Radiation Protection calculations

In this lecture

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
  - General concepts
  - Prompt radiation
  - Decay radiation
- **Activation**
  - Radiological characterization

Not in this lecture
(but in the FLUKA Advanced & Topical RP Courses)

- Advanced transport thresholds for RP calculations
- More on activation
  - Applications of radiological characterization: clearance, transport, emission/immission limits
  - Activation of liquids or gases in circuits
  - Fluence spectra-based methods
- Advanced scoring options in FLUKA
  - USRBIN generalized particles ACTOMASS and ACTIVITY
  - Accessing region-based full inventory information
  - User routines for advanced scoring

External Exposure – General concepts

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

- 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

- RP quantities (ambient dose equivalent or effective dose [Sv = J/kg]) are **not physical quantities** directly simulated
  - The (absorbed) dose (energy deposited per unit mass [Gy = J/kg]) is a physical quantity!
  - The fluence is a physical quantity!

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
  - From fluence [cm/primary/cm^3=1/primary/cm2], a dose-like quantity [Sv/primary] is obtained via a fluence-to-dose conversion coefficients [pSv cm^2]
  - From radiation fields to FLUKA generalized particles
  - **Several fluence-to-dose conversion coefficients are available in FLUKA**

Fluence-to-dose conversion coefficients for RP quantities

- **Ambient dose equivalent H*(10)**
  - Operational quantity for **area monitoring** (10mm depth in ICRU sphere)
  - Set of coefficients: "**`AMB74`**"
    - **Default choice for** dose equivalent calculation when selecting **DOSE-EQ**
    - Based on ICRP74 recommendations and Pelliccioni data

- **Effective dose (E)**
  - Based on Monte Carlo simulations of human phantoms in certain radiation fields
    - Several sets available, depending on different recommendations and weighting factors (e.g., ICRP74, ICRP116, ICRP60, and Pelliccioni)
  - **Recommended sets: ICRP 116** (ED* in **`AUXSCORE`** card, see later for **`AUXSCORE`** info):
    - Different irradiation geometries (see picture on the next slide and the FLUKA manual)
    - Defined for protons, neutrons, charged pions, muons, photons, electrons, alphas (AP, PA,ISO); other particles are approximated by these; zero coefficient is applied to all heavy ions

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 – ICRP 116

- ICRP 116 irradiation geometries:
  - Anterior-Posterior (**AP**), Posterior-Anterior (**PA**)
  - Left lateral (**LLAT**), Right lateral (**RLAT**)
  - Rotational (**ROT**), Isotropic (**ISO**)
  - Working Out Radiation Shielding Thicknesses (**WORST**):
    - WORST is the (actual) worst of all irradiation geometries
    - Recommended for shielding design

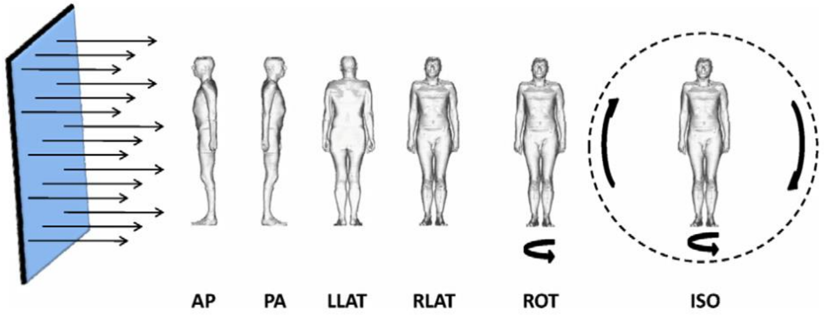
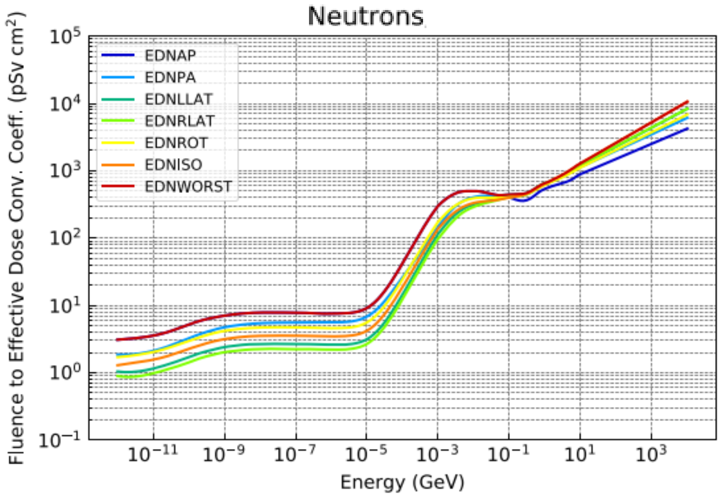
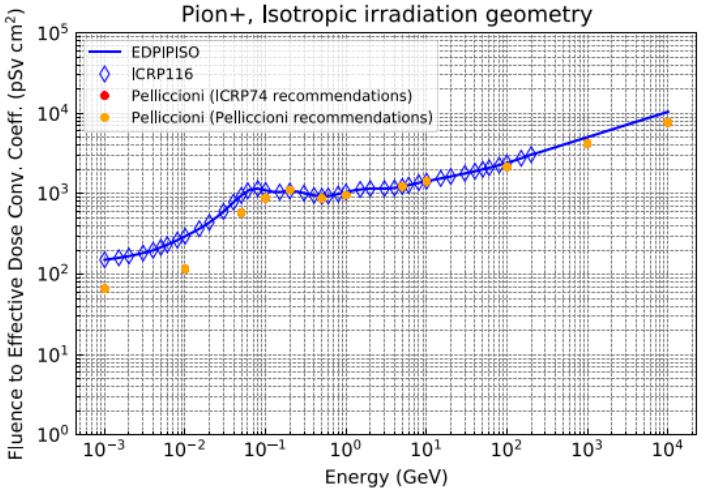


Fig. 3.2. Schematic representation of the idealised geometries considered. AP, antero-posterior; PA, postero-anterior; LLAT, left lateral; RLAT, right lateral; ROT, rotational; ISO, isotropic.

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

- How fluence-to-dose conversion coefficients look like:





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** operational quantities from International Commission on Radiation Units and Measurements (ICRU) - **ICRU 95**;
  - Ambient dose
  - Personal dose
    - 12 different conversion coefficients, depending on the irradiation geometry
  - Directional and personal absorbed dose in the lens of the eyes
    - 8 different conversion coefficients
  - Directional and Personal absorbed dose in the local skin
    - 6 different conversion coefficients
- More info in the FLUKA manual

External Exposure Scoring

- DOSE-EQ is a **track-length based** scoring
- Scoring options:
  - USRBIN **Mesh-based (cartesian or cylindrical)**:
    - Volume of scoring bin in USRBIN mesh is known to code: **volume normalization** is **automatically applied**
    - FLUKA results units for prompt radiation: **pSv / primary particle**
  - USRBIN **Region-based**:
    - Volume of scoring region is not known to code: **volume normalization** is **NOT applied**
    - FLUKA results units for prompt radiation: **pSv * (region volume) / primary particle**
      - 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** of dimensions **≥ 10cm** are typically used

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

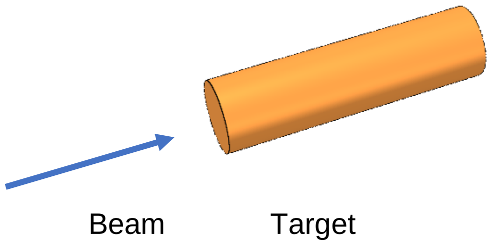
Note:
- Card **AUXSCORE** can be used to filter particles with all types of scoring
- Not only for RP purposes

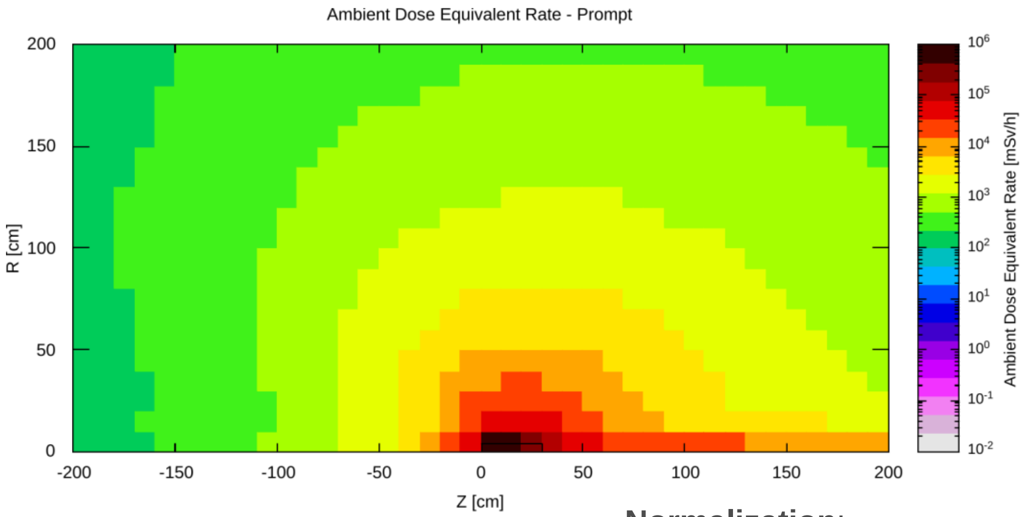
Note: This card can be used for prompt and residual scorings.

