Radioactivity

FLUKA Advanced Course

Residual radiation: evaluation and transport

The generation and transport of decay radiation (γ, β-, β+, X-rays, Conversion Electrons emissions and now also α) is possible during the same simulation which produces the radio-nuclides (one-step method).

For that, a dedicated database of decay emissions is used, based mostly on information obtained from **NNDC**, sometimes supplemented with other data and checked for consistency.

Two modes:

(1) semi-analytical mode ("Activation study case")

Monte Carlo to produce the residual nuclei
\+ Bateman Equations to evaluate decays and further residual nuclei from the decay chain

(2) semi-analog mode (pure Monte Carlo method)

Residual radiation: evaluation and transport

(1) "Activation study case"

For an arbitrary irradiation pattern, the time evolution of the system (build-up and decay during the irradiation and cooling) is obtained runtime *for fixed cooling times* via the exact analytical solution of the **Bateman equations**:

$$\frac{dN_i}{dt} = -\sum_{j \neq i} \left[\lambda^d_{ji} + \bar{\sigma}_{ji} \bar{\varphi} \right] N_i + \sum_{j \neq i} \left[\lambda^d_{ij} + \bar{\sigma}_{ij} \bar{\varphi} \right] N_j$$

where for each radionuclide in the material:

λ^d_{ji} $\rightarrow$ decay probability of the residual nucleus i in the residual nucleus j

σ_{ji} $\rightarrow$ cross section for transmutation of the residual nucleus i in the residual nucleus j

$$\bar{\varphi} = \int \varphi(E) dE \qquad \bar{\sigma}_{ji} = \frac{1}{\bar{\varphi}} \int \varphi(E) \sigma_{ji}(E) dE$$

In the simplified case of residual nuclei of one type, without other residual nuclei decaying in that species, at the cooling time t_{cool} we find the known formula for the specific activity:

$$a(t_{cool}) = N\sigma\phi(1 - e^{-\lambda t_{irr}})e^{-\lambda t_{cool}}$$

(2) Semi-analogue mode

Each radioactive nucleus is treated like all other unstable particles (pure Monte Carlo method: times are sampled randomly from the correspondent exponential distribution, radiation and daughters also randomly)

- all secondary particles/nuclei carry **time** stamp ("**age**")

This mode is called semi-analogue because the radiation spectra are **inclusive** (no correlation in the emitted radiation! i.e. no correlated gamma cascade). In an event-by-event analysis a full correlation is not guarantee

In **all cases** FLUKA can perform the generation and transport of the decay radiation

As a consequence, in the same run **results for production of residuals, their time evolution and residual doses due to their decays** can be obtained, for an arbitrary number of decay times and for a given irradiation profile.

FLUKA-Implementation – *Main features*

- up to 4 different decay branching for each isotope/isomer
- all gamma lines down to 0.1-0.01% branching, including X-ray lines following conversion electron emissions
- all beta emission spectra down to 0.1-0.01% branching: sampling of the beta+/- spectra includes screening Coulomb corrections
- Auger and conversion electrons
- **Isomers**: production can be activated via what(2) in RADDECAY
  The present models do not distinguish among ground state and isomeric states (it would require spin/parity dependent calculations in evaporation).
  * (new! see Franceco's talk) for isomer production by neutrons below 20 MeV branchings are based on JEFF activation file
  * for all other isomer production a rough estimate, based on equal sharing among states, can be performed
- Different transport thresholds can be set for the prompt and decay radiation parts, as well as some (limited) biasing differentiation (see later)

Input options - *Overview*

Input card: RADDECAY

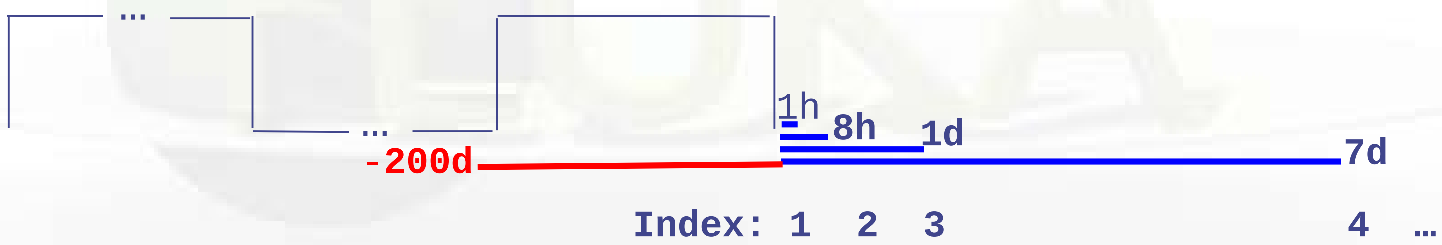
requests simulation of decay of produced radioactive nuclides and allows to modify biasing and transport thresholds (defined with other cards) for the transport of decay radiation

Input card: IRRPROFI

definition of an irradiation profile (irradiation times and intensities)

Input card: DCYTIMES

definition of decay (cooling) times



Input card: DCYSCORE

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

Input card: AUXSCORE

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

allows to filter individually isotopes (ACTIVIY / ACTOMASS and USRBIN)

Particle Types

Name	Number	Units	Description
DOSE	228	GeV/g	Dose (energy deposited per unit mass)
DOSE-EQ	240	pSv	Dose Equivalent (AUXSCORE)
ACTIVITY	234	Bq/cm^3	Activity per unit volume
ACTOMASS	235	Bq/g	Activity per unit mass
SI1MEVNE	236	cm^{-2}	Silicon 1 MeV-neutron equivalent flux
HADGT20M	237	cm^{-2}	Hadrons with energy > 20 MeV

Normalization

All quantities are expressed:

- per primary particle if they are <u>not</u> connected to a specific decay time
- per time unit (per s) if they are related to a specific decay time via DCYSCORE (and they are referred to this time)

Card: RADDECAY [1/2]

```
* 1) request radioactive decays
RADDECAY          1.0        0        3.0          0000099999         0
```

