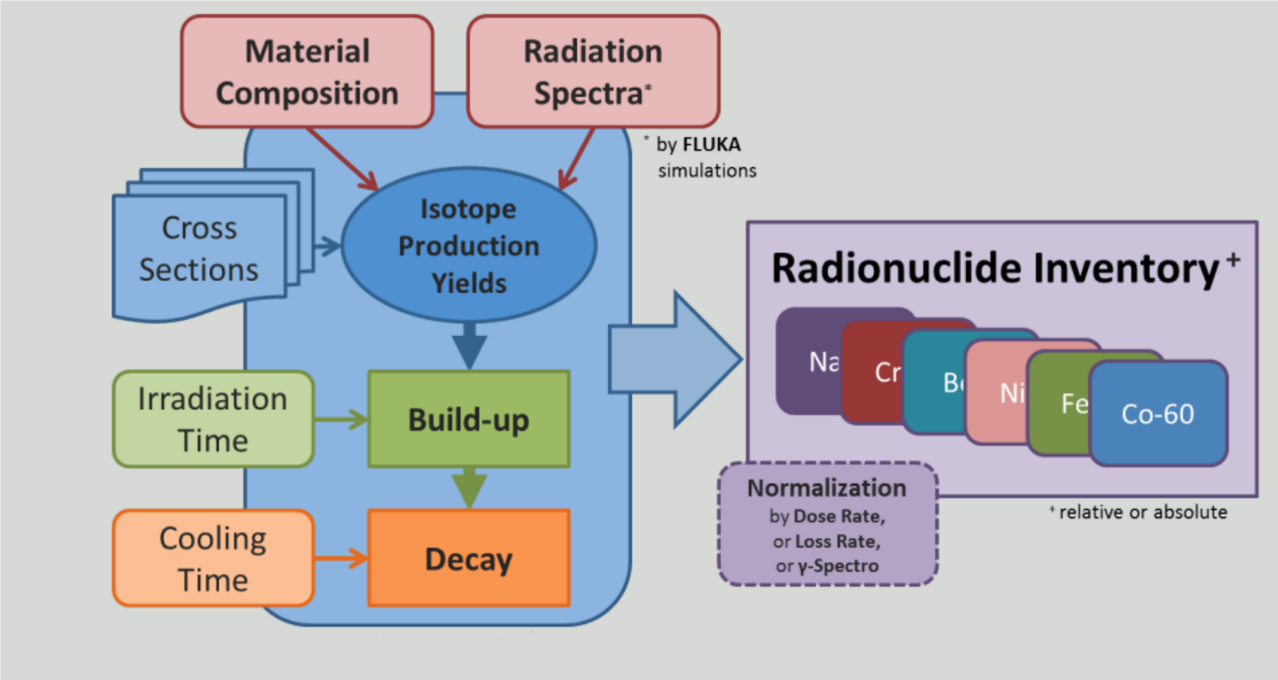

Na-22 * 10 ACTOMASS after 10 years cool-down


Multiple of Clearance Limit ACTOMASS after 10 years cool-down


Na-22 ACTOMASS after 10 years cool-down

Activation - Fluence spectra-based methods

- Methodology
  1. **Score particle spectra** with USRTRACK [FLUKA part]
     - Typically, neutrons, protons, charged pions and photons)
  2. **Weight spectra off-line** with radionuclide production **cross-sections**
     - Production yields
  3. Perform **build-up** and **decay** of radionuclides offline
- Several codes exist
  - CINDER
  - ORIGEN
  - ActiWiz
  - JEREMY
  - DCHAIN-PHITS
- **Improved convergence** with respect to event-based scorings
  - RESNUCLE, ACTOMASS



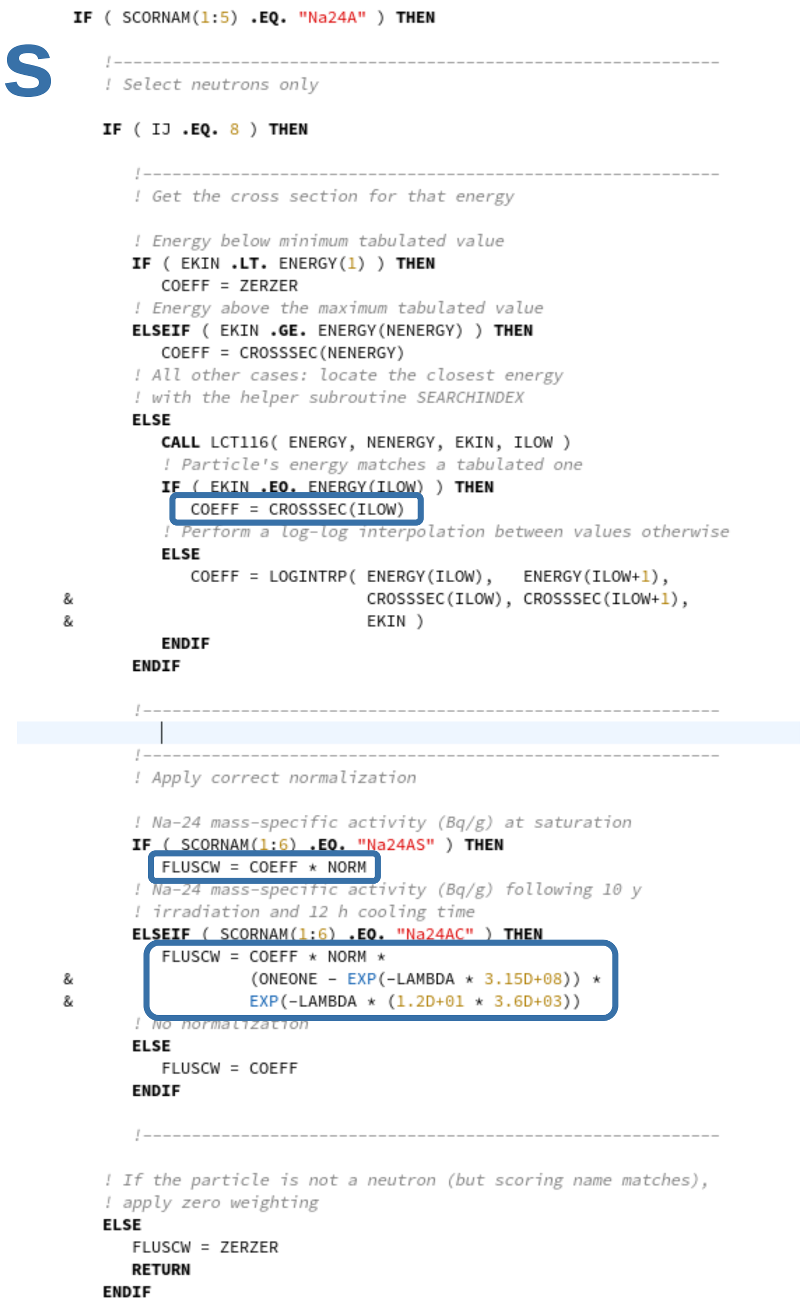
N. Walter, R. Froeschl, B. Cellerier, L. Ulrici. The Use of Integral Gamma-ray Measurement Chambers as Part of the Clearance Procedure for Waste from CERN's Accelerators and Experimental Facilities, IRPA 2014, Geneva, June 2014.

Activation – FLUSCW based methods

- FLUSCW with (ISCRNG .EQ. 2 , i.e. Track-length binning)


USERWEIG ϕ Weight: FLUSCW+ ▾ Resnuclei: No weight ▾ Density Weight: COMSCW+ ▾

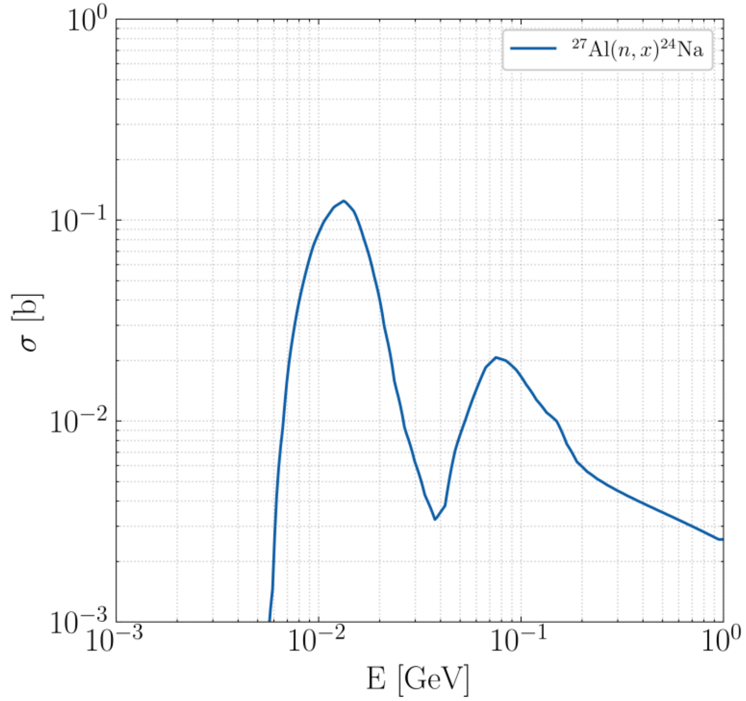
- Simple example of Al(n,α)Na-24 user routine
    - **Reaction cross-sections** in code
    - Two scorings
        - **Saturation specific activity**
        - **Specific activity** after 8 hours irradiation and 10 hours of cool-down



