Radioactivity

FLUKA Advanced Course

FLUKA-Implementation – *Main features*

The generation and transport of decay radiation (limited to γ, β-, β+, X-rays, and Conversion Electrons emissions for the time being and extended to α with the next release) 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 information obtained from NNDC, sometimes supplemented with other data and checked for consistency.

As a consequence, results for production of residuals, their time evolution and residual doses due to their decays can be obtained in the same run, 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: the sampling of the beta+/- spectra including screening Coulomb corrections
- Auger and conversion electrons

- Isomers: the present models do not distinguish among ground state and isomeric states (it would require spin/parity dependent calculations in evaporation). A rough estimate (equal sharing among states) of isomer production can be activated in the RADDECAY option.

- 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

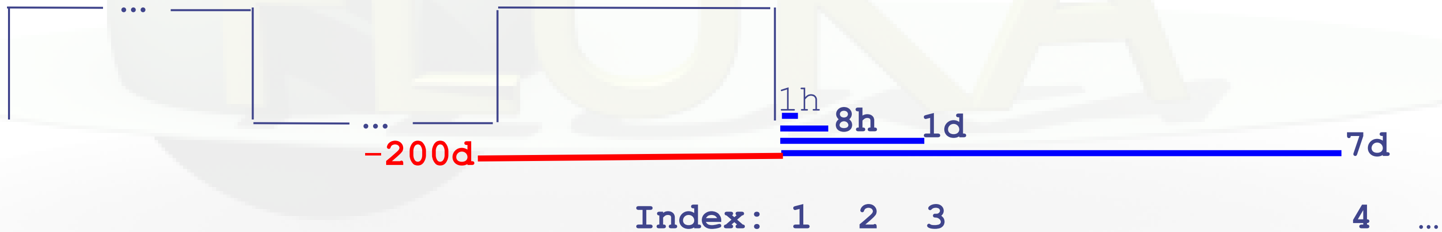
requests simulation of decay of produced radioactive nuclides and allows to modify biasing and transport thresholds (defined with other cards) for the transport of decay radiation

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

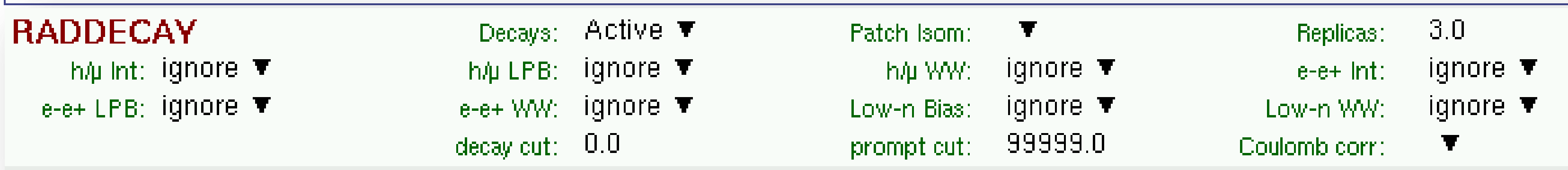
allows to associate scoring estimators with dose equivalent conversion factors or/and to filter them according to (generalized) particle identity

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

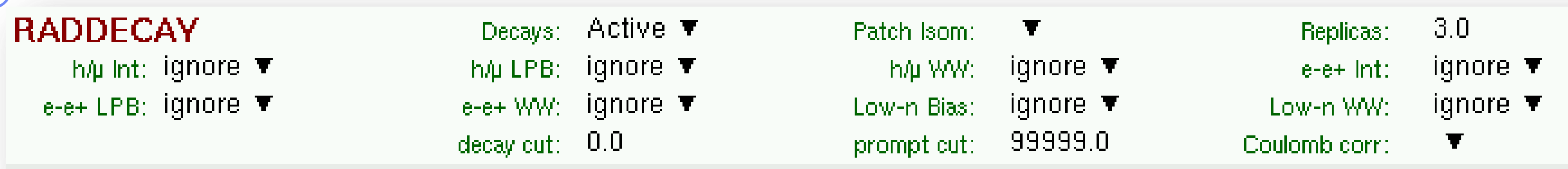
Card: RADDECAY [1/2]

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



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	5.9×10^5 p/s
	(beam-off)	