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:	

WHAT(1) **= 1** **radioactive decays activated <u>for requested cooling times</u>**

Decays: Active "activation study case": time evolution calculated analytically for *<u>fixed</u>* (cooling) times. Daughter nuclei as well as associated radiation is considered at these (fixed) times

> 1 **radioactive decays activated <u>in (semi-)analogue mode</u>**

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

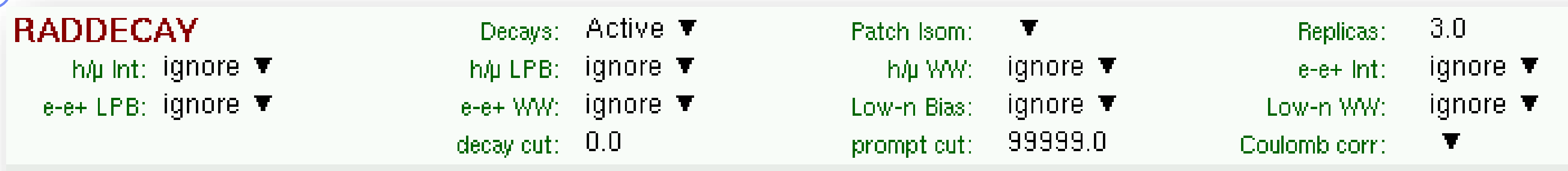
WHAT(2) **> 0** **isomer "production" activated**

Patch Isom: On

WHAT(3) **number of "replicas" of the decay of each individual nucleus**

Replicas: #

Card: RADDECAY [2/2]



WHAT(4) **switch for applying various biasing features only to prompt radiation or only to particles from radioactive decays**

h/μ Int .. Low-n WW — 9 digits, each responsible for a different biasing

Example:

5th digit, e+/e-/gamma leading particle biasing applied
000010000 to prompt radiation only
000020000 to decay radiation only
000030000 to both

Default: 111111111 (or blank as above)

WHAT(5) **multiplication factors to be applied to e+/e-/gamma transport energy cutoffs**

decay cut: #
prompt cut: #

10 digits, first five for decay radiation, second five for prompt radiation (see manual)

Special cases:

0000099999 kill EM cascade for prompt radiation
9999900000 kill EM cascade for residual radiation

Card: IRRPROFI

```
* 2) definition of irradiation pattern
*              180days    part/s    185days              180days    part/s
IRRPROFI     1.5552E7  5.9175E5  1.5984E7        0.0  1.5552E7  5.9175E5
```

```
        180days   part/s   185days        180days   part/s
IRRPROFI
                                   Δt: 1.5552E7              p/s: 5.9175E5
                                   Δt: 1.5984E7              p/s: 0.0
                                   Δt: 1.5552E7              p/s: 5.9175E5
```

WHAT(1,3,5) **irradiation time (second)**

Δt: #

WHAT(2,4,6) **beam intensity (particles per second)**

p/s # Note: zero intensity is accepted and can be used e.g., to define beam-off periods

Note: Several cards can be combined up to a maximum of 2500 irradiation intervals.

Example (see above):

180 days	185 days	180 days
5.9×10^5 p/s	0 p/s (beam-off)	5.9×10^5 p/s

Card: DCYTIMES

```
* 3) definition of cooling times
*              1hour     8hours      1day      7days     1month    4months
DCYTIMES       3600.     28800.    8.64E4    6.048E5    2.592E6  1.0368E7
```