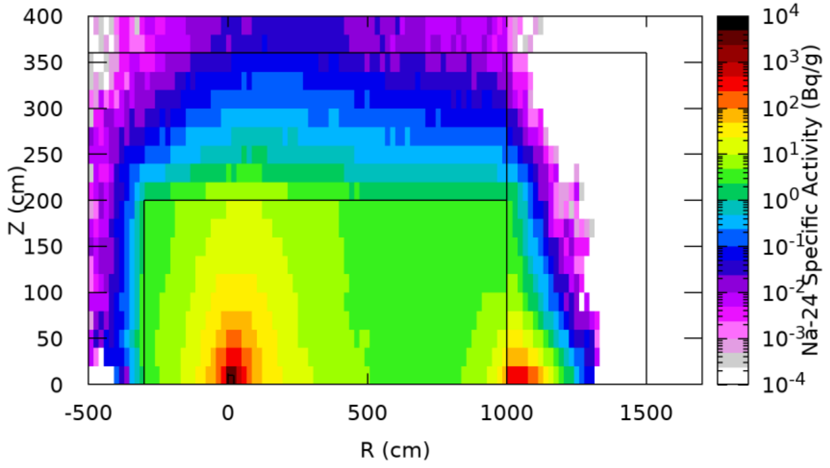
```
 IF ( SCORNAM(1:5) .EQ. "Na24A" ) THEN

    !-------------------------------------------------------------
    ! Select neutrons only

    IF ( IJ .EQ. 8 ) THEN

       !----------------------------------------------------------
       ! Get the cross section for that energy

       ! Energy below minimum tabulated value
       IF ( EKIN .LT. ENERGY(1) ) THEN
          COEFF = ZERZER
       ! Energy above the maximum tabulated value
       ELSEIF ( EKIN .GE. ENERGY(NENERGY) ) THEN
          COEFF = CROSSSEC(NENERGY)
       ! All other cases: locate the closest energy
       ! with the helper subroutine SEARCHINDEX
       ELSE
          CALL LCT116( ENERGY, NENERGY, EKIN, ILOW )
          ! Particle's energy matches a tabulated one
          IF ( EKIN .EQ. ENERGY(ILOW) ) THEN
             COEFF = CROSSSEC(ILOW)
          ! Perform a log-log interpolation between values otherwise
          ELSE
             COEFF = LOGINTRP( ENERGY(ILOW),   ENERGY(ILOW+1),
&                              CROSSSEC(ILOW), CROSSSEC(ILOW+1),
&                              EKIN )
          ENDIF
       ENDIF

       !----------------------------------------------------------

       !----------------------------------------------------------
       ! Apply correct normalization

       ! Na-24 mass-specific activity (Bq/g) at saturation
       IF ( SCORNAM(1:6) .EQ. "Na24AS" ) THEN
          FLUSCW = COEFF * NORM
       ! Na-24 mass-specific activity (Bq/g) following 10 y
       ! irradiation and 12 h cooling time
       ELSEIF ( SCORNAM(1:6) .EQ. "Na24AC" ) THEN
          FLUSCW = COEFF * NORM *
&                  (ONEONE - EXP(-LAMBDA * 3.15D+08)) *
&                  EXP(-LAMBDA * (1.2D+01 * 3.6D+03))
       ! No normalization
       ELSE
          FLUSCW = COEFF
       ENDIF

       !----------------------------------------------------------

    ! If the particle is not a neutron (but scoring name matches),
    ! apply zero weighting
    ELSE
       FLUSCW = ZERZER
       RETURN
    ENDIF
```

Activation – FLUSCW based methods

Al(n,α)Na-24 reaction cross-section

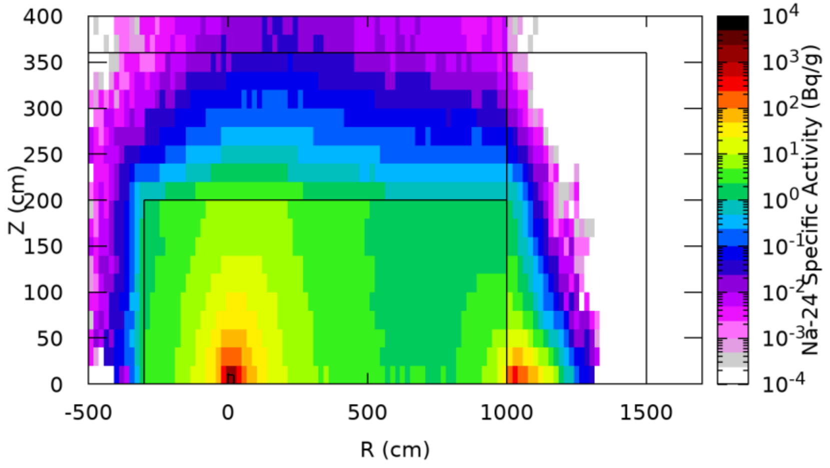


Expected saturation activity of Na-24 (irradiation 1.0E+08 p/s)



Neutron induced component only

Expected activity of Na-24 (10y irradiation 1.0E+08 p/s - 12 h cooling time)

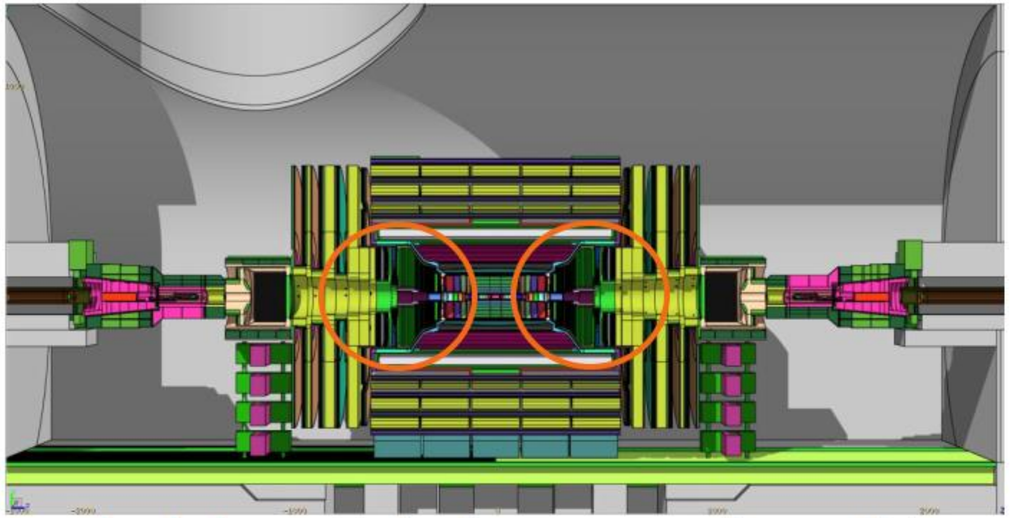


Neutron induced component only

Activation – FLUSCW based methods

- General concept:
  1. Precompute factors from fluence to radiological hazard factor (e.g. clearance limits)
  2. Apply during transport via FLUSCW

CMS Experiment – Clearance of future End-cap calorimeters for two different stainless steel compositions



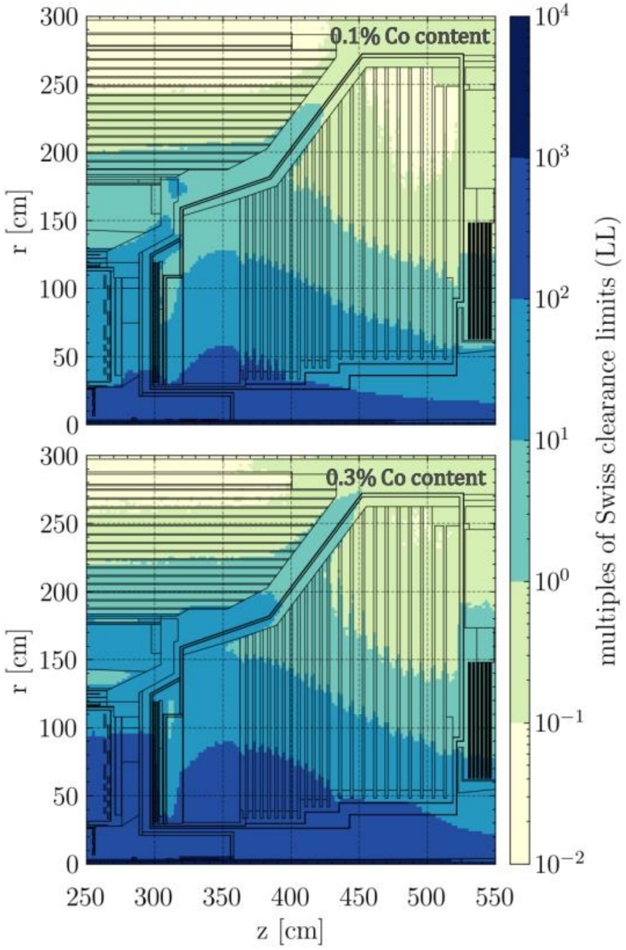


Figure 5: FLUKA simulation of multiples of Swiss clearance limits (LL_{tot}) for different stainless steel 304L compositions for CMS HGCal at 30 years from end of irradiation (0.1% Co top; 0.3% Co bottom): *r* is the radial distance from the beam line, *z* the longitudinal distance from the interaction point of the colliding beams.