External Exposure – Prompt radiation

External Exposure - Prompt radiation

- Scoring prompt radiation
  - Common application: **prompt H*(10) rate maps**
    - USRBIN with DOSE-EQ generalized particle [pSv/primary]
    - Default fluence-to-dose conversion coefficient: **`AMB74`**
  - Other sets: see AUXSCORE (next slide)
- Example (RP calculations exercise)
  - Annular beam, protons at 3.5 GeV kinetic energy
  - Hitting a copper target
    - Radius 4 cm, thickness 30 cm
  - Cylindrical symmetry
  - Scoring DOSE-EQ
  - Normalization: beam intensity is required






```
Prompt AMB rate with R-Phi-Z binning: 10 cm binning
USRBIN                                  Unit: 21 BIN ▾     Name: PrDR-rz
    Type: R-Φ-Z ▾      Rmin: 0.         Rmax: 200.           NR: =200/10
    Part: DOSE-EQ ▾       X: 0.            Y: 0.             NΦ: 1.
                       Zmin: -200.      Zmax: 200.           NZ: =400/10
```

Normalization:
1e-9 * 3600 * 1e+10

pSv → mSv

1/primary → 1/s

1/s → 1/h

External Exposure - Decay radiation

External Exposure - Residual radiation

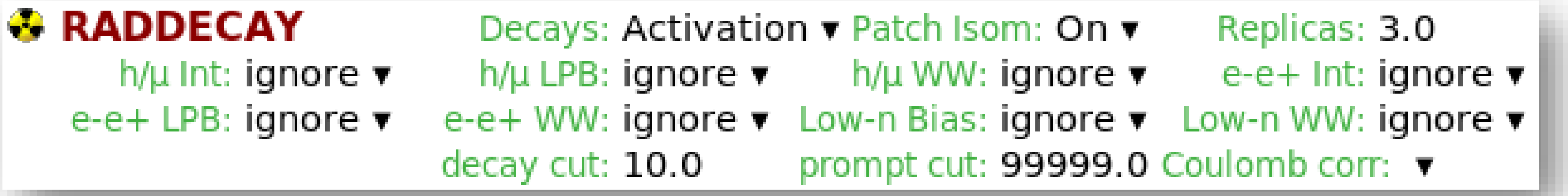
- **The generation and transport of decay radiation** (including α, β, γ, X-rays, and conversion electrons emissions) is possible during the same simulation which produces the radionuclides (**one-step method**)

- 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

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



Decays — **Activation study mode**

radioactive decays activated for requested cooling times

"activation study 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

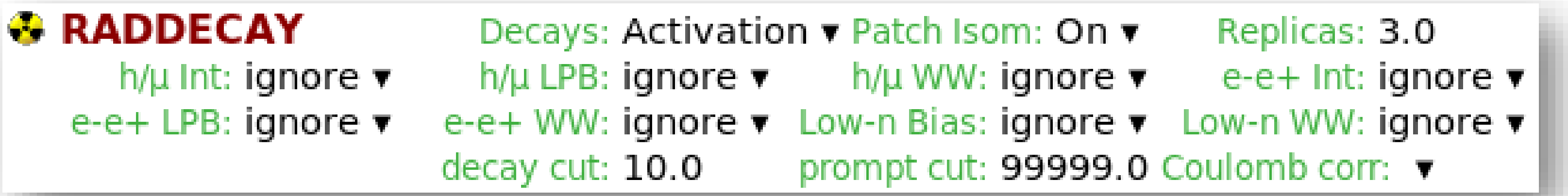
each radioactive nucleus is treated like all other unstable particles (random decay time, daughters and radiation), all secondary particles/nuclei carry time stamp ("age")
Necessary to simulate radioactive sources

Patch Isom — On — **isomer "production" activated:** present model roughly estimate the equal sharing among states

Replicas — # — **number of "replicas" of the decay of each individual nucleus**

Input option: RADDECAY [2/2]

Requests the calculation of radioactive decays



h/µ Int .. Low-n WW — **switch for applying various biasing features only to prompt radiation or only to particles from radioactive decays**

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)

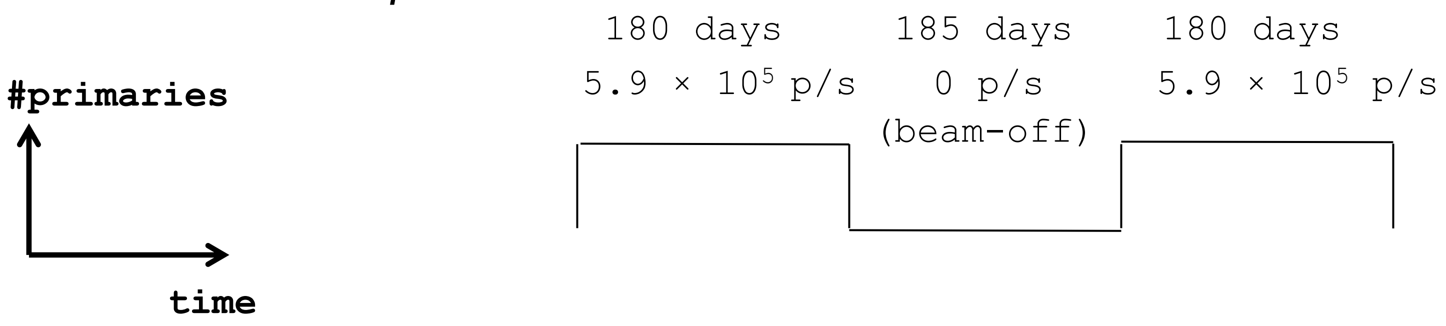
IRRPROFI	Δt: =180* day	p/s: 5.9e5
	Δt: = 185 * 86400	p/s: 0
	Δt: =1.553e7	p/s: 5.9e5

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:



Input option: DCYTIMES

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

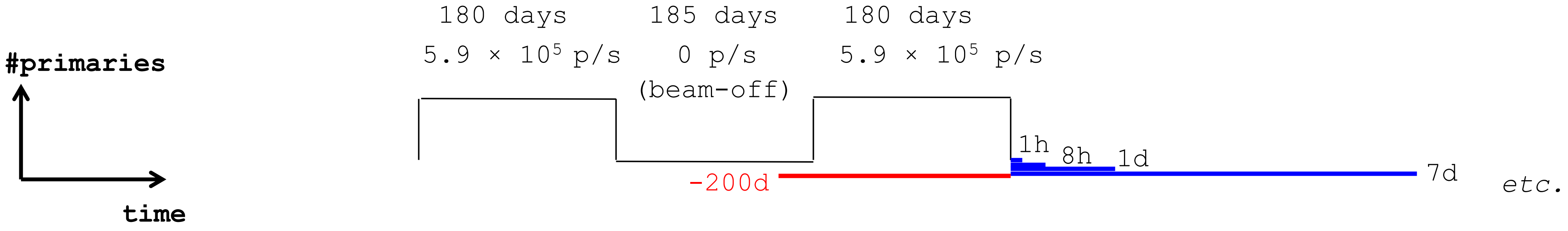
	1hour	8hours	1day	7days	1month	4months

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.

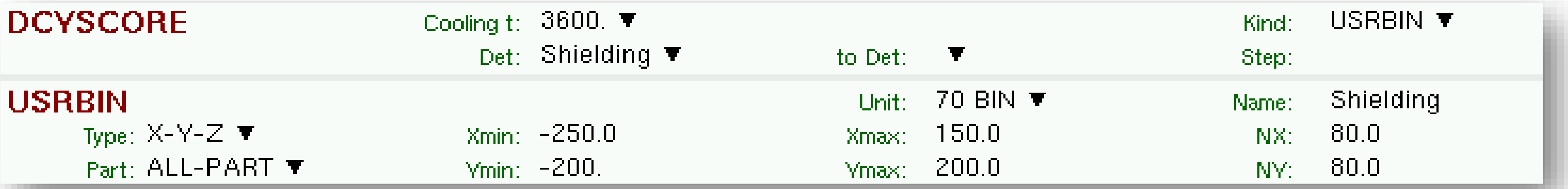
Each cooling time is assigned an index, following the order in which it has been input.
This index can be used in option **DCYSCORE** to assign that cooling time to one or more scoring detectors.
A negative decay time is admitted: scoring is performed at the chosen time "during irradiation"

Example:



Input option: DCYSCORE [1/2]

- associates scoring detectors (radio-nuclides, fluence, dose) with different cooling times (and the irradiation profile)



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:

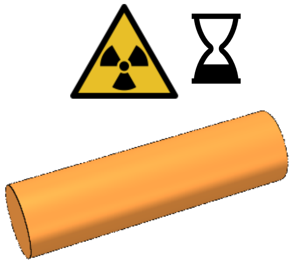
All quantities are expressed per unit time when associated to a cool-down time