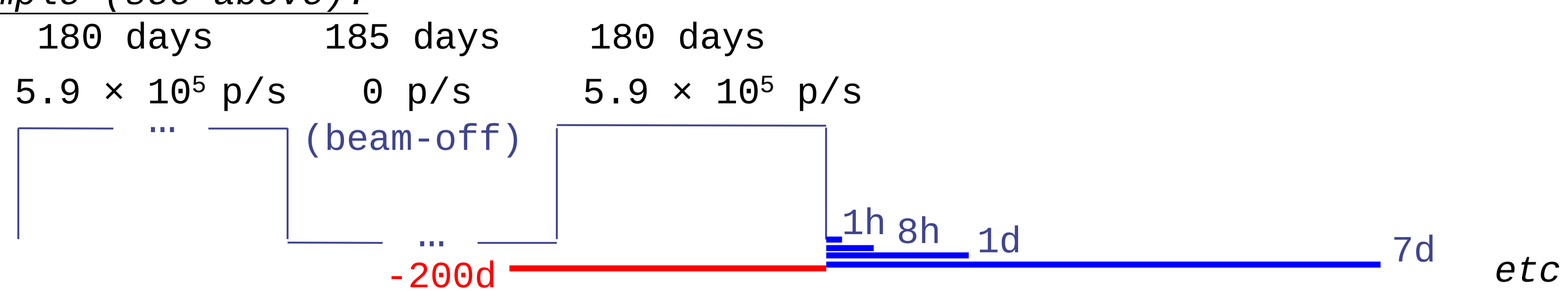
1hour 8hours 1day 7days 1month 4months

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

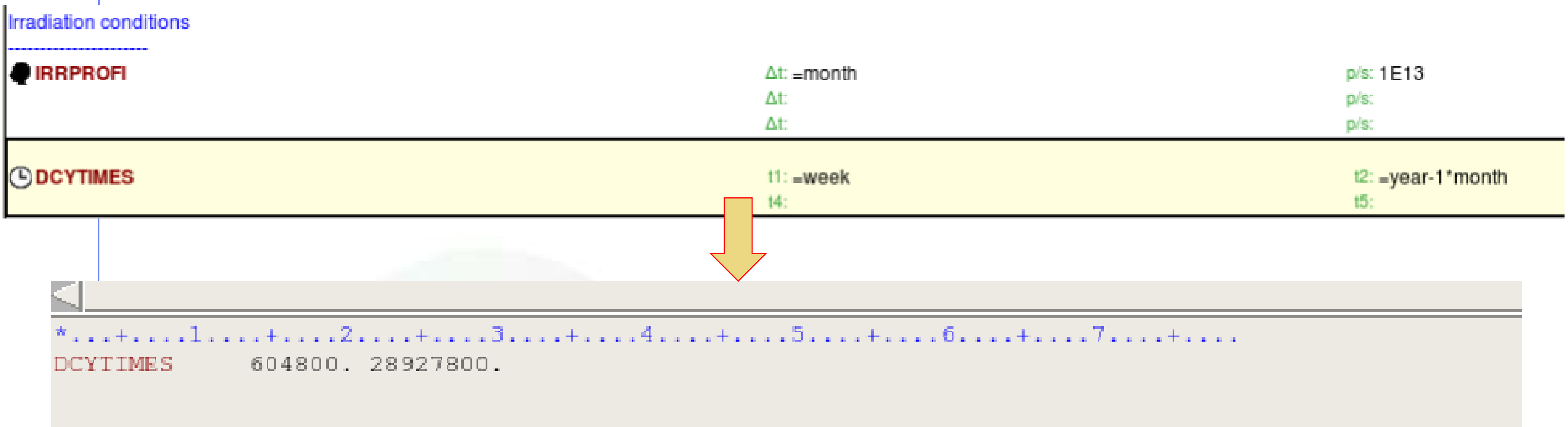
WHAT(1) – WHAT(6) cooling time (in seconds) after the end of the irradiation
t1 .. t6 Note: Several cards can be defined.

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 particular cooling time to one or more scoring detectors. A negative decay time is admitted: scoring is performed at the chosen time "during irradiation"

Example (see above):



FLAIR style : defined variables

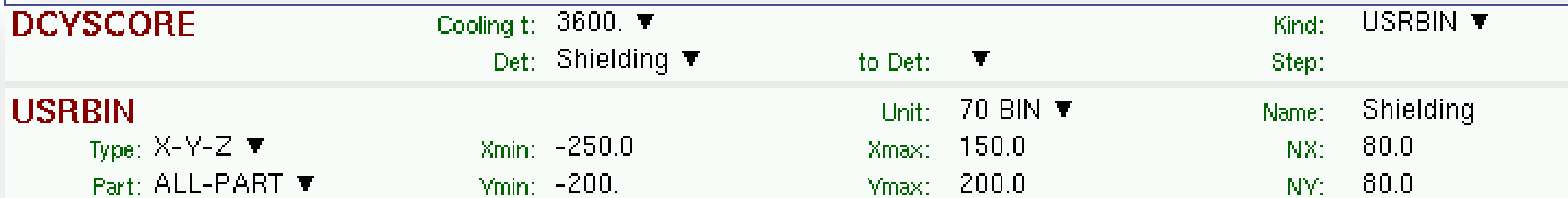


Can be used for IRRPROFI or DCYTIMES
Use of defined variables : s (1 s), min (60 s), hour(3600 s), day (86400 s), week (7*86400 s), month (365.25/12*86400 s), year (365.25*86400 s)

Avoid converting to seconds (risk of errors)
Possibility to use operators (convenient for negative cooling times)
Converted into seconds in the input file

Card: DCYSCORE [1/2]

```
* Associate scoring with different cooling times
DCYSCORE          1.0                      Shielding                     USRBIN
USRBIN           10.0       201.      -70.0      150.0      200.0    5000.0Shielding
USRBIN         -250.0      -200.        0.0       80.0       80.0        1.0&
```



WHAT(1) — **Cooling time index to be associated with the detectors**
Cooling: # — Drop down list of available cooling times

WHAT(4)..WHAT(5) — **Detector index / name of kind (SDUM / Kind)**
Det .. to Det — Drop down list of available detectors of kind (Kind)

WHAT(6) — **step lengths in assigning indices**
Step #

SDUM — **Type of estimator**
Kind — RESNUCLE, USRBIN/EVENTBIN, USRBDX, USRTRACK...

Units: All quantities are expressed per unit time. For example:

RESNUCLE Bq
USRBIN fluence rate / dose rate

Card: DCYSCORE [2/2]

In the *semi-analogue decay mode*, estimators can include the decay contribution (on top of the prompt one) through association by DCYSCORE with a cooling time index $\leq$ -1.0

Card: AUXSCORE

```
* associate scoring with dose equivalent conversion factors
AUXSCORE      USRBIN PHOTON                           Target                   EWT74
```

AUXSCORE	Type: USRBIN ▼	Part: PHOTON ▼	Set: EWT74 ▼
	Det: Target ▼	to Det: ▼	Step:

WHAT(1) Type:		**Type of estimator to associate with** drop down list of estimator types (USRBIN, USRBDX...)
WHAT(2) Part:	#	**particle or isotope to filter scoring** Particle or particle family list. If empty then flair will prompt for Z, A, and State for filtering on specific isotopes
WHAT(4,5) Det .. to Det		**Detector range** Drop down list to select detector range of type WHAT(1)
WHAT(6) Step:	#	**Step in assigning indices of detector range**
SDUM Set:		**Conversion set for dose equivalent (DOSE-EQ) scoring** Drop down list of available dose conversion sets

Since 2016 release possibility to select an individual isotope (ACTIVITY or ACTOMASS with USRBIN)