Plots from:
D. Bozzato, R. Froeschl, V. Kouskoura,
"Operational radiation protection challenges for the LHC experiments".
IRPA 2022. Radiation Protection Dosimetry (2023). [Accepted for publication].

References:
R. Froeschl. A method for radiological characterization based on fluence conversion coefficients
http://dx.doi.org/10.1088/1742-6596/1046/1/012006 (https://cds.cern.ch/record/2636326?ln=en)
D. Bozzato, R. Froeschl. The Fluence Conversion Coefficients method : applications to radiological characterizatio the FLUKA and PHITS codes. CERN EDMS 2404506 (https://cds.cern.ch/record/2730147?ln=en)

Activation of gases and fluids

- Gases and fluids often are **non-stationary materials**
  - Forced flow (circuits)
  - Natural convection and diffusion
- Standard concept for assessments
  - Scoring **production yields**
    - production yields directly with RESNCULE (no association with DCYSCORE) or
    - Fluence (USRTRACK) + off-line weighting with radionuclide production cross-sections (see before)
  - **Build-up** and **decay** taking **characteristics of circuits** into account
    - Cossairt [Fermilab Report TM-1834] (Sec. 8.2.2)
    - Build-up and decay with **effective half-life** (in simple case)
      - Correction at the end from effective Bq to physical Bq
    - **Compartment models** in more complex cases

Summary

- **FLUKA** features **cover** all **standard domains** of **Radiation Protection assessments**
  - **External exposure**
    - Prompt and residual radiation
    - Latest ICRP 116 conversion coefficients available
  - **Activation**
    - Access to full radionuclide inventories
    - Build-up during beam operation and cool-down available
- All based on **very well benchmarked FLUKA physics models** and **data**
- FLUKA **user routines** structure allows **customization** to meet **advanced needs**
  - Weighting of fluences or radionuclide-specific activities
  - Clearance, transport, radioactive waste pathways

FLUKA

Summary of main input cards

`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 intensities)

`DCYTIMES`

definition of decay (cooling) times

`DCYSCORE`

associates scoring detectors (radionuclides, fluence, dose equivalent) with different cooling times

Summary of main input cards

`AUXSCORE`

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

`RESNUCLE`

allows to score residual nuclei production or activity on a region basis

`PHYSICS`

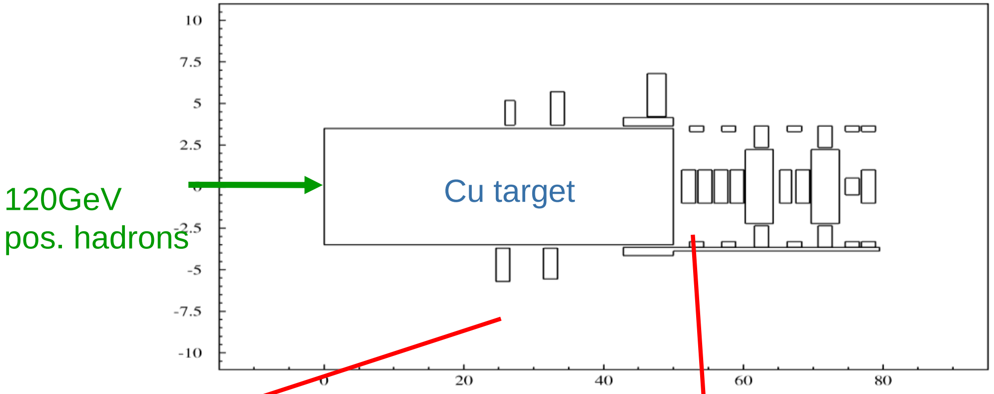
switch to activate the evaporation of heavy fragments (up to A=24) and the simulation of coalescence

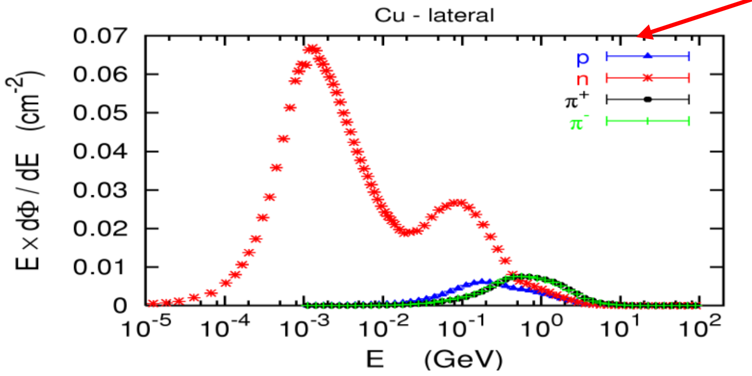
Benchmarks - Selection

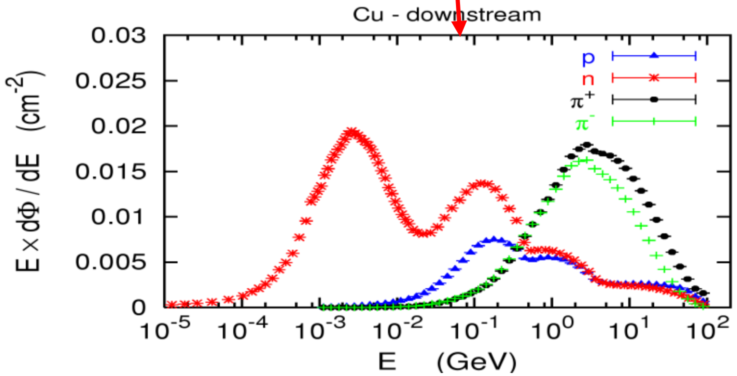
CERF Benchmark experiment

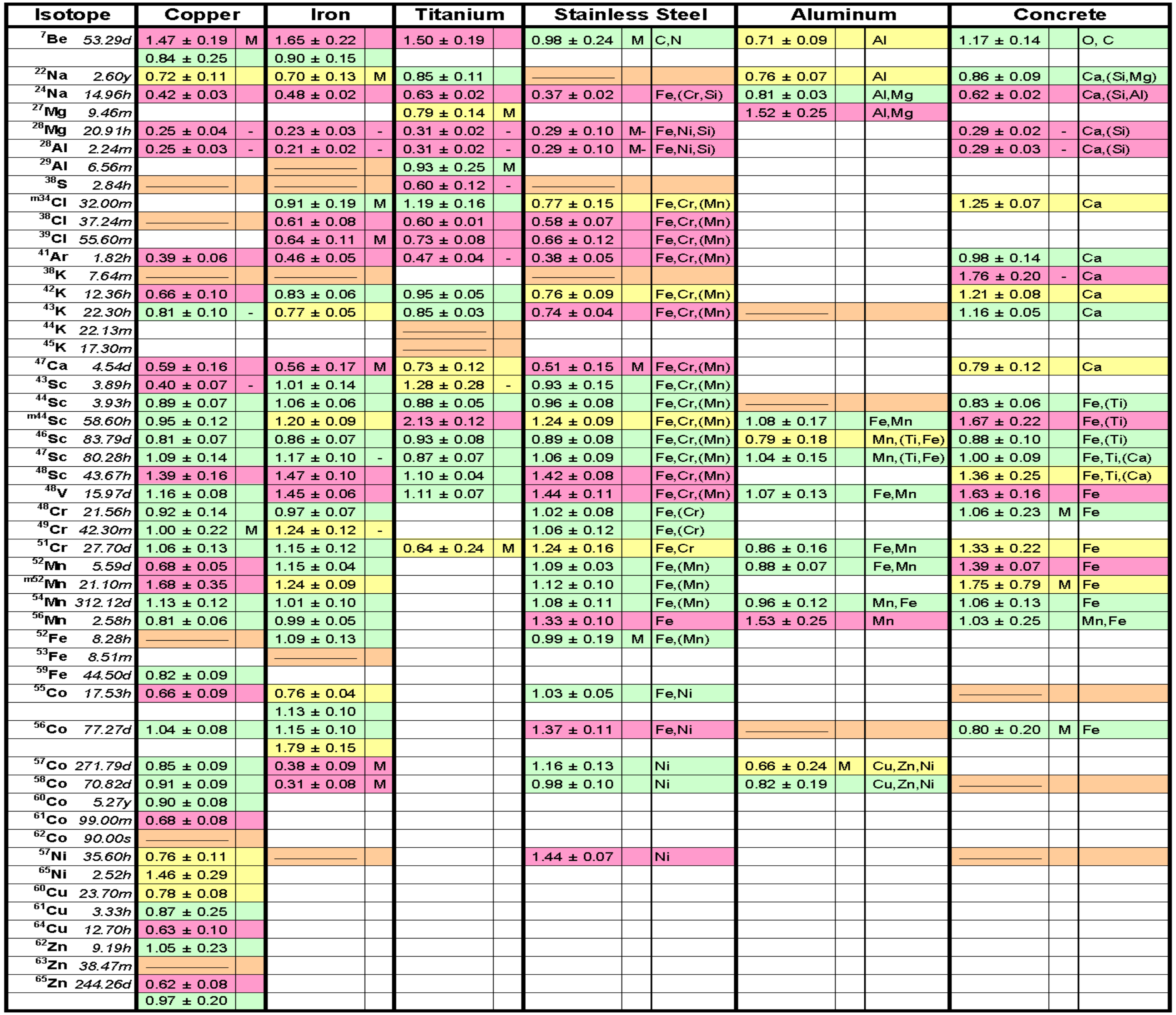
Irradiation of samples of different materials to the stray radiation field created by the interaction of a 120 GeV positively charged hadron beam in a copper target