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

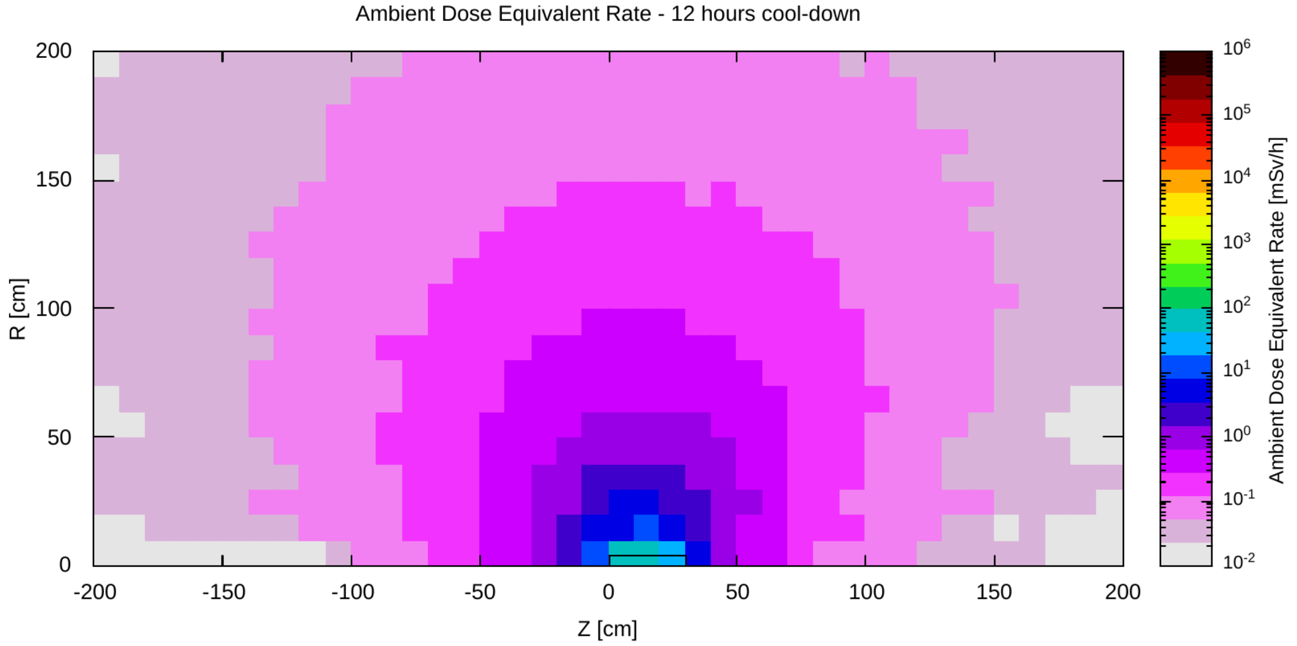
In the semi-analogue decay mode, estimators can include the decay contribution (on top of the prompt one) if associated to **DCYSCORE** with a cooling time index -1.0

External Exposure – Residual radiation

- Residual H*(10) dose rate in one-step simulation
- Example (RP calculations exercise):
  - Irradiation profile: 180 days of irradiation at 1e+10 protons/s
  - Cool-down time: 12 hours
  - USRBIN map normalization