Available Conversion Coefficients

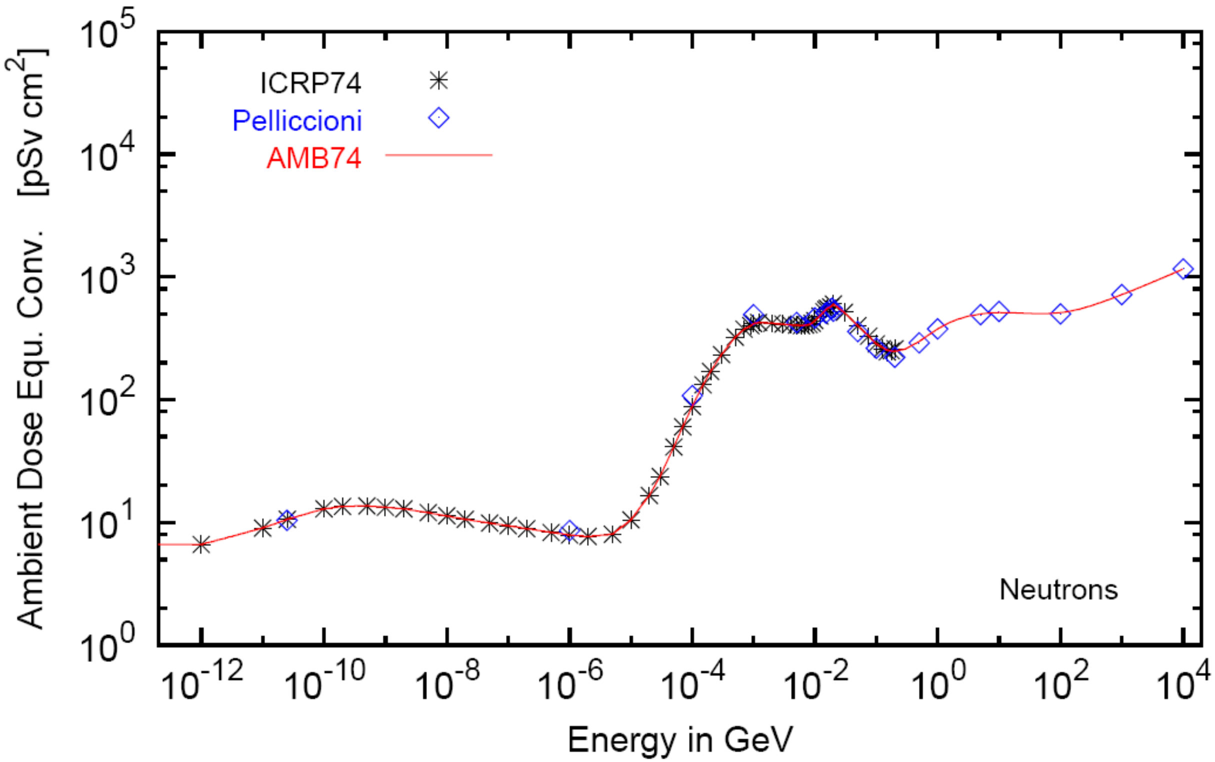
The following dose conversion coefficients sets are available:

1) Effective dose sets from ICRP74 and Pelliccioni data calculated with ICRP radiation weighting factors Wr
   (a) **EAP74** : Anterior-Posterior irradiation
   (b) **ERT74** : Rotational irradiation geometry
   (c) **EWT74** : WORST possible geometry for the irradiation
2) Effective dose sets from ICRP74 and Pelliccioni data calculated with the Pelliccioni radiation weighting factors Wr
   (a) **EAPMP** : Anterior-Posterior irradiation
   (b) **ERTMP** : Rotational irradiation geometry
   (c) **EWTMP** : WORST possible geometry for the irradiation
3) Ambient dose equivalent from ICRP74 and Pelliccioni data
   (a) **AMB74** : **[Default]**
4) Ambient dose equivalent with old "GRS"-conversion factors
   (a) **AMBGS**

(**see backup slides for details**)

Conversion Coefficients

Conversion coefficients from fluence to ambient dose equivalent are based on ICRP74 values and values calculated by M.Pelliccioni. They are implemented for protons, neutrons, charged pions, muons, photons, electrons (conversion coefficients for other particles are approximated by these). AMB74 is the default choice for dose equivalent calculation.