Reference: M. Brugger, S. Roesler, *et al.,* Nuclear Instruments and Methods A 562 (2006) 814-818









Isotope		Copper		Iron		Titanium		Stainless Steel			Aluminum			Concrete		
^{7}Be	*53.29d*	1.47 ± 0.19	M	1.65 ± 0.22		1.50 ± 0.19		0.98 ± 0.24	M	C,N	0.71 ± 0.09		Al	1.17 ± 0.14		O, C
		0.84 ± 0.25		0.90 ± 0.15												
^{22}Na	*2.60y*	0.72 ± 0.11		0.70 ± 0.13	M	0.85 ± 0.11		—			0.76 ± 0.07		Al	0.86 ± 0.09		Ca,(Si,Mg)
^{24}Na	*14.96h*	0.42 ± 0.03		0.48 ± 0.02		0.63 ± 0.02		0.37 ± 0.02		Fe,(Cr,Si)	0.81 ± 0.03		Al,Mg	0.62 ± 0.02		Ca,(Si,Al)
^{27}Mg	*9.46m*					0.79 ± 0.14	M				1.52 ± 0.25		Al,Mg			
^{28}Mg	*20.91h*	0.25 ± 0.04	-	0.23 ± 0.03	-	0.31 ± 0.02	-	0.29 ± 0.10	M-	Fe,Ni,Si)				0.29 ± 0.02	-	Ca,(Si)
^{28}Al	*2.24m*	0.25 ± 0.03	-	0.21 ± 0.02	-	0.31 ± 0.02	-	0.29 ± 0.10	M-	Fe,Ni,Si)				0.29 ± 0.03	-	Ca,(Si)
^{29}Al	*6.56m*			—		0.93 ± 0.25	M									
^{38}S	*2.84h*	—		—		0.60 ± 0.12	-	—								
^{m34}Cl	*32.00m*			0.91 ± 0.19	M	1.19 ± 0.16		0.77 ± 0.15		Fe,Cr,(Mn)				1.25 ± 0.07		Ca
^{38}Cl	*37.24m*	—		0.61 ± 0.08		0.60 ± 0.01		0.58 ± 0.07		Fe,Cr,(Mn)						
^{39}Cl	*55.60m*			0.64 ± 0.11	M	0.73 ± 0.08		0.66 ± 0.12		Fe,Cr,(Mn)						
^{41}Ar	*1.82h*	0.39 ± 0.06		0.46 ± 0.05		0.47 ± 0.04	-	0.38 ± 0.05		Fe,Cr,(Mn)				0.98 ± 0.14		Ca
^{38}K	*7.64m*	—		—				—						1.76 ± 0.20	-	Ca
^{42}K	*12.36h*	0.66 ± 0.10		0.83 ± 0.06		0.95 ± 0.05		0.76 ± 0.09		Fe,Cr,(Mn)				1.21 ± 0.08		Ca
^{43}K	*22.30h*	0.81 ± 0.10	-	0.77 ± 0.05		0.85 ± 0.03		0.74 ± 0.04		Fe,Cr,(Mn)	—			1.16 ± 0.05		Ca
^{44}K	*22.13m*					—										
^{45}K	*17.30m*					—										
^{47}Ca	*4.54d*	0.59 ± 0.16		0.56 ± 0.17	M	0.73 ± 0.12		0.51 ± 0.15	M	Fe,Cr,(Mn)				0.79 ± 0.12		Ca
^{43}Sc	*3.89h*	0.40 ± 0.07	-	1.01 ± 0.14		1.28 ± 0.28	-	0.93 ± 0.15		Fe,Cr,(Mn)						
^{44}Sc	*3.93h*	0.89 ± 0.07		1.06 ± 0.06		0.88 ± 0.05		0.96 ± 0.08		Fe,Cr,(Mn)	—			0.83 ± 0.06		Fe,(Ti)
^{m44}Sc	*58.60h*	0.95 ± 0.12		1.20 ± 0.09		2.13 ± 0.12		1.24 ± 0.09		Fe,Cr,(Mn)	1.08 ± 0.17		Fe,Mn	1.67 ± 0.22		Fe,(Ti)
^{46}Sc	*83.79d*	0.81 ± 0.07		0.86 ± 0.07		0.93 ± 0.08		0.89 ± 0.08		Fe,Cr,(Mn)	0.79 ± 0.18		Mn,(Ti,Fe)	0.88 ± 0.10		Fe,(Ti)
^{47}Sc	*80.28h*	1.09 ± 0.14		1.17 ± 0.10	-	0.87 ± 0.07		1.06 ± 0.09		Fe,Cr,(Mn)	1.04 ± 0.15		Mn,(Ti,Fe)	1.00 ± 0.09		Fe,Ti,(Ca)
^{48}Sc	*43.67h*	1.39 ± 0.16		1.47 ± 0.10		1.10 ± 0.04		1.42 ± 0.08		Fe,Cr,(Mn)				1.36 ± 0.25		Fe,Ti,(Ca)
^{48}V	*15.97d*	1.16 ± 0.08		1.45 ± 0.06		1.11 ± 0.07		1.44 ± 0.11		Fe,Cr,(Mn)	1.07 ± 0.13		Fe,Mn	1.63 ± 0.16		Fe
^{48}Cr	*21.56h*	0.92 ± 0.14		0.97 ± 0.07				1.02 ± 0.08		Fe,(Cr)				1.06 ± 0.23	M	Fe
^{49}Cr	*42.30m*	1.00 ± 0.22	M	1.24 ± 0.12	-			1.06 ± 0.12		Fe,(Cr)						
^{51}Cr	*27.70d*	1.06 ± 0.13		1.15 ± 0.12		0.64 ± 0.24	M	1.24 ± 0.16		Fe,Cr	0.86 ± 0.16		Fe,Mn	1.33 ± 0.22		Fe
^{52}Mn	*5.59d*	0.68 ± 0.05		1.15 ± 0.04				1.09 ± 0.03		Fe,(Mn)	0.88 ± 0.07		Fe,Mn	1.39 ± 0.07		Fe
^{m52}Mn	*21.10m*	1.68 ± 0.35		1.24 ± 0.09				1.12 ± 0.10		Fe,(Mn)				1.75 ± 0.79	M	Fe
^{54}Mn	*312.12d*	1.13 ± 0.12		1.01 ± 0.10				1.08 ± 0.11		Fe,(Mn)	0.96 ± 0.12		Mn,Fe	1.06 ± 0.13		Fe
^{56}Mn	*2.58h*	0.81 ± 0.06		0.99 ± 0.05				1.33 ± 0.10		Fe	1.53 ± 0.25		Mn	1.03 ± 0.25		Mn,Fe
^{52}Fe	*8.28h*	—		1.09 ± 0.13				0.99 ± 0.19	M	Fe,(Mn)						
^{53}Fe	*8.51m*			—												
^{59}Fe	*44.50d*	0.82 ± 0.09														
^{55}Co	*17.53h*	0.66 ± 0.09		0.76 ± 0.04				1.03 ± 0.05		Fe,Ni				—		
				1.13 ± 0.10												
^{56}Co	*77.27d*	1.04 ± 0.08		1.15 ± 0.10				1.37 ± 0.11		Fe,Ni	—			0.80 ± 0.20	M	Fe
				1.79 ± 0.15												
^{57}Co	*271.79d*	0.85 ± 0.09		0.38 ± 0.09	M			1.16 ± 0.13		Ni	0.66 ± 0.24	M	Cu,Zn,Ni			
^{58}Co	*70.82d*	0.91 ± 0.09		0.31 ± 0.08	M			0.98 ± 0.10		Ni	0.82 ± 0.19		Cu,Zn,Ni	—		
^{60}Co	*5.27y*	0.90 ± 0.08														
^{61}Co	*99.00m*	0.68 ± 0.08														
^{62}Co	*90.00s*	—														
^{57}Ni	*35.60h*	0.76 ± 0.11		—				1.44 ± 0.07		Ni				—		
^{65}Ni	*2.52h*	1.46 ± 0.29														
^{60}Cu	*23.70m*	0.78 ± 0.08														
^{61}Cu	*3.33h*	0.87 ± 0.25														
^{64}Cu	*12.70h*	0.63 ± 0.10														
^{62}Zn	*9.19h*	1.05 ± 0.23														
^{63}Zn	*38.47m*	—														
^{65}Zn	*244.26d*	0.62 ± 0.08														
		0.97 ± 0.20														