Card: DCYTIMES

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

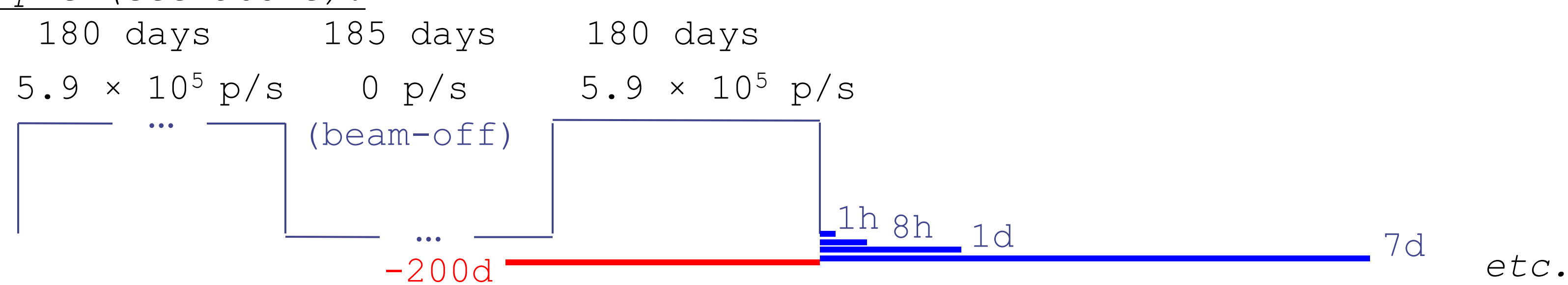
	1hour	8hours	1day	7days	1month	4months
DCYTIMES	t1:	3600.	t2:	28800.	t3:	8.64E4
	t4:	6.048E5	t5:	2.592E6	t6:	1.0368E7

WHAT(1) – WHAT(6) cooling time (in seconds) after the end of the irradiation

t1 .. t6 — Note: Several cards can be defined.

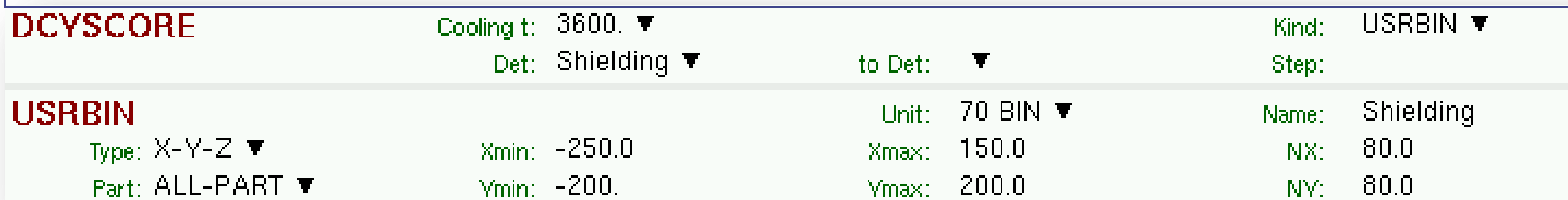
Each cooling time is assigned an index, following the order in which it has been input. This index can be used in option DCYSCORE to assign that particular cooling time to one or more scoring detectors. A negative decay time is admitted: scoring is performed at the chosen time "during irradiation"

Example (see above):