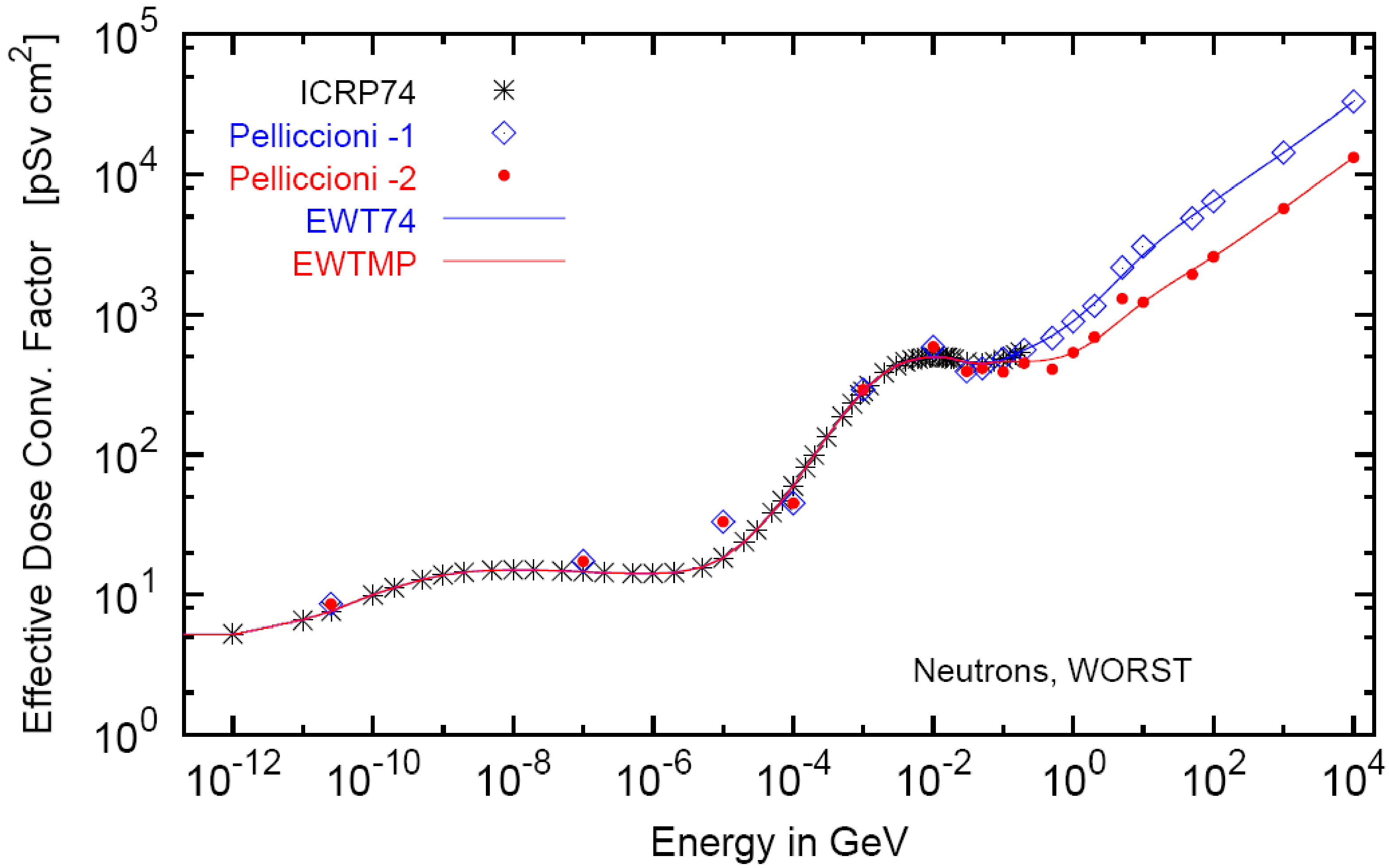


For more info: http://cern.ch/info-fluka-discussion/download/deq2.pdf

Fluence to effective dose coefficients

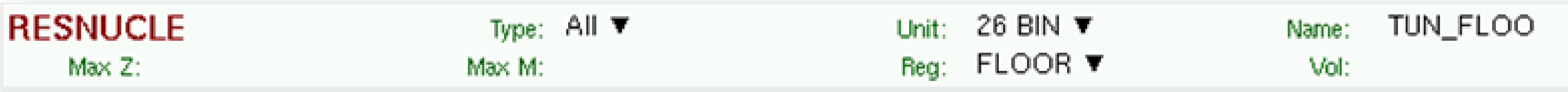
- Conversion coefficients from fluence to effective dose are implemented for three different irradiation geometries:
  - anterior-posterior
  - rotational
  - WORST ("Working Out Radiation Shielding Thicknesses") is the maximum coefficient of anterior-posterior, posterior-anterior, right-lateral and left-lateral geometries. It is recommended to be used for shielding design.
- Implemented for radiation weighting factors recommended by ICRP60 (e.g., SDUM=ETW74) and recommended by M.Pelliccioni (e.g., SDUM=EWTMP). The latter anticipate the 2007 recommendations of ICRP.
- Implemented for protons, neutrons, charged pions, muons, photons, electrons (conversion coefficients for other particles are approximated by these)
- Zero coefficient is applied to all heavy ions

Fluence to effective dose coefficients



Card: RESNUCLEi [1/3]

```
RESNUCLE        3.0     -26.        0        0     FLOOR        TUN_FLOO
```



Scoring of residual nuclei or activity on a region basis

WHAT(1) **type of products to be scored**

Type:

- 1.0 spallation products (except from low-energy neutron interactions)
- 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)

WHAT(2) **logical output unit (Default = 11.0)**

Unit:

WHAT(3) **Maximum atomic number Z of the residual nuclei distribution**

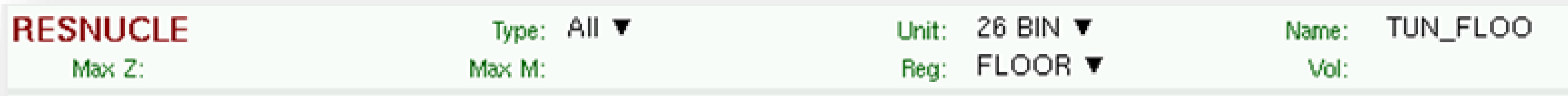
Max Z: Default: according to the Z of the element(s) of the material assigned to the scoring region

WHAT(4) **Maximum M = N - Z - NMZ_min**

Max M: 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.

Card: RESNUCLEi [2/3]



WHAT(5) scoring region number/name
Reg: (Default = 1.0 ; -1.0 or @ALLREGS all regions)

WHAT(6) volume of the region in cm^3
Vol: (Default = 1.0)

SDUM character string identifying the detector
Name: (max. 10 characters)

Notes:

1. In the case of heavy ion projectiles the default NMZ, 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. Protons are scored, together with ^{2}H, ^{3}H, ^{3}He, ^{4}He, at the end of their path

Card: RESNUCLEi [3/3]

```
**** Isotope Yield as a function of Mass Number ****
****             (nuclei / cmc / pr)            ****


A_min: 1 -   A_max: 198

A:           186  1.5870372E-08 +/-   9.9000000E+01 %
A:           185  3.7605012E-09 +/-   9.9000000E+01 %
A:           184  1.4581326E-08 +/-   9.9000000E+01 %
A:           183  1.0712972E-08 +/-   9.9000000E+01 %
A:           182  7.4882118E-09 +/-   9.9000000E+01 %
...

**** Isotope Yield as a function of Atomic Number ****
****             (nuclei / cmc / pr)              ****


Z_min: 1 -   Z_max: 78

Z:            74  5.2413383E-08 +/-   9.9000000E+01 %
Z:            42  3.0072785E-07 +/-   9.9000000E+01 %
Z:            41  4.7906228E-08 +/-   9.9000000E+01 %
Z:            40  3.7605012E-09 +/-   9.9000000E+01 %
Z:            38  3.7605012E-09 +/-   9.9000000E+01 %
...
```