R = Ratio FLUKA/Exp

$0.8 < R < 1.2$

$0.8 < R \pm \text{Error} < 1.2$

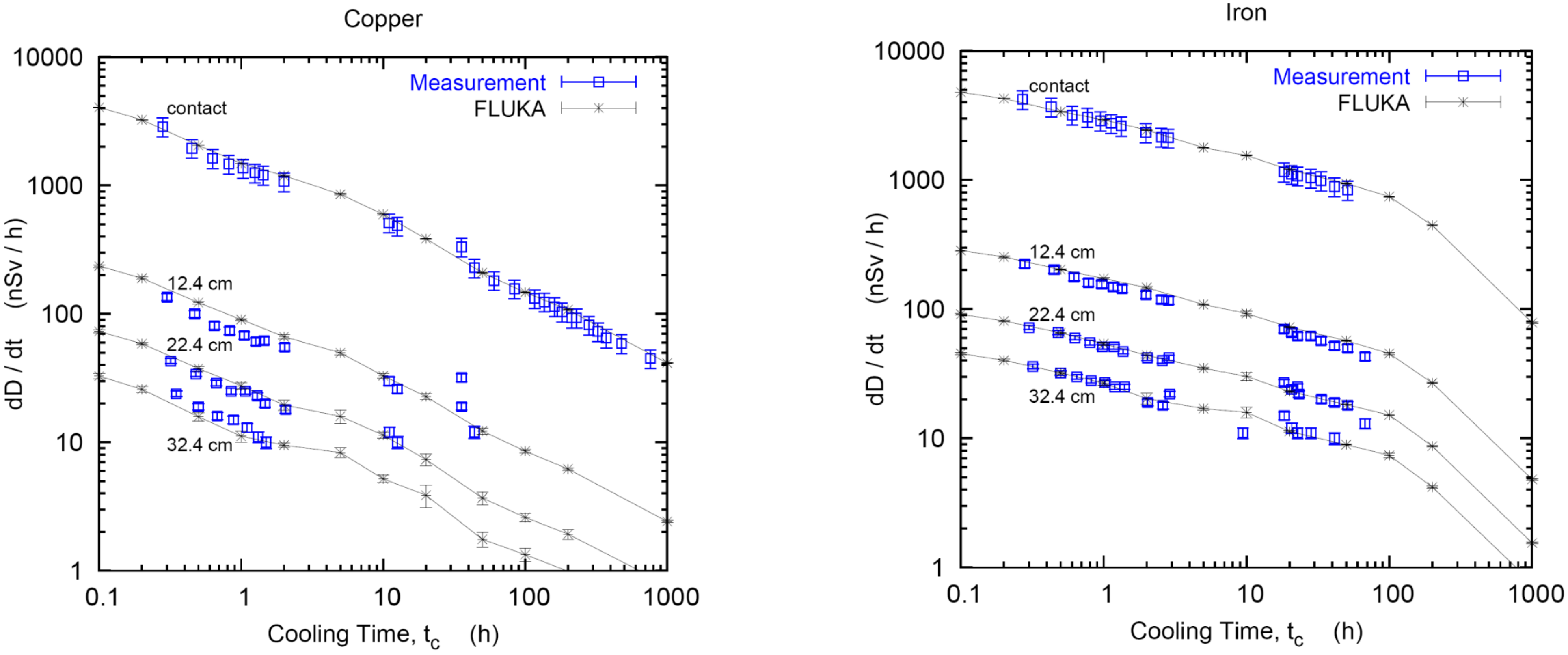
Exp/MDA < 1

$R + \text{Error} < 0.8$ or
$R - \text{Error} > 1.2$

Reference:
M. Brugger, S. Roesler *et al.*, Nuclear Instruments and Methods A 562 (2006) 814-818

CERF Benchmark experiment - *Results*

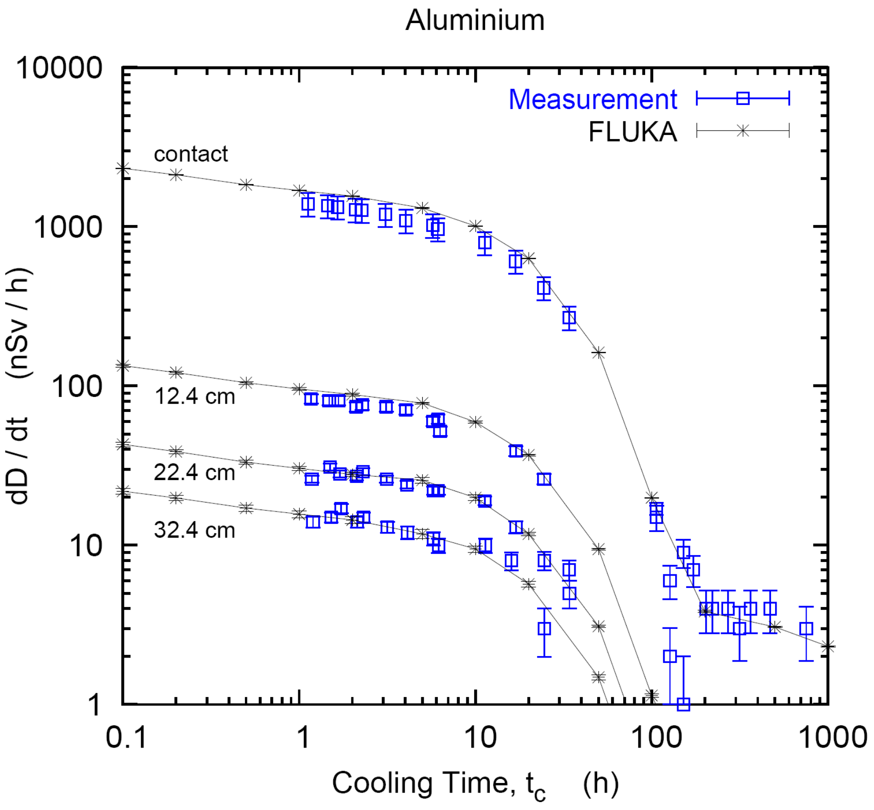
Dose rate as function of cooling time for different distances between sample and detector

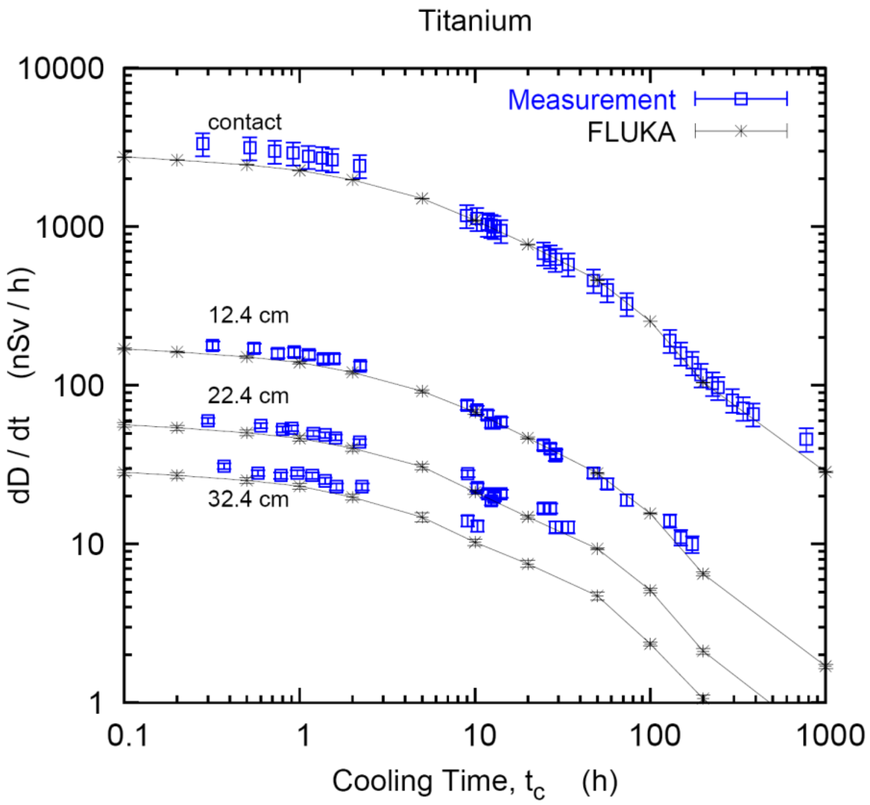


<u>Reference:</u> M. Brugger, S. Roesler *et al.*, Radiat. Prot. Dosim. 116 (2005) 12-15