Target



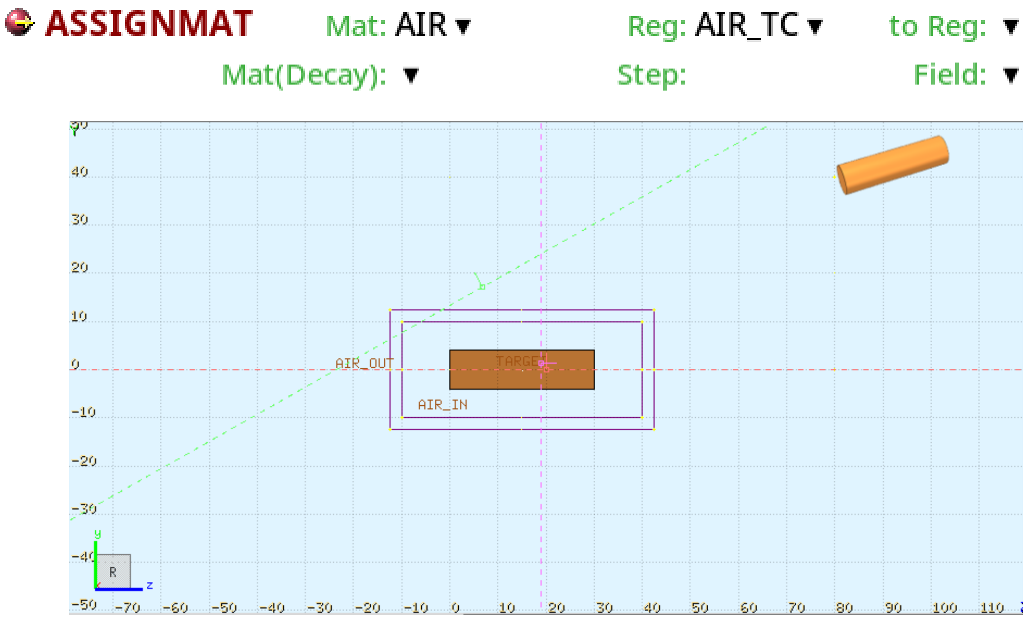
Normalization:
1e-9 * 3600

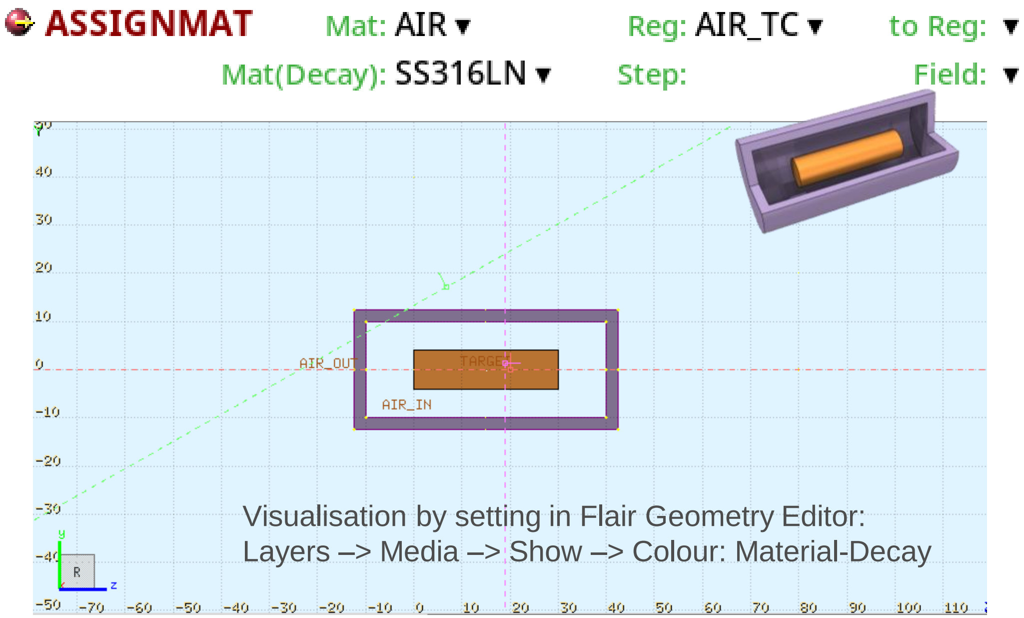
pSv → mSv

1/s → 1/h

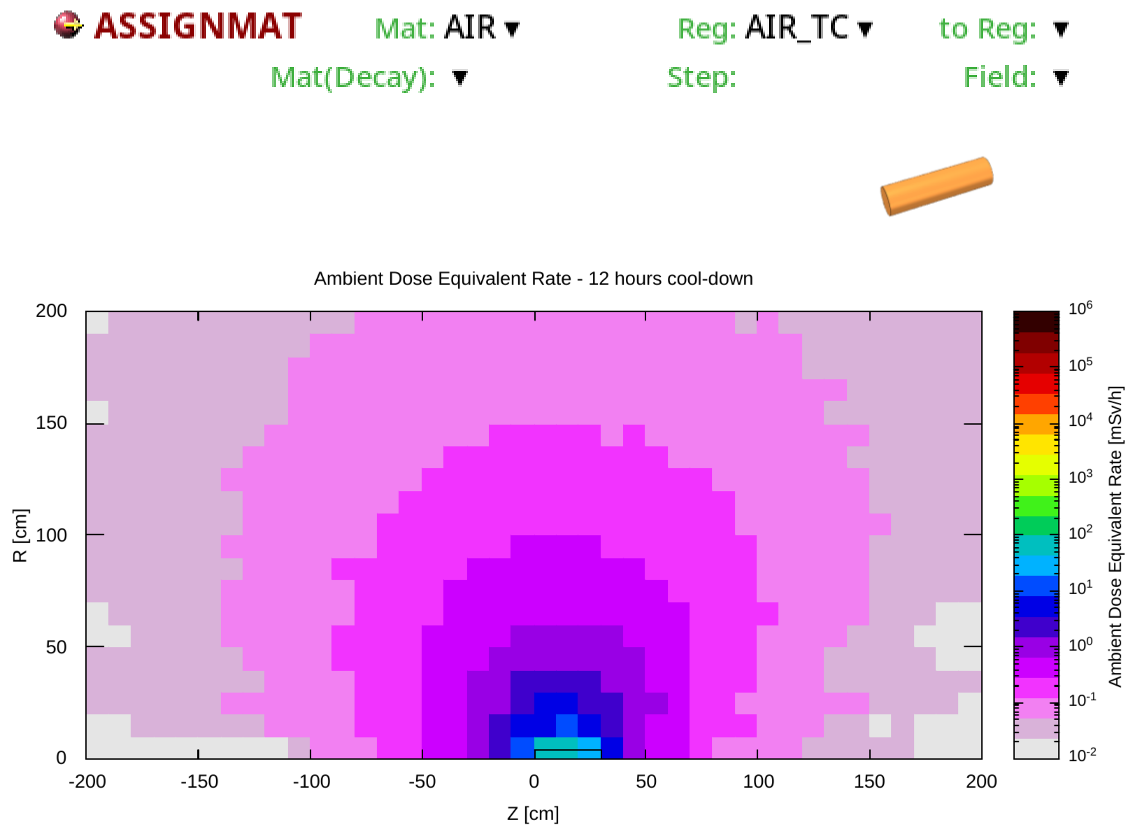
Geometry modifications

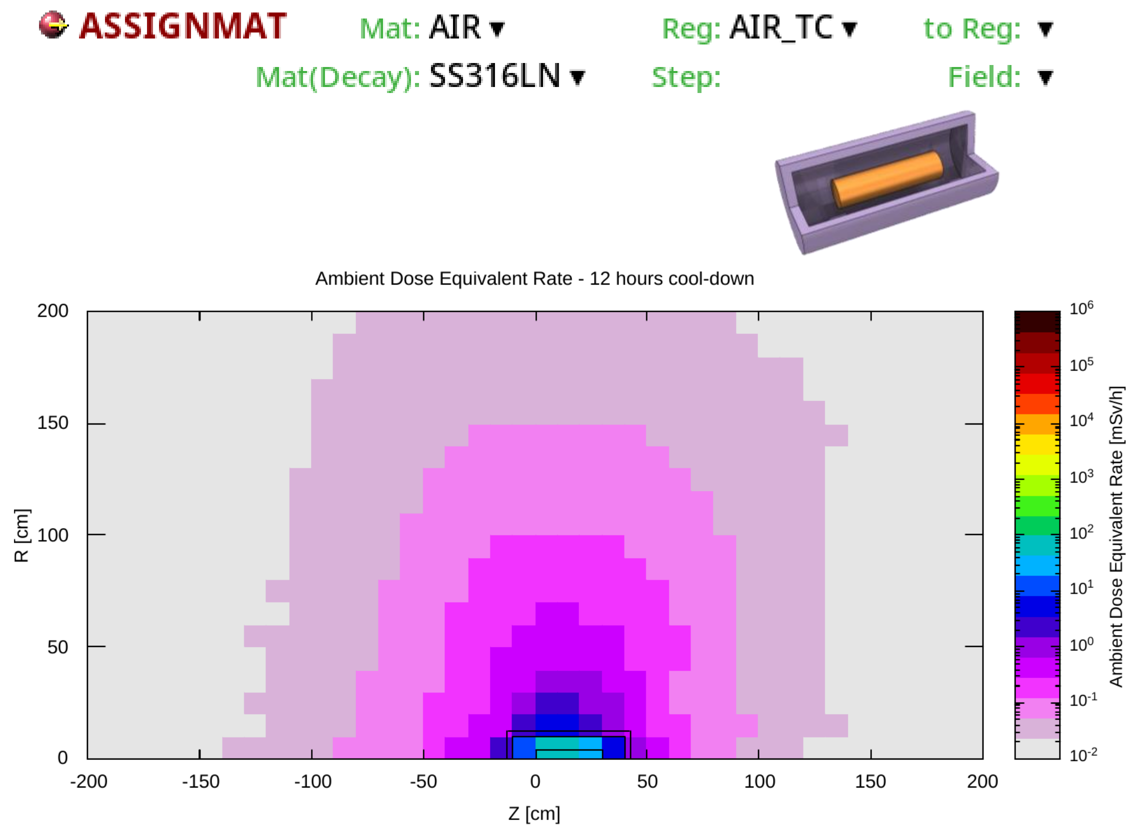
- Exploiting ASSIGNMAT card for describing simple changes of geometry configuration in the simulation
- Examples: target irradiated in a facility and
  - *Addition* of a container for simulating a simple transport scenario (see example below)
  - *Removal* of the surrounding structures and shielding 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.





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.

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, …
- Basic **Scoring options** in FLUKA
  - RESNUCLE - **Region based**
    - Gives access to full inventory information (radionuclide specific incl. isomeric states)
  - Other options: FLUKA Advanced course

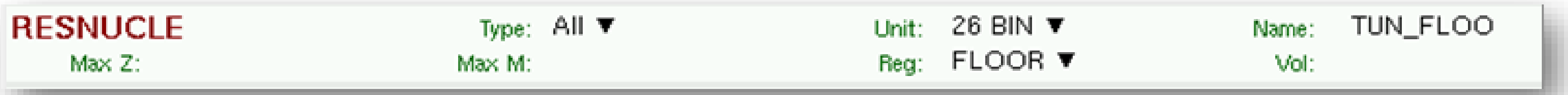
Scoring: RESNUCLE [0/3]

- 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
- All residual nuclei are scored when they have been fully de-excited down to their ground or isomeric state.
- Units:
  - If no normalization is provided, results are expressed in **[#nuclei/primary]**
  - If mass of the region is provided in the card: **[#nuclei/g/primary]**

- **Radioactive decay** of residual nuclei over time can be simulated:
  - in combination with RADDECAY, DCYSCORE, DCYTIMES and IRRPROFIle
  - results are expressed in [Bq] at the given cool-down time (DCYSCORE)

Scoring: RESNUCLE [1/3]

Scoring of residual nuclei or activity on a region basis



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)

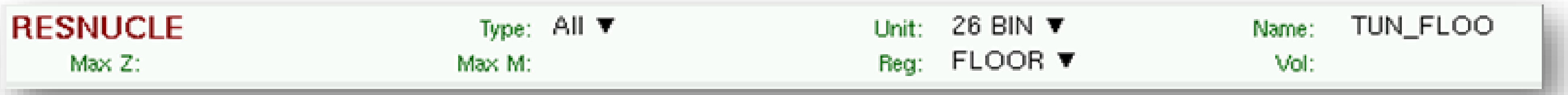
Unit — **Logical output unit** (Default = 11.0)

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 [2/3]

Scoring of residual nuclei or activity on a region basis



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:

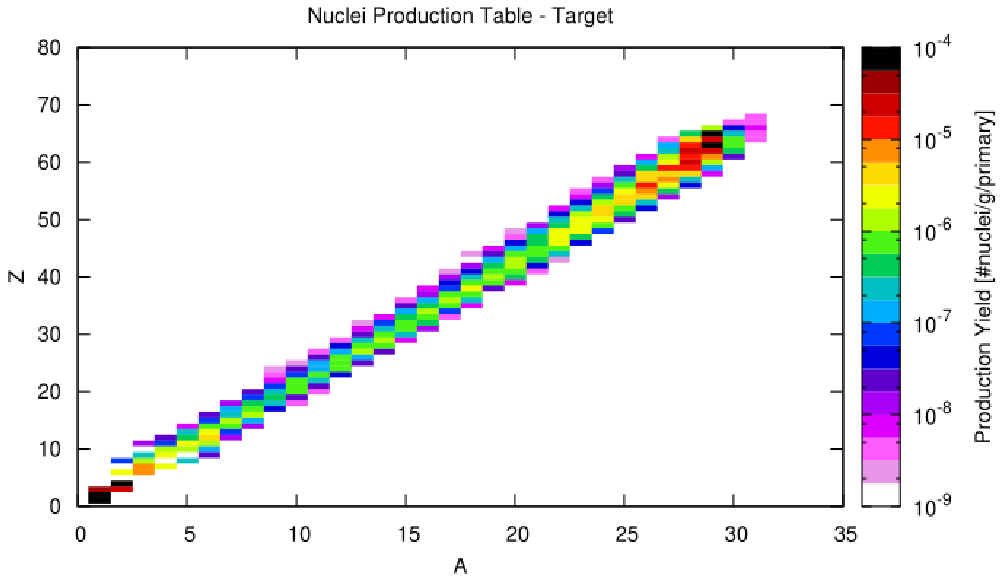
1. In the case of heavy ion projectiles, the default **Max M**, based on the region material, is not necessarily sufficient to score all the residual nuclei, which could include possible ion fragments
2. Residual nuclei from low-energy neutron interactions are only scored if that information is available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

Input option for Activation: RESNUCLE[3/3]

Output example (…tab.lis format)

```
# Detector n:      1
ProdTarg
# A_min-A_max     1    78
   78   0.000        0.000
...
   70   0.000        0.000
   69   0.000        0.000
   68  5.2866E-09    58.88
   67  8.4585E-09    35.36
   66  1.1567E-06    3.919
   65  9.0705E-05   0.2184
   64  2.4312E-05   0.6704
...
 # Z_min-Z_max             1           33
   33   0.000        0.000
   32   0.000        0.000
   31  2.1146E-08    26.93
   30  2.0290E-06    2.901
   29  3.7067E-04   0.2059
   28  9.8531E-05   0.3745
   27  3.9925E-05   0.4396
...
# A/Z Isotopes:
   68   23   0.000        0.000
...
   68   30  1.0573E-09   99.00
   68   31  4.2292E-09   75.00
...
   67   30  4.2292E-09   35.36
```

```
   67   31  4.2292E-09   35.36
...
   66   29  1.1070E-06   4.374
   66   30  4.3350E-08   21.22
   66   31  6.3439E-09   39.67
...
   65   28  5.4874E-07   3.121
   65   29  8.9877E-05  0.2307
   65   30  2.7596E-07   6.742
   65   31  3.1719E-09   69.39
...
   64   27  4.2292E-09   52.04
   64   28  4.3730E-06   1.471
   64   29  1.9291E-05  0.8280
   64   30  6.4073E-07   5.916
   64   31  3.1719E-09   69.39
...
   63   27  1.1313E-07   10.85
   63   28  1.0566E-05  0.7723
   63   29  2.2026E-04  0.3408
   63   30  6.8937E-07   3.173
...
# A/Z/m Isomers:
   24   11    1  1.5490E-07   4.344
....
   58   27    1  5.2770E-06  0.6021
   60   25    1  5.2866E-10   99.00
   60   27    1  2.1416E-06   1.697
   62   27    1  2.0723E-07   4.304
```