Units:
- nuclei/cm3 per primary particle if RESNUCLEi is not connected to a cooling time
- Bq /cm3 for a specific cooling time assigned via DCYSCORE

```
 **** Residual nuclei distribution   ****
 ****     (nuclei / cmc / pr)         ****


  A \ Z   68         69         70         71         72         73         74         75         76         77         78
 186    0.00E+00   0.00E+00   0.00E+00   0.00E+00   0.00E+00   0.00E+00   1.59E-08   0.00E+00   0.00E+00   0.00E+00   0.00E+00
       +/- 0.0 %  +/- 0.0 %  +/- 0.0 %  +/- 0.0 %  +/- 0.0 %  +/- 0.0 %  +/-99.0 %  +/- 0.0 %  +/- 0.0 %  +/- 0.0 %  +/- 0.0 %
 185    0.00E+00   0.00E+00   0.00E+00   0.00E+00   0.00E+00   0.00E+00   3.76E-09   0.00E+00   0.00E+00   0.00E+00   0.00E+00
       +/- 0.0 %  +/- 0.0 %  +/- 0.0 %  +/- 0.0 %  +/- 0.0 %  +/- 0.0 %  +/-99.0 %  +/- 0.0 %  +/- 0.0 %  +/- 0.0 %  +/- 0.0 %
 184    0.00E+00   0.00E+00   0.00E+00   0.00E+00   0.00E+00   0.00E+00   1.46E-08   0.00E+00   0.00E+00   0.00E+00   0.00E+00
       +/- 0.0 %  +/- 0.0 %  +/- 0.0 %  +/- 0.0 %  +/- 0.0 %  +/- 0.0 %  +/-99.0 %  +/- 0.0 %  +/- 0.0 %  +/- 0.0 %  +/- 0.0 %
 183    0.00E+00   0.00E+00   0.00E+00   0.00E+00   0.00E+00   0.00E+00   1.07E-08   0.00E+00   0.00E+00   0.00E+00   0.00E+00
       +/- 0.0 %  +/- 0.0 %  +/- 0.0 %  +/- 0.0 %  +/- 0.0 %  +/- 0.0 %  +/-99.0 %  +/- 0.0 %  +/- 0.0 %  +/- 0.0 %  +/- 0.0 %
...
```

Card: PHYSICS

Please activate the following two cards if residuals are of interest:

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

```
PHYSICS     3.0                                                      EVAPORAT
PHYSICS     1.0                                                      COALESCE
```

special options for coalescence treatment

ISOTOPE 'beam'

to simulate a radioactive source:

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 base of cylinder at origin

```
BEAM                                                                  ISOTOPE
HI-PROPE         27.0      60.0
BEAMPOS           0.0       0.0       0.1       0.0       0.0       0.0
BEAMPOS           0.0       1.0       0.0       0.2       0.0       0.0CYLI-VOL
```

→ request decay by the RADDECAY card

Example (semi-analogue): an ^{131}I therapeutic source

Define the beam characteristics			
BEAM	Beam: Momentum ▼	p:	Part: ISOTOPE ▼
Δp: Flat ▼	Δp:	Δϕ: Flat ▼	Δϕ:
Shape(X): Rectangular ▼	Δx:	Shape(Y): Rectangular ▼	Δy:
HI-PROPE	Z: 53	A: 131	Isom:
Define the beam position			
BEAMPOS	x:	y:	z:
	cosx:	cosy:	Type: POSITIVE ▼
Define the beam position			
BEAMPOS	Rin: 0	Rout: 5	Type: SPHE-VOL ▼
GEOBEGIN	Log: ▼	Acc:	Opt: ▼
	Inp: ▼	Out: ▼	Fmt: COMBNAME ▼
Title:			
Black body			
SPH blkbody	x: 0.0	y: 0.0	z: 0.0
	R: 100000.0		
Void sphere			
SPH void	x: 0.0	y: 0.0	z: 0.0
	R: 10000.0		
Void sphere			
SPH target	x: 0.0	y: 0.0	z: 0.0
	R: 5.0		
END			
Black hole			
REGION BLKBODY		Neigh: 5	Volume:
expr: +blkbody -void			
Void around			
REGION VOID		Neigh: 5	Volume:
expr: +void -target			
Target			
REGION TARGET		Neigh: 5	Volume:
expr: +target			
END			

Example (semi-analogue): an ^{131}I therapeutic source

Requests simulation of radioactive decays and sets the corresponding biasing and transport conditions

RADDECAY	Decays: Semi-Analogue ▼	Patch Isom: ▼	Replicas:
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: 0.0	Coulomb corr: ▼
TCQUENCH	t cut-off: 3600	Birks c1:	Birks c2:
	Bin: 1hpdose ▼	to Bin: ▼	Step:
USRBIN		Unit: 21 BIN ▼	Name: 1hpdose
Type: X-Y-Z ▼	Xmin: -5	Xmax: 5	NX: 100
Part: DOSE ▼	Ymin: -5	Ymax: 5	NY: 100
	Zmin: -5	Zmax: 5	NZ: 100
USRBIN		Unit: 21 BIN ▼	Name: physdose
Type: X-Y-Z ▼	Xmin: -5	Xmax: 5	NX: 100
Part: DOSE ▼	Ymin: -5	Ymax: 5	NY: 100
	Zmin: -5	Zmax: 5	NZ: 100

Associates selected scoring detectors with user-defined decay times

DCYSCORE	Cooling t: Semi-Analogue ▼	Kind: USRBIN ▼	
	Det: 1hpdose ▼	to Det: physdose ▼	Step:

..+....1....+....2....+....3....+....4....+....5....+....6....+....7..

ASSIGNMA	Mat: BLCKHOLE ▼	Reg: BLKBODY ▼	to Reg: ▼
	Mat(Decay): ▼	Step:	Field: ▼
ASSIGNMA	Mat: VACUUM ▼	Reg: VOID ▼	to Reg: ▼
	Mat(Decay): ▼	Step:	Field: ▼
ASSIGNMA	Mat: WATER ▼	Reg: TARGET ▼	to Reg: ▼
	Mat(Decay): ▼	Step:	Field: ▼

Geometry modifications [1]

FLUKA.2011 contains the possibility of selectively changing a region material (and/or switching on/off possible fields) when transporting radioactive decay products. Radioactive decay products originating from that regions are ignored. This is helpful for situations where the emissions of an activated object in a complex environment have to be evaluated standalone.