Card: DCYSCORE [1/2]

```
* Associate scoring with different cooling times
DCYSCORE          1.0                          Shieldling                        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

Available Conversion Coefficients

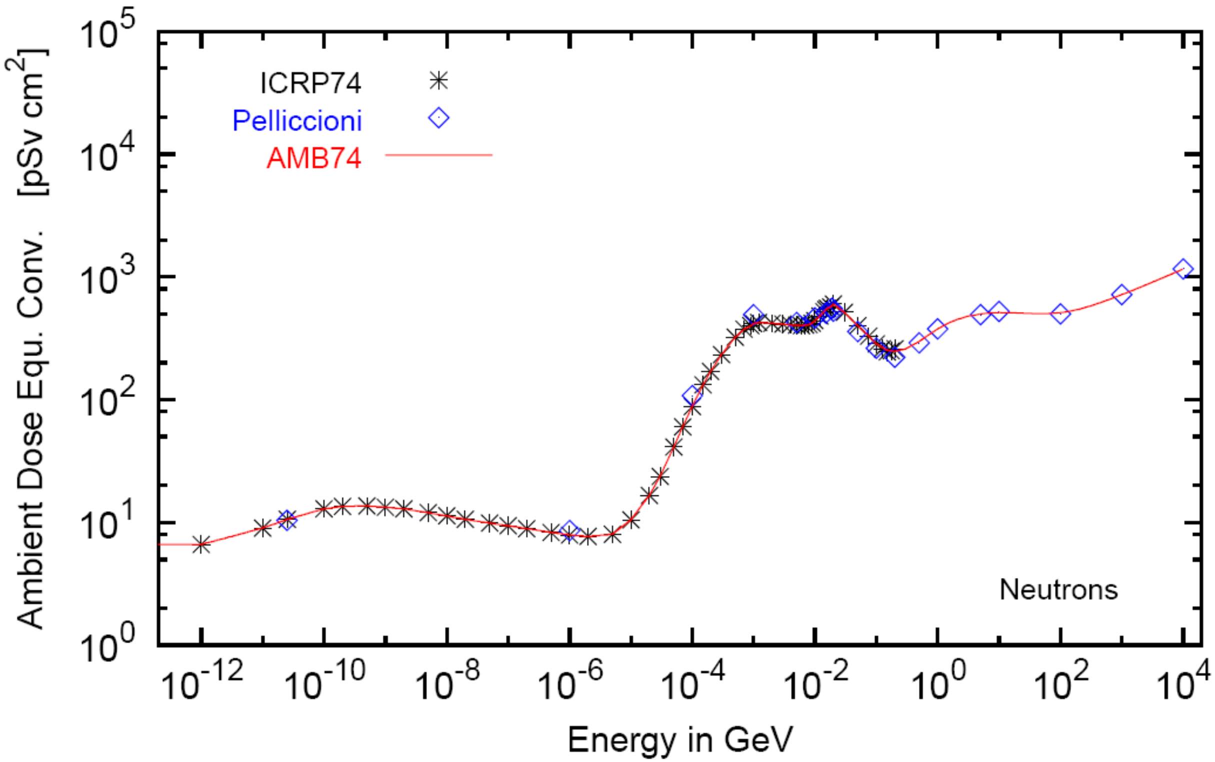
The following dose conversion coefficients sets are available:

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.

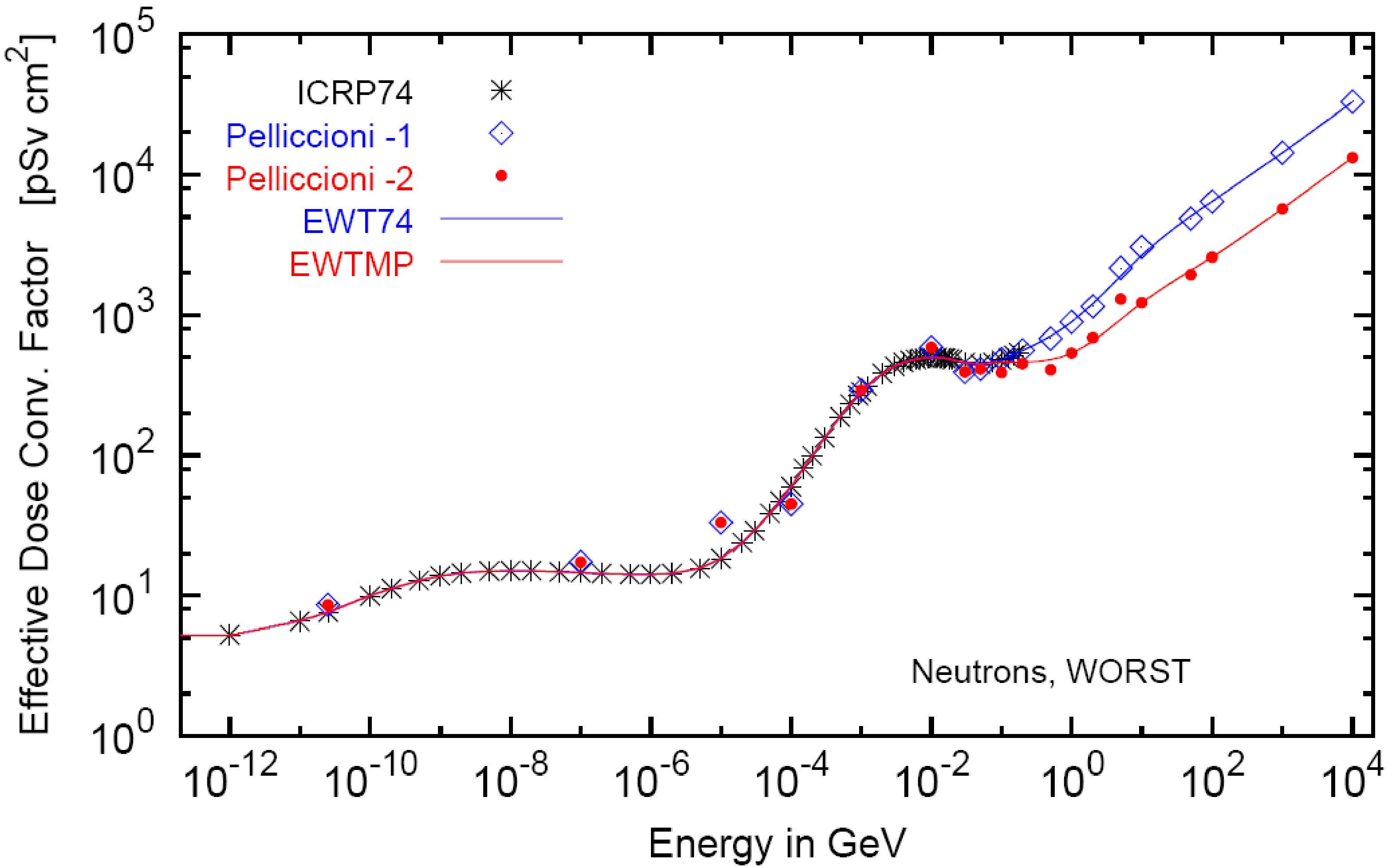


For more info: http://cern.ch/info-fluka-discussion/download/deq2.pdf

Fluence to effective dose coefficients

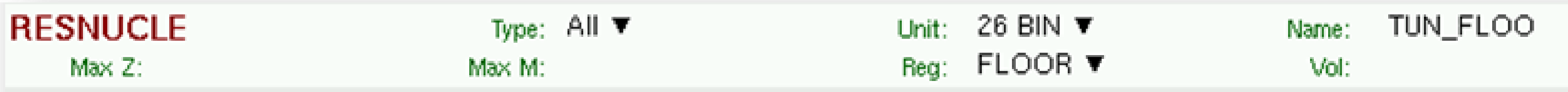
- Conversion coefficients from fluence to effective dose are implemented for three different irradiation geometries:
  - anterior-posterior
  - rotational
  - WORST ("Working Out Radiation Shielding Thicknesses") is the maximum coefficient of anterior-posterior, posterior-anterior, right-lateral and 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:

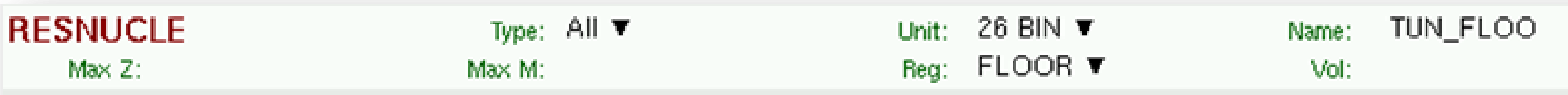