Input options: PHYSICS and packages

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

Evaporation of heavy fragments

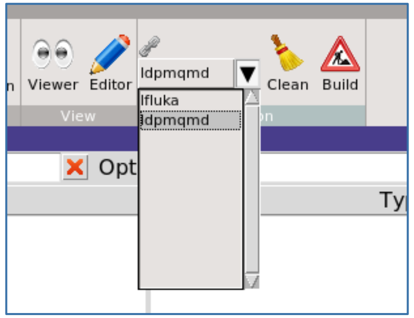
PHYSICS Type: COALESCE ▼ Activate On ▼

Activation of **coalescence** treatment

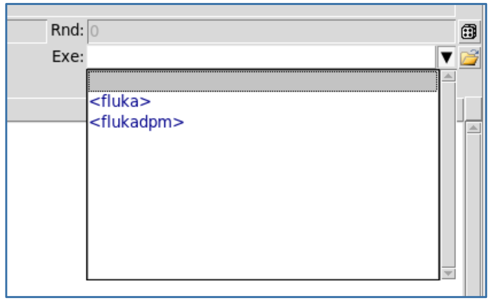
PHYSICS Type: EVAPORAT ▼ Model: New Evap with heavy frag ▼

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

Compile tab



Run tab



Input option: `BEAM/HI-PROPE`

Simulation of a radioactive source

Example:

Radioactive source of ^{60}Co (two main γ-emissions: 1332.5 keV and 1173.2 keV)
cylindrical shape, 2cm diameter, 2mm height along z, centre of cylinder at origin

BEAM		Beam: Momentum ▼	p:	Part: ISOTOPE ▼
	Δp: Flat ▼	Δp:	Δϕ: Flat ▼	Δϕ:
	Shape(X): Rectangular ▼	Δx:	Shape(Y): Rectangular ▼	Δy:
HI-PROPE		Z: 27.	A: 60.	Isom:
BEAMPOS		x:	y:	z:
		cosx:	cosy:	Type: POSITIVE ▼
BEAMPOS		Rin:	Rout: 1.	Type: CYLI-VOL ▼
		Hin:	Hout: 0.2	

Notes:

- Do not forget switching on radioactive decays with the `RADDECAY` card in semi-analogue mode and to associate the scoring detectors with `DCYSCORE` to semi-analogue decay mode!
- Also, a point source is perfectly valid for ISOTOPE beam cards!

Summary

- **FLUKA** features **cover** all the **typical needs** for **RP assessments**
- In this lecture we have covered, at a beginner level:
  - **External exposure**
    - Prompt and residual radiation
  - **Activation**
    - Radiological characterization (region-based)
- All based on **very well benchmarked FLUKA physics models** and **data**
- Non-standard needs correspond to advanced solutions (FLUKA Advanced + Topical RP courses):
  - FLUKA **user routines**
  - Weighting of fluences or radionuclide-specific activities
  - Clearance, transport, radioactive waste pathways

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

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

Summary of main input cards

DCYSCORE

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

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

FLUKA

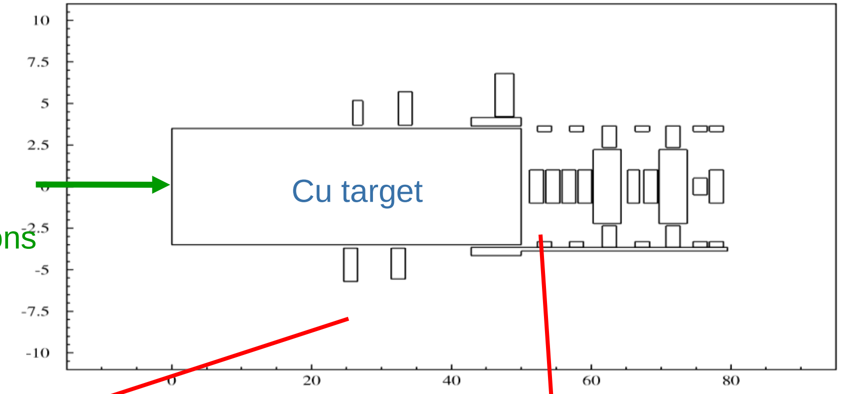
Benchmarks - Selection

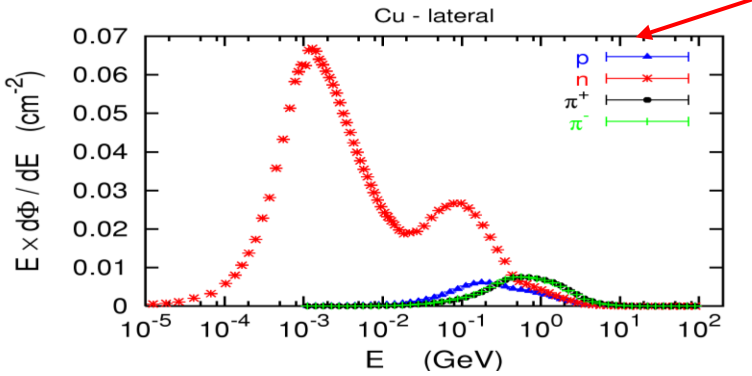
CERF Benchmark experiment

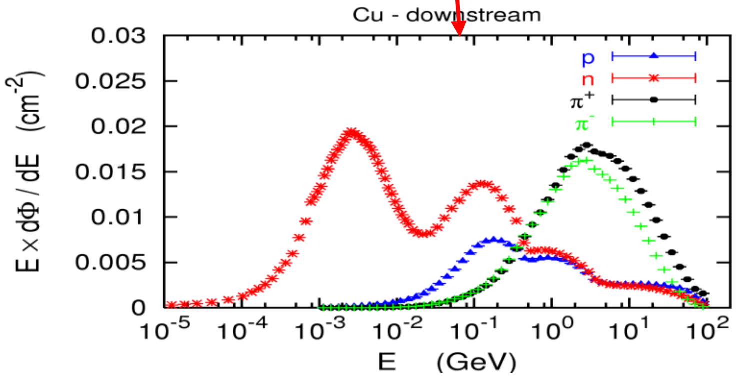
Irradiation of samples of different materials to the stray radiation field created by the interaction of a 120 GeV positively charged hadron beam in a copper target