Through Input card: ASSIGNMA

(a (single-element or compound) material is assigned to each geometry region)

Example

```
*...+....1....+....2....+....3....+....4....+....5....+....6....+....7....+...
ASSIGNMA       GOLD      REG1      REG2       1.0       0.0    VACUUM
```

MATERIAL | from REGION | to REGION | in steps of | no field | MATERIAL for decay products

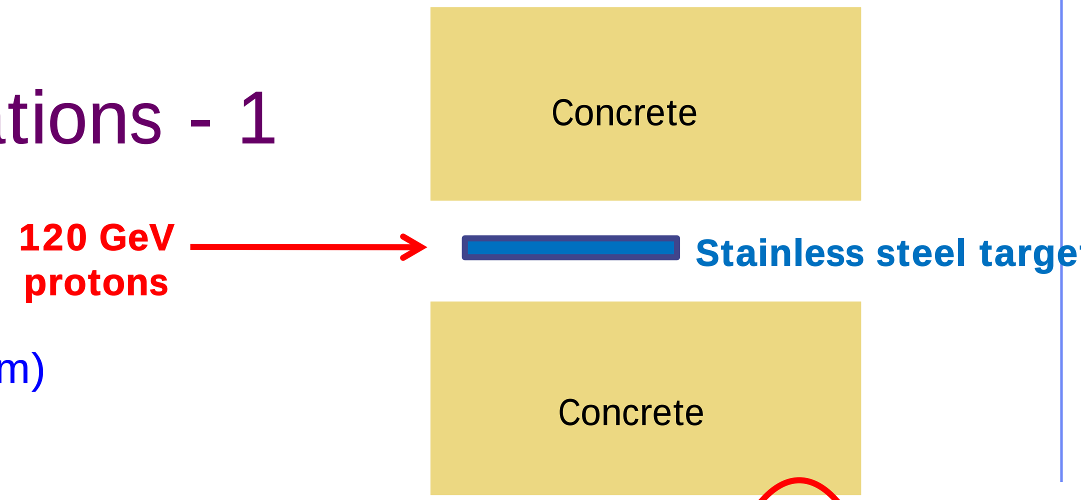
WHAT(5) = 1/2/3: a magnetic/electric/both field(s) is(are) present in the region(s) defined by WHAT(2), (3), and (4), for both prompt and radioactive decay products

= 4/5/6: same as above, but for prompt products only

= 7/8/9: same as above, but for radioactive decay products only

Note: so far distinction between lattices (all instances are affected)

Geometry modifications - 1



1) Target only (shielding set to vacuum)

```
ASSIGNMA    BLCKHOLE   EXTVOID
ASSIGNMA      VACUUM   VACTRGT
ASSIGNMA      SS316L    TARGET
ASSIGNMA    CONCRETE  SHIELDIN                                          VACUUM
*  ..+....1....+....2....+....3....+....4....+....5....+....6....+....7..
```

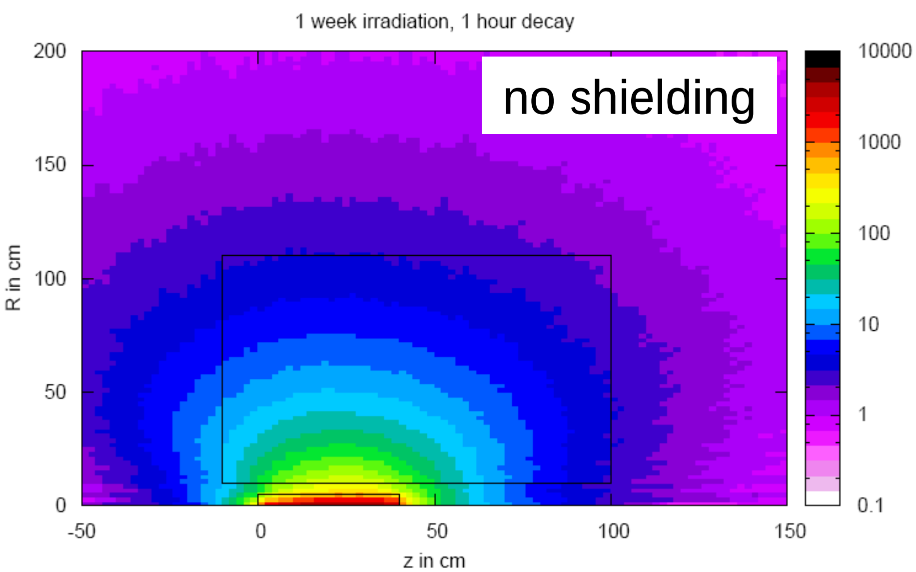
2) Shielding only (target set to vacuum)