CERF Benchmark experiment - *Results*

Dose rate as function of cooling time for different distances between sample and detector



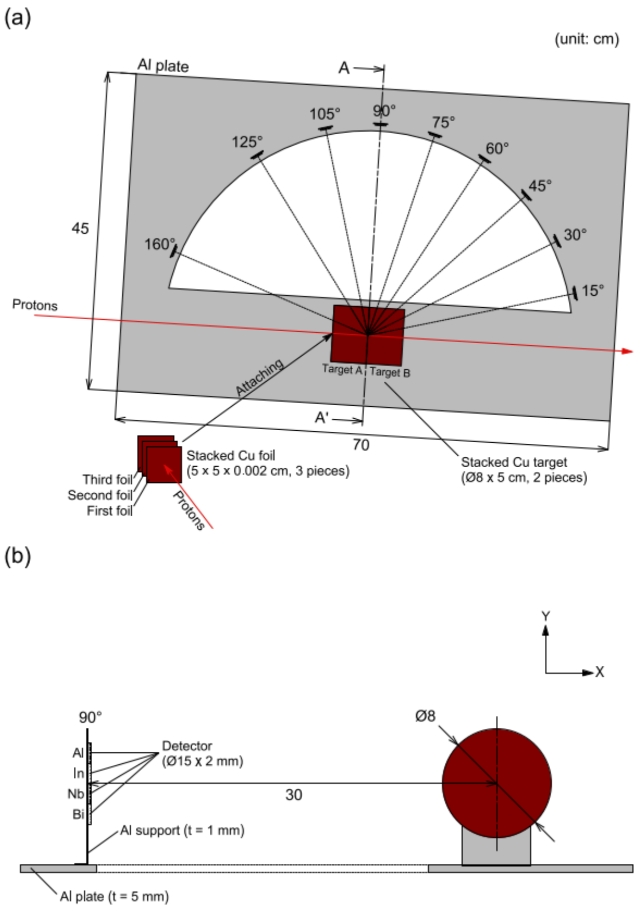


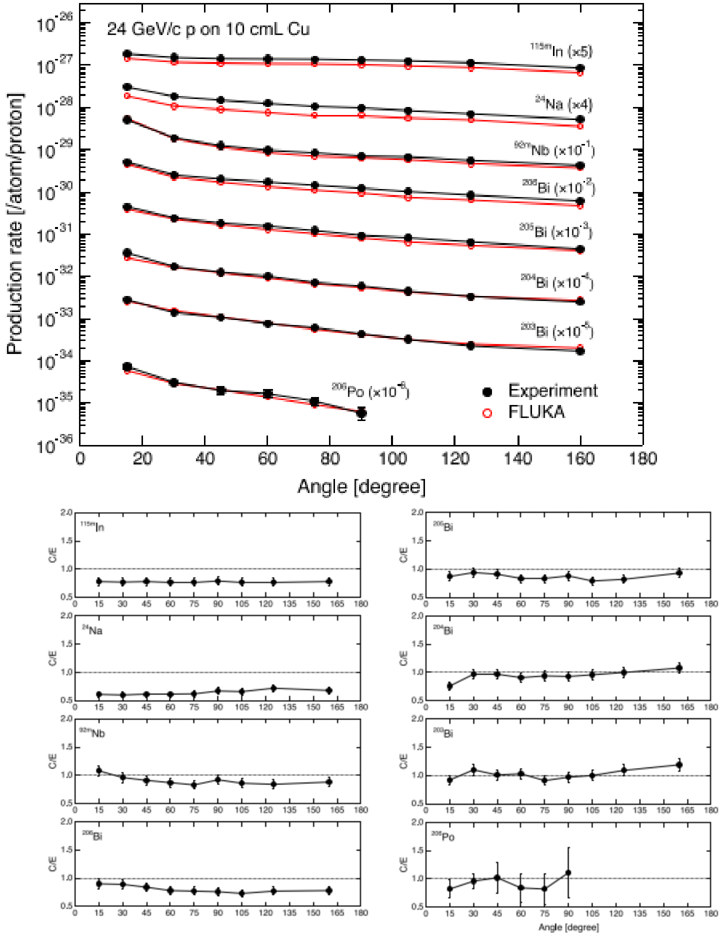
Reference: M. Brugger, S. Roesler *et al.,* Radiat. Prot. Dosim. 116 (2005) 12-15

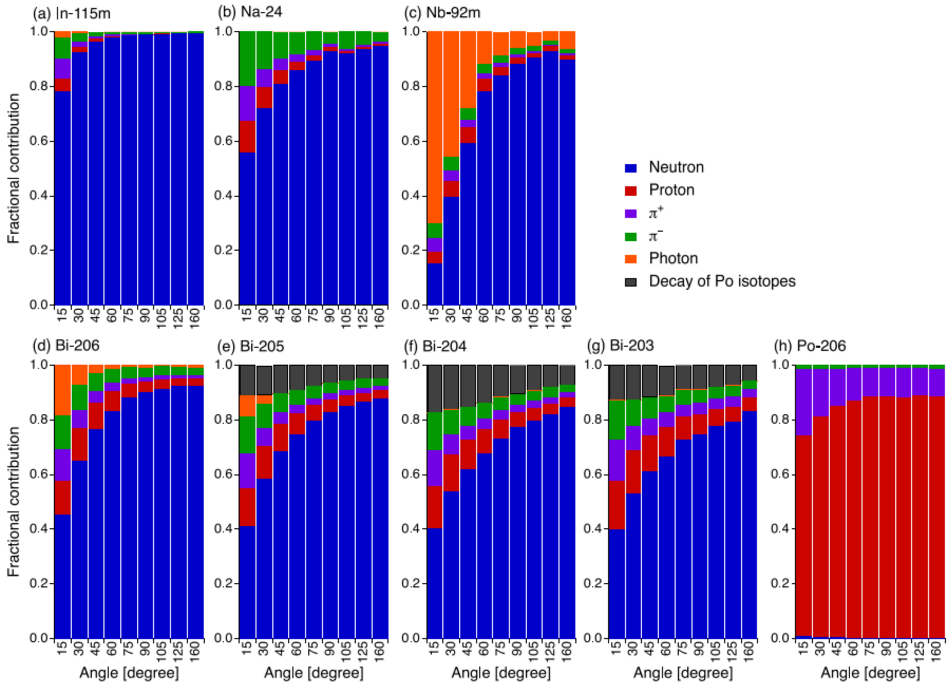
T. Oyama et al. - Published in: Nucl.Instrum.Meth.A 990 (2021) 164977
https://doi.org/10.1016/j.nima.2020.164977

FLUKA 2011.2x.7

Measurements of secondary-particle emissions from copper target bombarded with 24-GeV/c protons



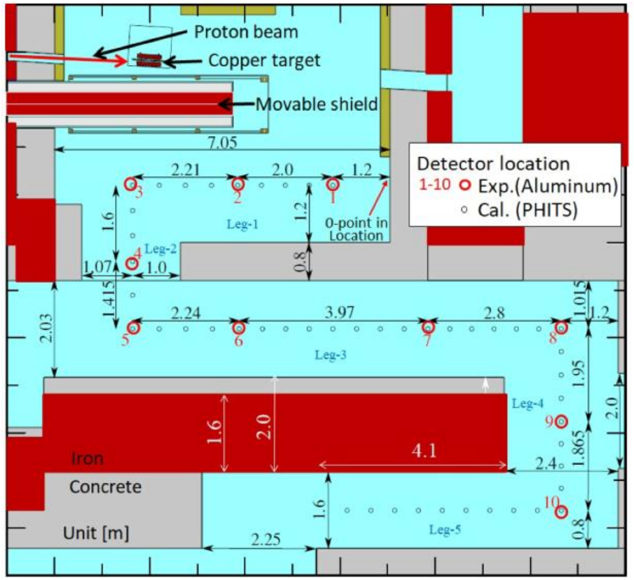


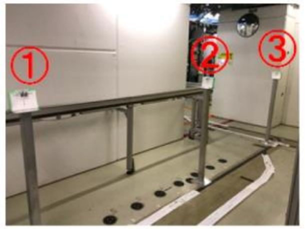


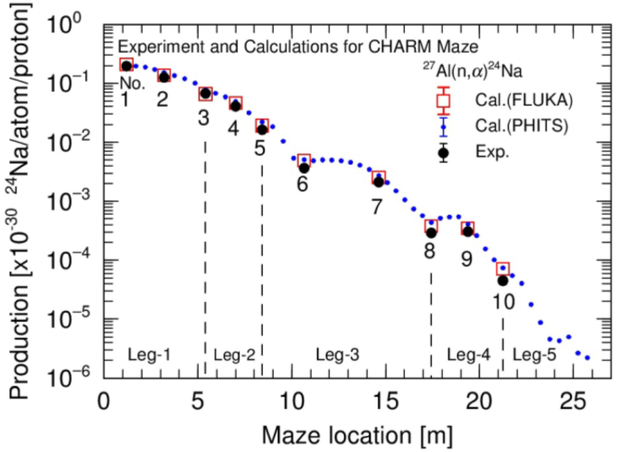
N. Nakao et al. - Published in: J.Nucl.Sci.Tech. 58 (2021) 8, 899-907
https://doi.org/10.1080/00223131.2021.1887003