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

120GeV
pos. hadrons







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 ± Error < 1.2

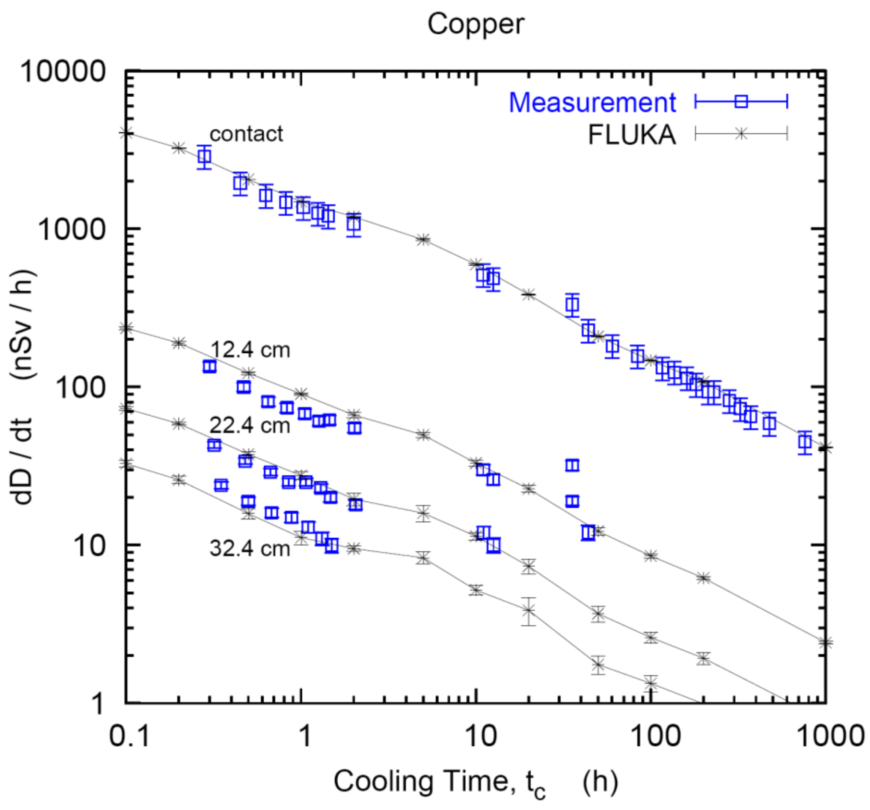
Exp/MDA < 1

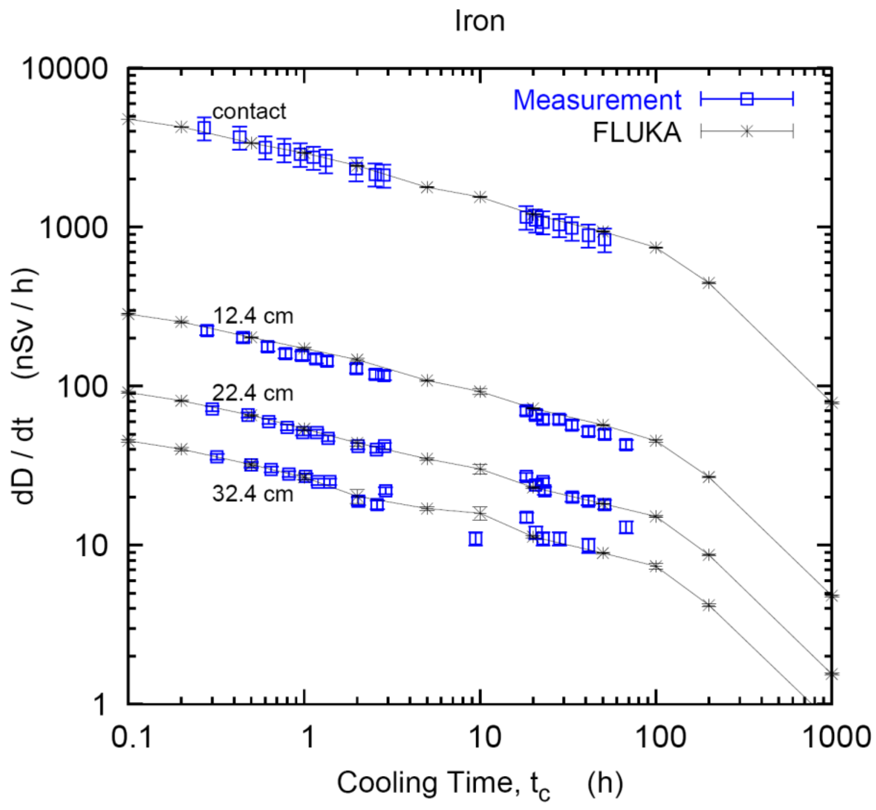
R + Error < 0.8 or
R – Error > 1.2

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





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

CERF Benchmark experiment - *Results*

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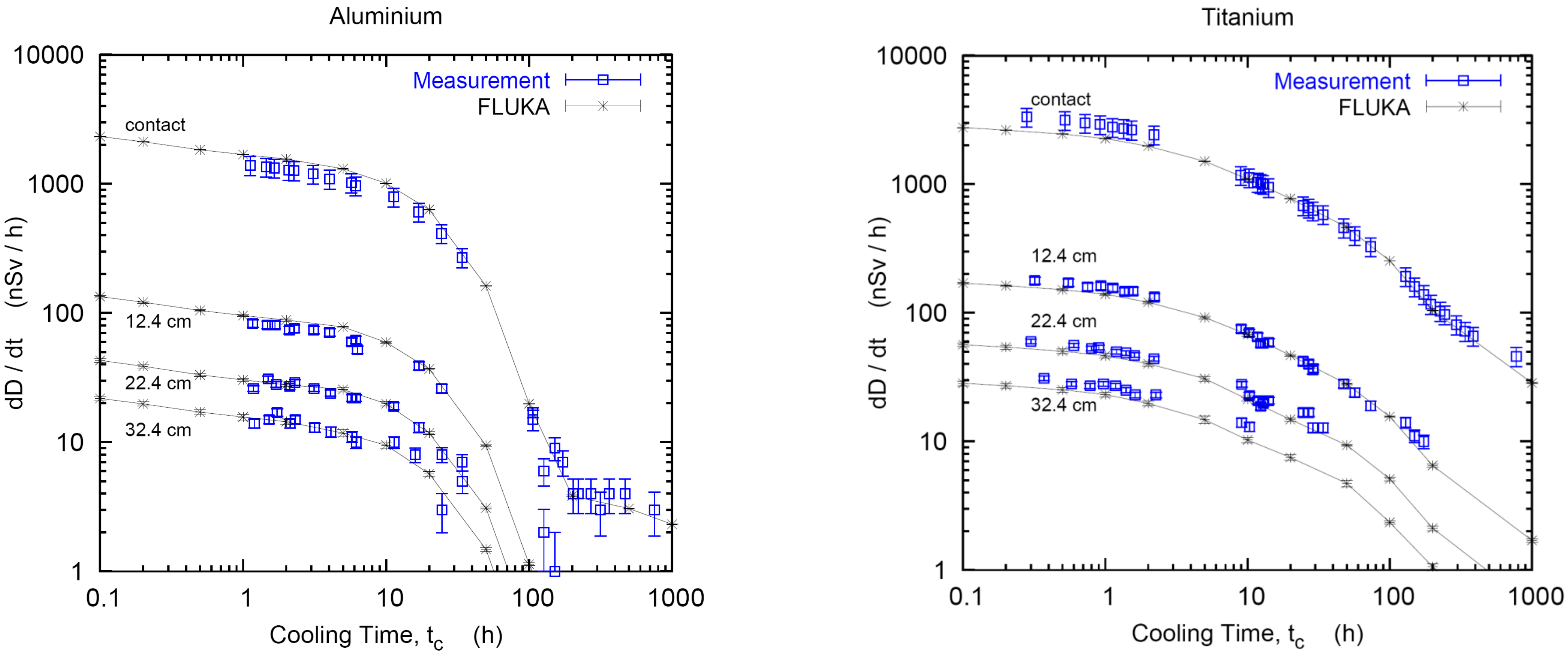

<u>Reference:</u> M. Brugger, S. Roesler *et al.*, Radiat. Prot. Dosim. 116 (2005) 12-15

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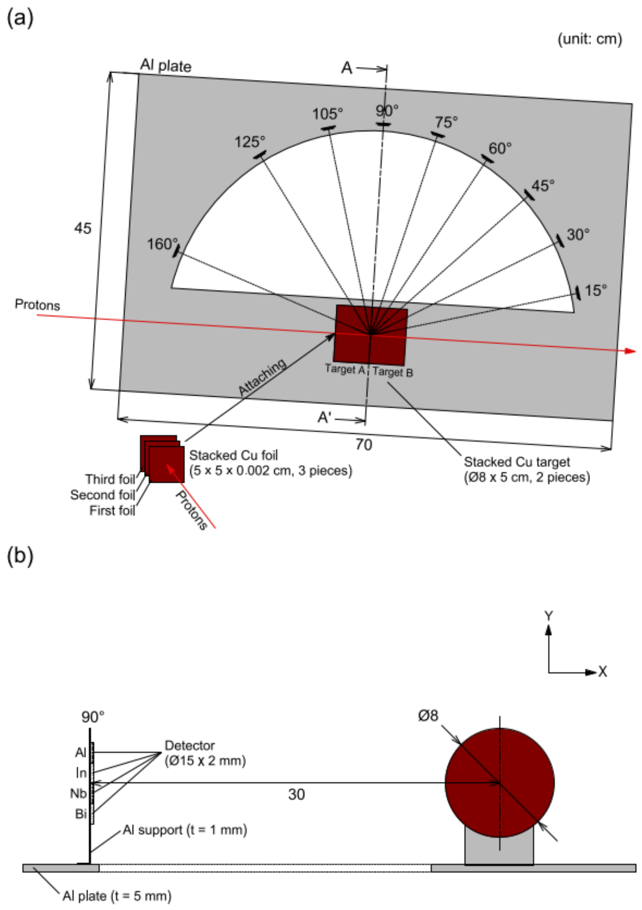
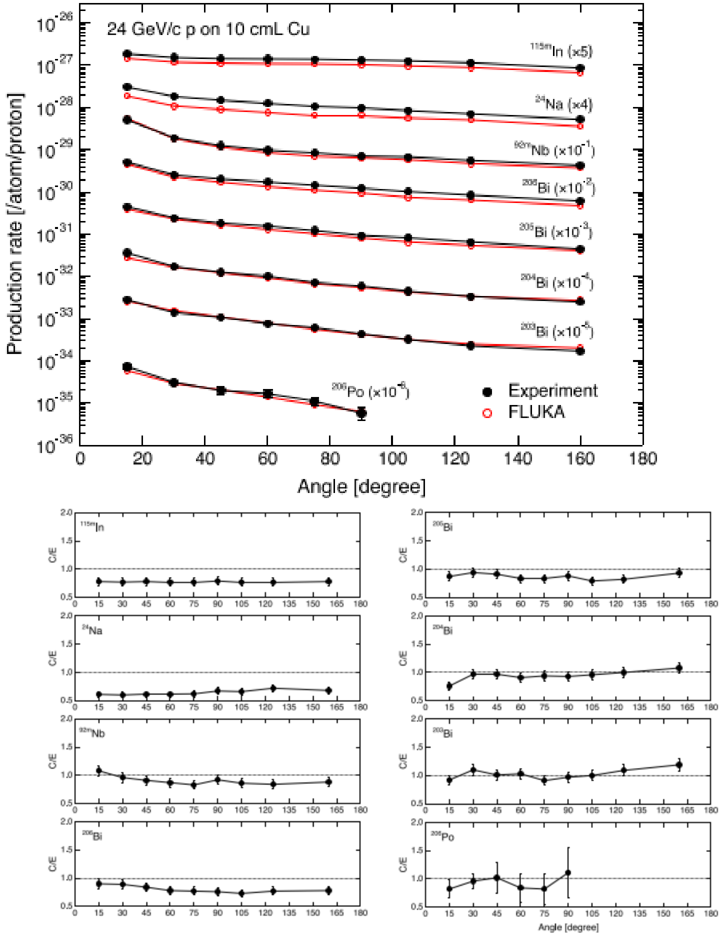
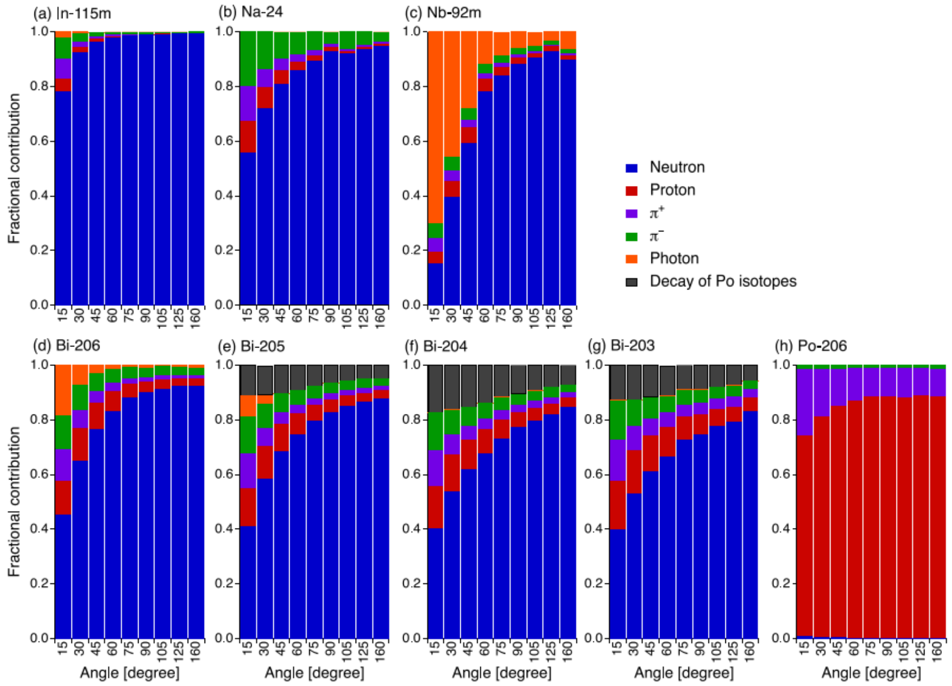
https://doi.org/10.1016/j.nima.2020.164977