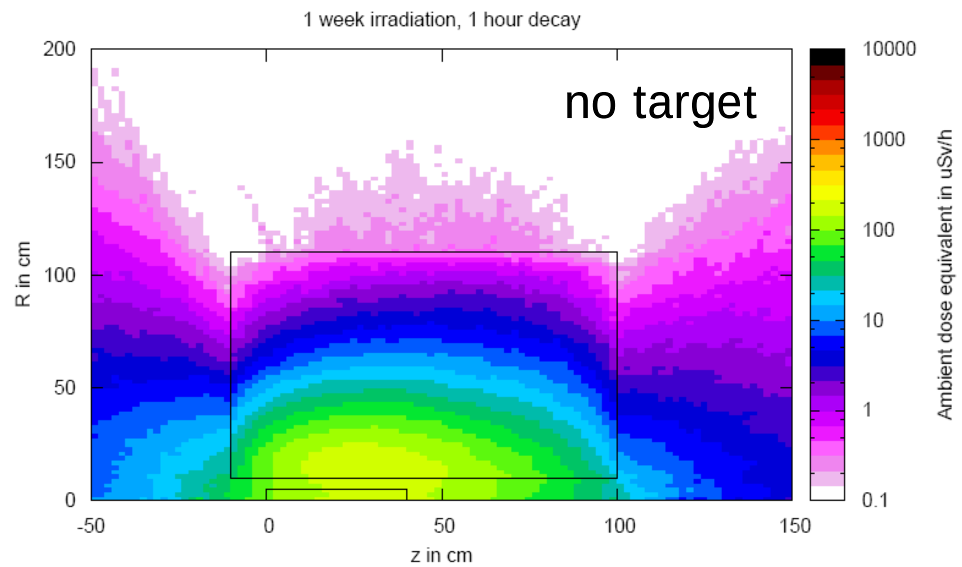
```
ASSIGNMA    BLCKHOLE   EXTVOID
ASSIGNMA      VACUUM   VACTRGT
ASSIGNMA      SS316L    TARGET                                          VACUUM
ASSIGNMA    CONCRETE  SHIELDIN
*  ..+....1....+....2....+....3....+....4....+....5....+....6....+....7..
```

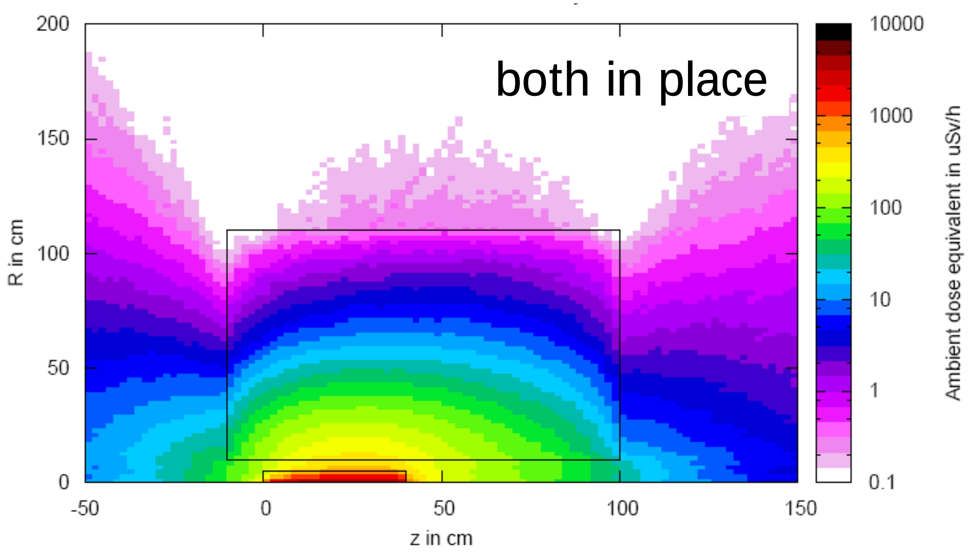
3) Target and shielding

```
ASSIGNMA    BLCKHOLE   EXTVOID
ASSIGNMA      VACUUM   VACTRGT
ASSIGNMA      SS316L    TARGET
ASSIGNMA    CONCRETE  SHIELDIN
*  ..+....1....+....2....+....3....+....4....+....5....+....6....+....7..
```

Geometry modifications - 2

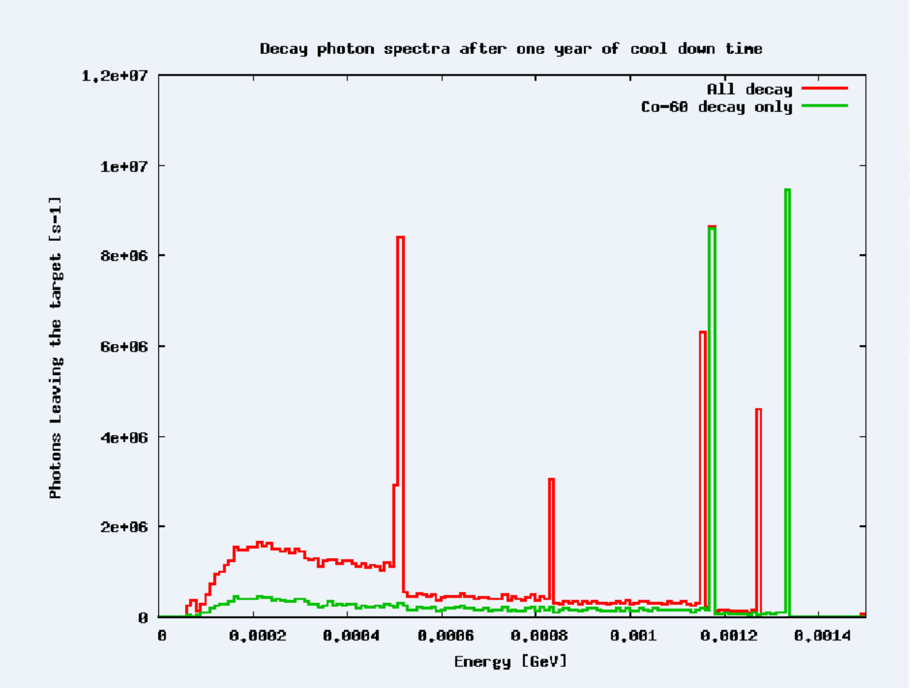






Filtering contribution of particles from decay

- Possibility to use the Iaztrk (variable in common block (TRACKR)) to flag parent isotope if any
- Iaztrk = A + 1000 Z + 1000000 * m
- The variable is propagated throughout the code to daughters
- Convenient to use it in comscw or fluscw (see exercise)



Example: Photons out of a steel target (USRBDX) after one month of irradiation and one week of cool down time. The spectrum in red has the contribution of all decay inside the target while the one in green has the contribution from the ^{60}Co decay only

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 (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

PHYSICS

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