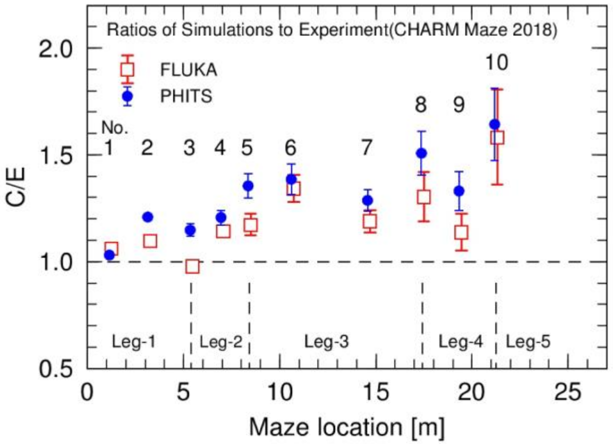
PHITS 3.20
FLUKA v4-0.0

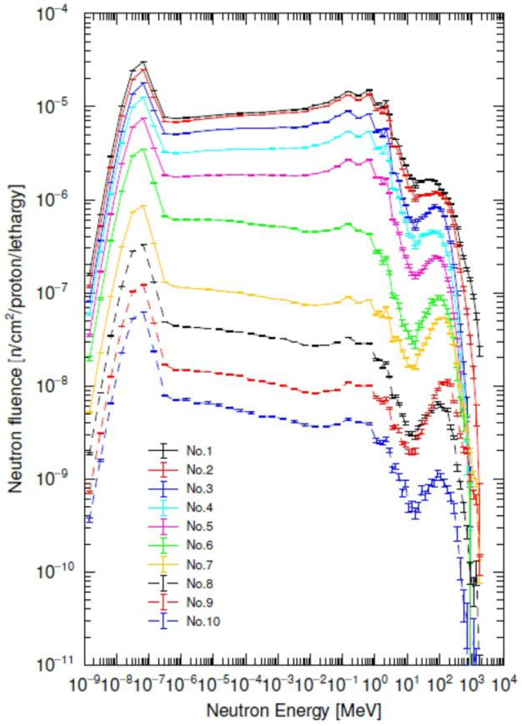
Measurements and Monte Carlo simulations of high-energy neutron streaming through the access maze using activation detectors at 24 GeV/c proton beam facility of CERN/CHARM

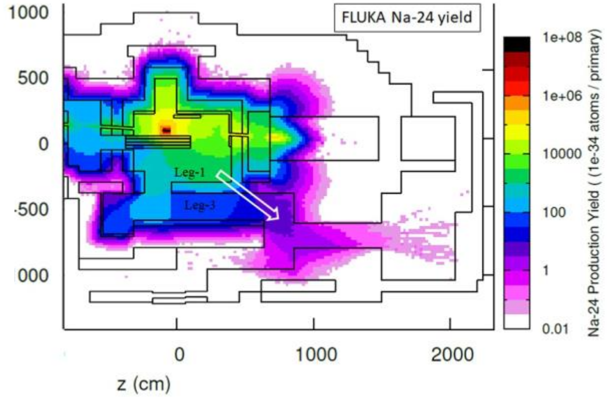


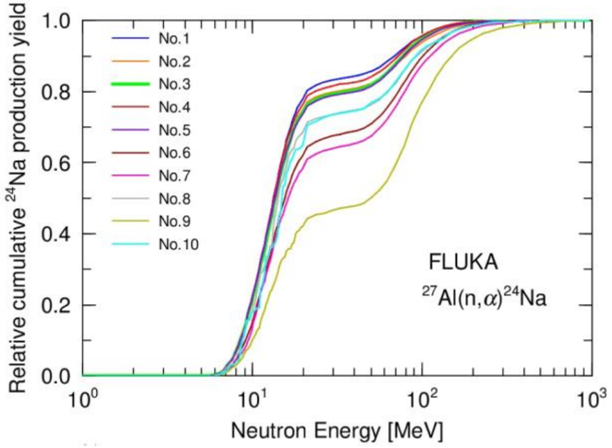












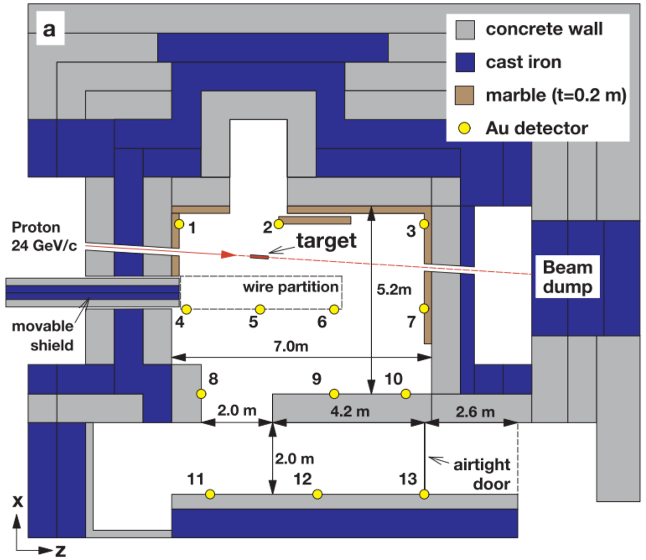
T. Oyama et al. - Published in: Nucl.Instrum.Meth.B 434 (2018) 29-36
https://doi.org/10.1016/j.nimb.2018.08.016

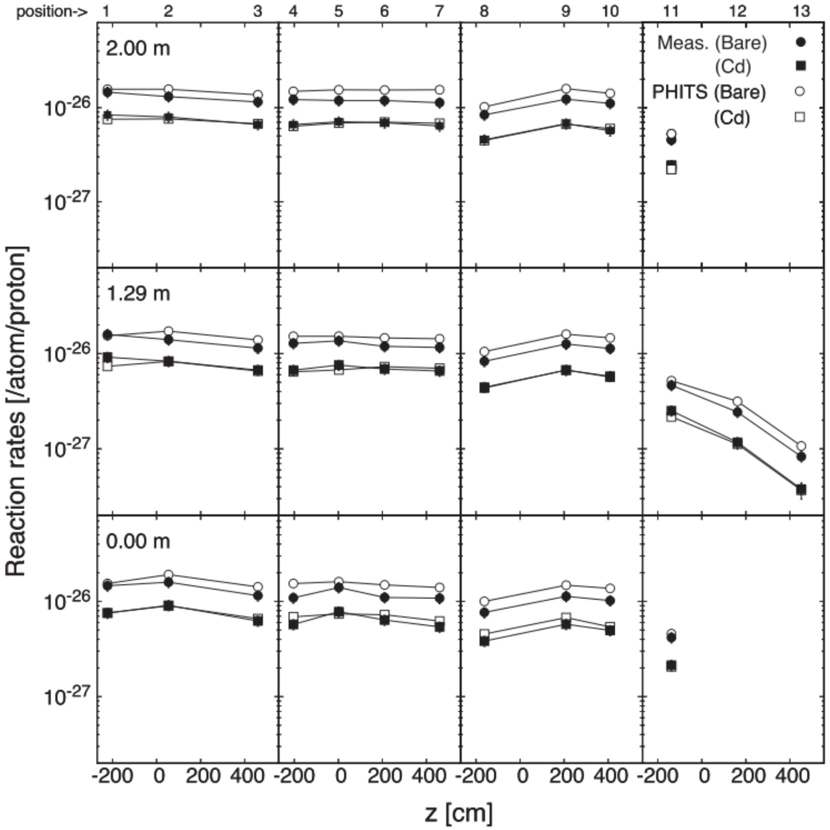
PHITS – JENDL-4.0
FLUKA – GW
MARS – MCNP4C-ENDF/B-VI

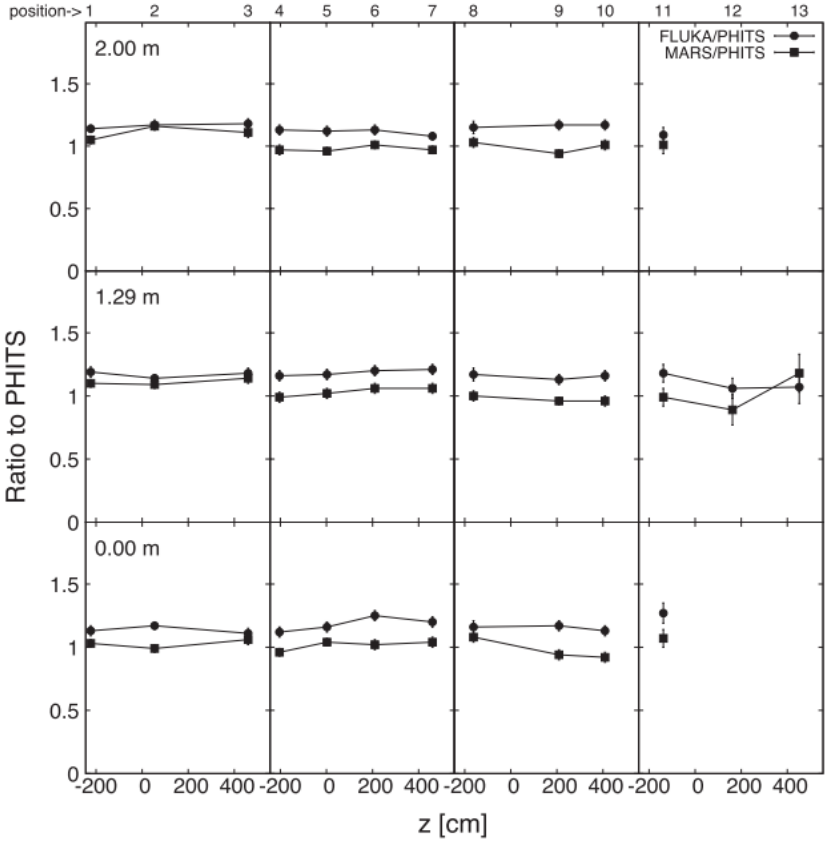
Measurement and calculation of thermal neutrons induced by the 24 GeV/c/c proton bombardment of a thick copper target