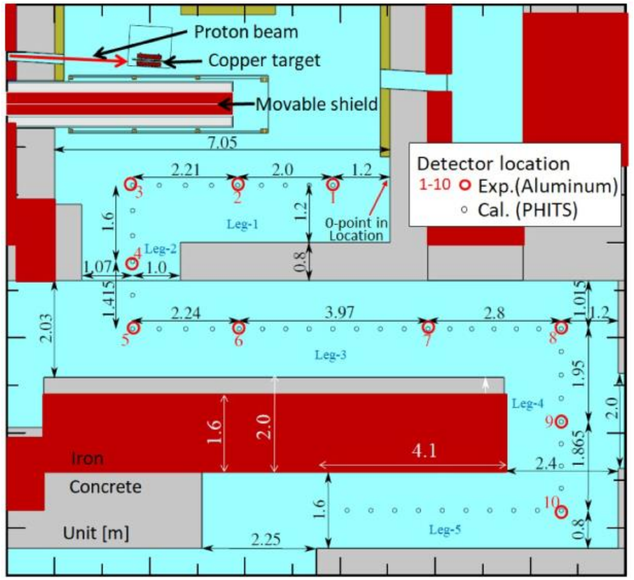
Measurements of secondary-particle emissions from copper target bombarded with 24-GeV/c protons

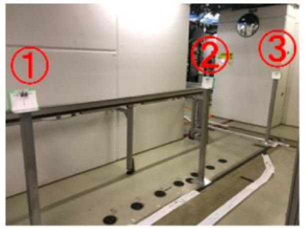


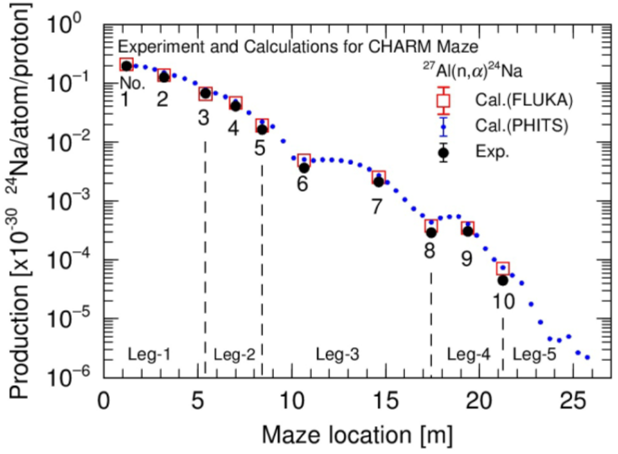


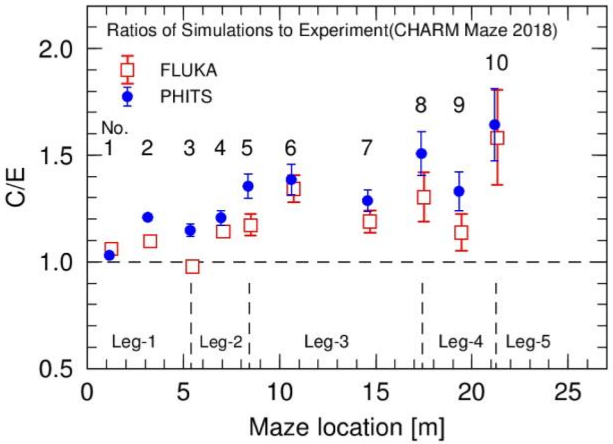


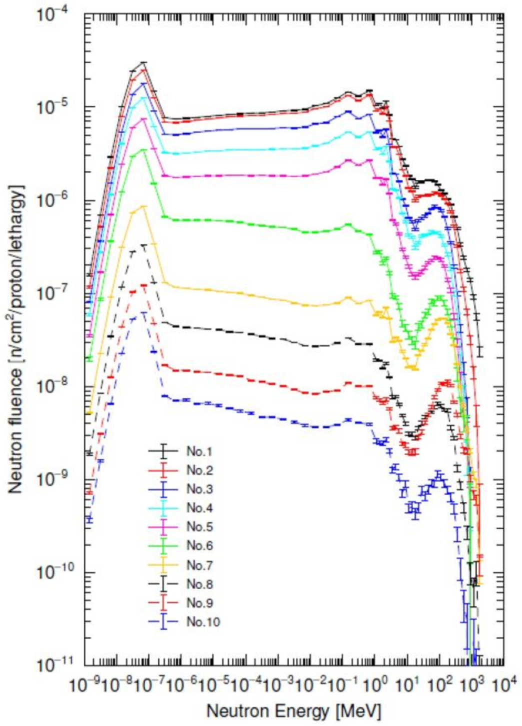
Measurements and Monte Carlo simulations of high-energy neutron streaming through the access maze using activation detectors at 24 GeV/c proton beam facility of CERN/CHARM

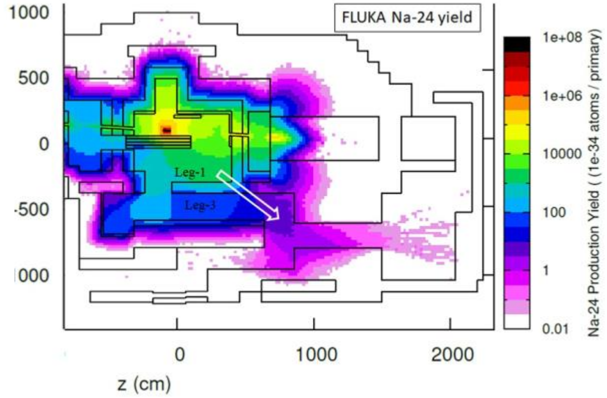


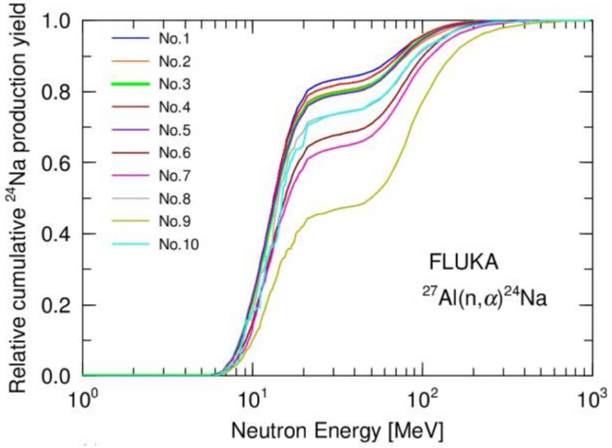












T. Oyama et al. - Published in: Nucl.Instrum.Meth.B 434 (2018) 29-36
https://doi.org/10.1016/j.nimb.2018.08.016

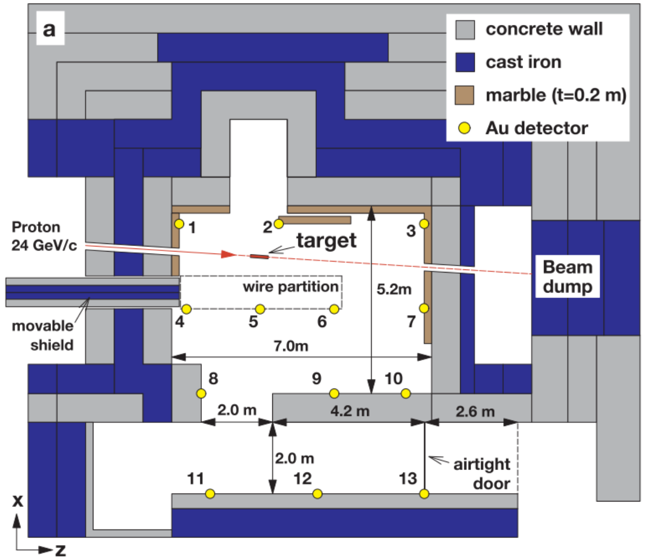
Measurement and calculation of thermal neutrons induced by the 24 GeV/c/c proton bombardment of a thick copper target

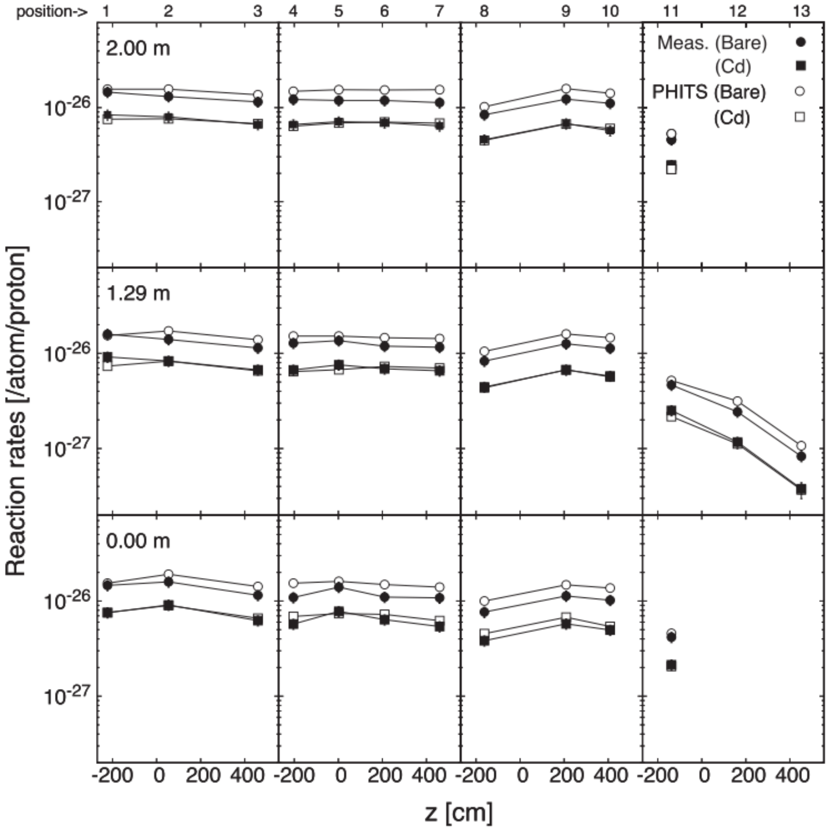
PHITS – JENDL-4.0
FLUKA – GW
MARS – MCNP4C-ENDF/B-VI

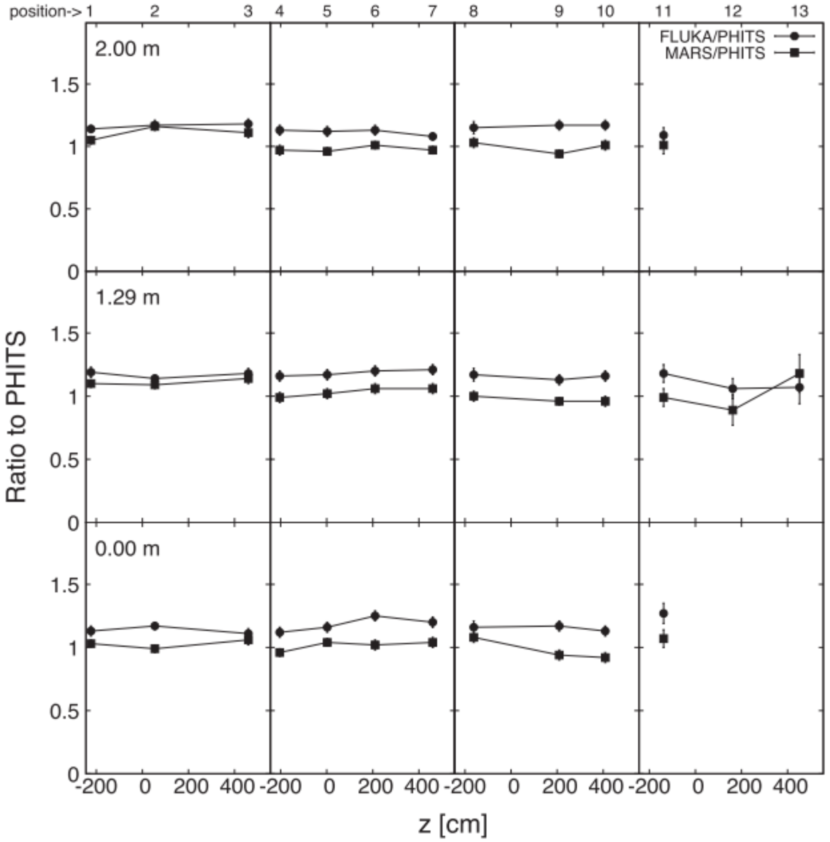
Low energy neutrons for Ar 41 predictions

Gold foils at 3 heights

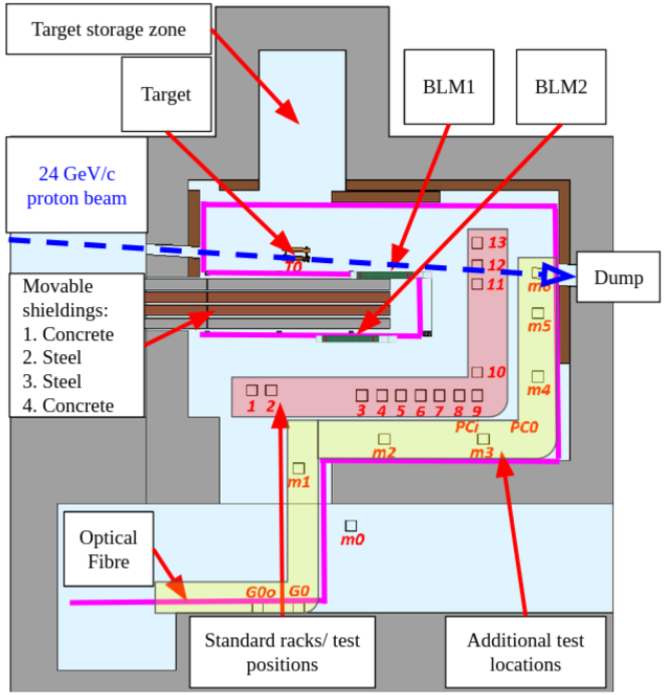
- Bare
- Cd coated

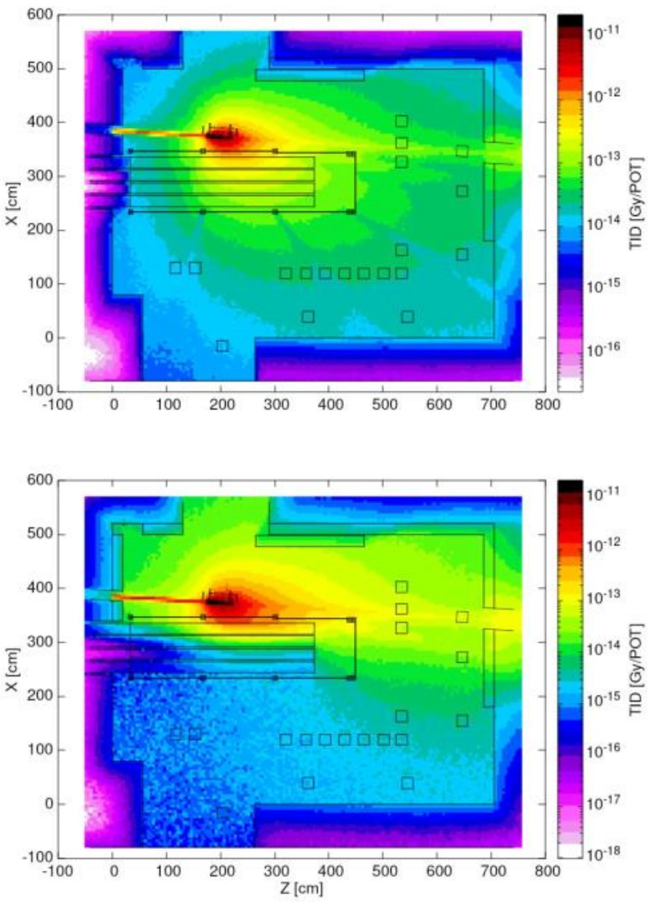


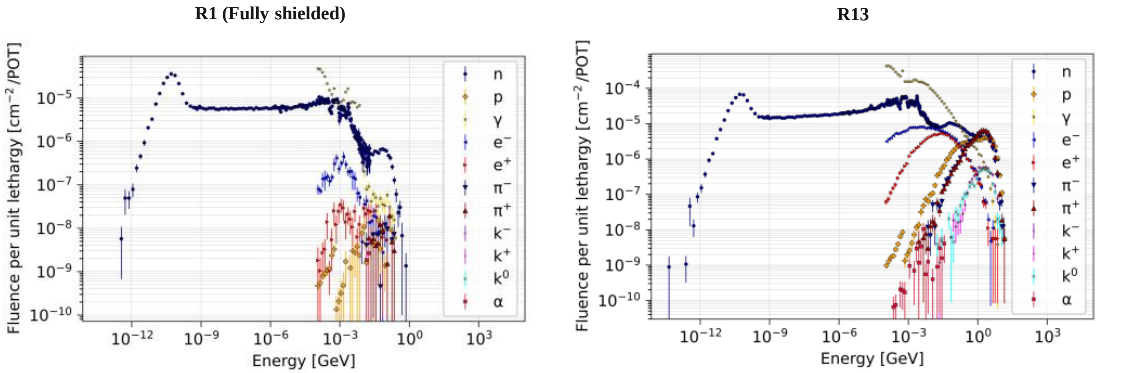




Benchmark Between Measured and Simulated Radiation Level Data at the Mixed-Field CHARM Facility at CERN







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**