Low energy neutrons for Ar 41 predictions

Gold foils at 3 heights
- Bare
- Cd coated

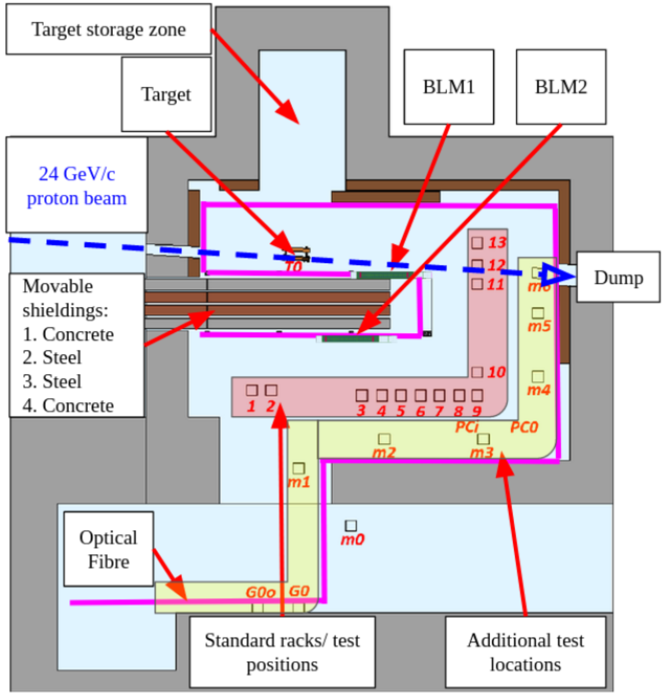




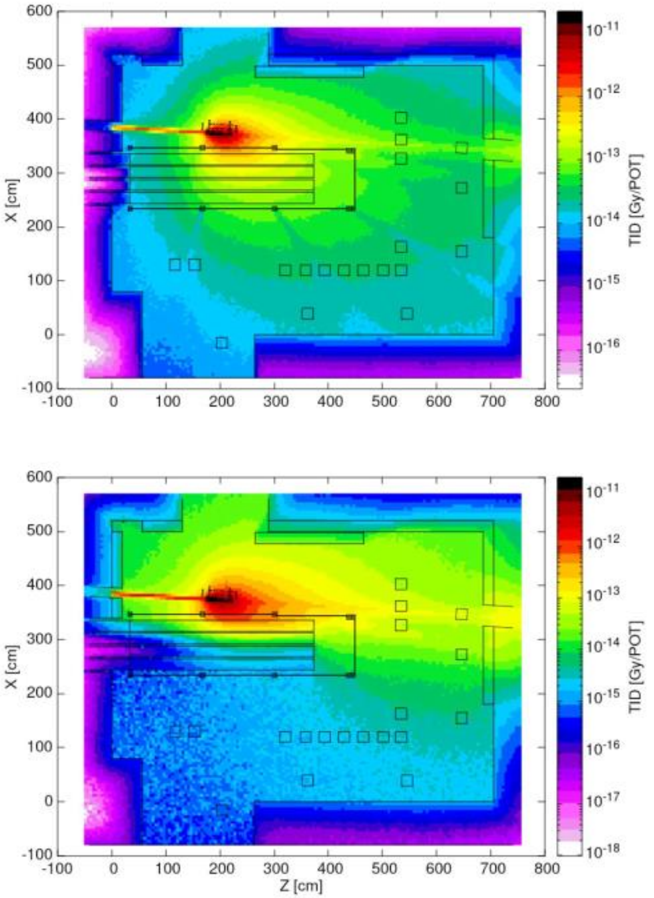


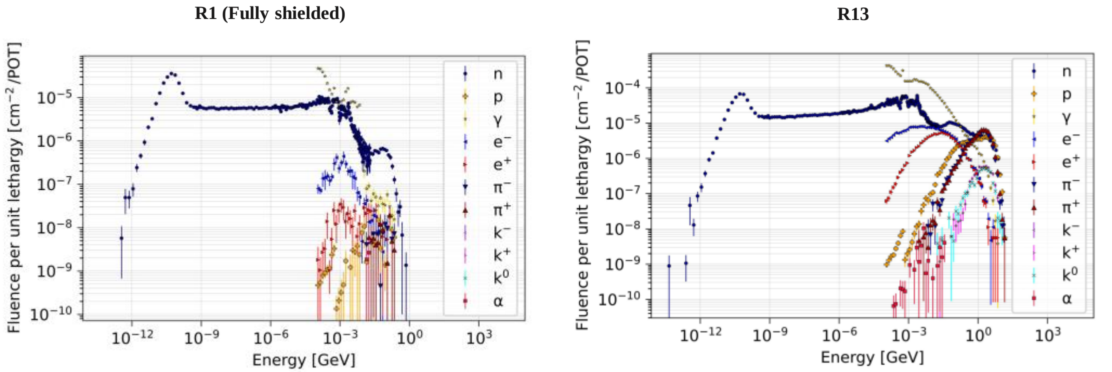
D. Prelipcean et al. - Published in IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 69, NO. 7, JULY 2022
https://doi.org/10.1109/TNS.2022.3169756

Benchmark Between Measured and Simulated Radiation Level Data at the Mixed-Field CHARM Facility at CERN



Quantity @ R10	Maximum Rate	Integrated Rate (per week)
Total Ionizing Dose	2.70 Gy/h	360 Gy
Thermal neutron fluence	3×10^{6} cm^{-2}s^{-1}	1.5×10^{12} cm^{-2}
High-energy hadron fluence	1.5×10^{6} cm^{-2}s^{-1}	8×10^{11} cm^{-2}





		BLM1			BLM2			BLM1/2 ratio		
CONF.	**POT**	**measured [Gy/POT]**	**simulated [Gy/POT]**	**measured/ simulated**	**measured [Gy/POT]**	**simulated [Gy/POT]**	**measured/ simulated**	**measured**	**simulated**	**measured/ simulated**
CuOOOO	$3.14\times10^{+17}$	4.74×10^{-14}	5.33×10^{-14}	**0.89**	2.39×10^{-14}	3.22×10^{-14}	**0.74**	1.98	1.66	**1.20**
CuOOOC	$4.53\times10^{+13}$	5.86×10^{-14}	5.34×10^{-14}	**1.10**	2.01×10^{-14}	3.36×10^{-14}	**0.60**	2.92	1.59	**1.84**
CuCOOO	$3.21\times10^{+13}$	5.96×10^{-14}	5.64×10^{-14}	**1.06**	1.21×10^{-14}	1.10×10^{-14}	**1.10**	4.93	5.14	**0.96**
CuOOSC	$1.73\times10^{+13}$	5.92×10^{-14}	5.49×10^{-14}	**1.08**	4.27×10^{-15}	5.52×10^{-15}	**0.77**	13.86	9.95	**1.39**
CuCSOO	$8.46\times10^{+14}$	5.06×10^{-14}	5.66×10^{-14}	**0.89**	2.32×10^{-15}	3.13×10^{-15}	**0.74**	21.81	18.09	**1.21**
CuOSSC	$1.83\times10^{+13}$	5.97×10^{-14}	5.58×10^{-14}	**1.07**	2.67×10^{-15}	2.87×10^{-15}	**0.93**	22.36	19.45	**1.15**
CuCSSO	$9.00\times10^{+14}$	5.99×10^{-14}	5.76×10^{-14}	**1.04**	2.03×10^{-15}	2.44×10^{-15}	**0.83**	29.51	23.62	**1.25**
CuCSSC	$2.46\times10^{+16}$	5.20×10^{-14}	5.80×10^{-14}	**0.90**	1.71×10^{-15}	2.99×10^{-15}	**0.57**	30.41	19.37	**1.57**
AVG				**1.00±0.09**			**0.79±0.17**			**1.32±0.27**