WHAT(3) — **Maximum atomic number Z of the residual nuclei distribution**

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) Reg:	scoring region number/name (Default = 1.0 ; -1.0 or @ALLREGS all regions)
WHAT(6) Vol:	volume of the region in cm^3 (Default = 1.0)
SDUM Name:	character string identifying the detector (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 %
...

**** 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 regions to *vacuum/blackhole* (and/or switching on/off possible fields) when transporting radioactive decay products. Radioactive decay products originating from regions switched to vacuum/blackhole 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

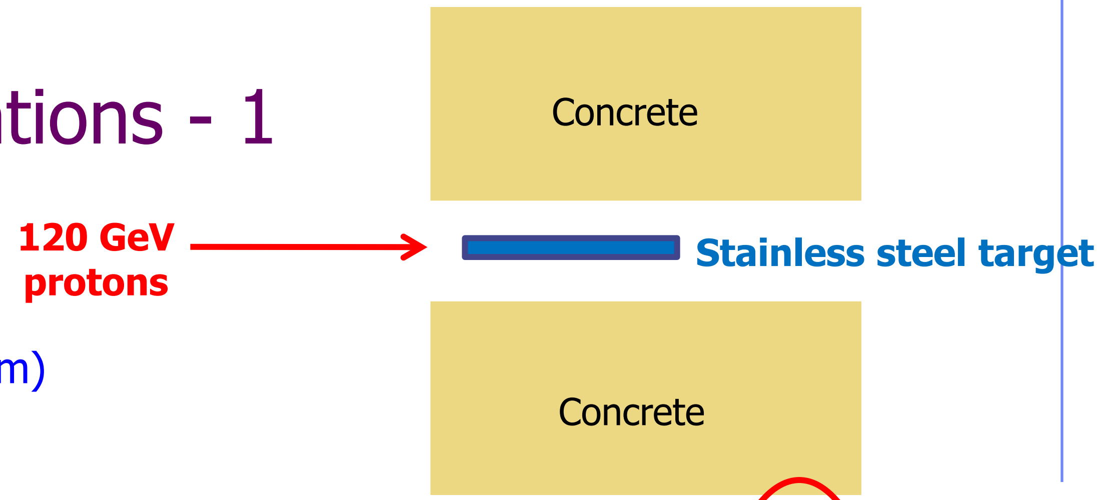
WHAT(5) = 1/2/3: a magnetic/electric/both field(s) is(are) present in the region(s) defined by WHAT(2), (3), and (4), for both prompt and radioactive decay products

= 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..
```

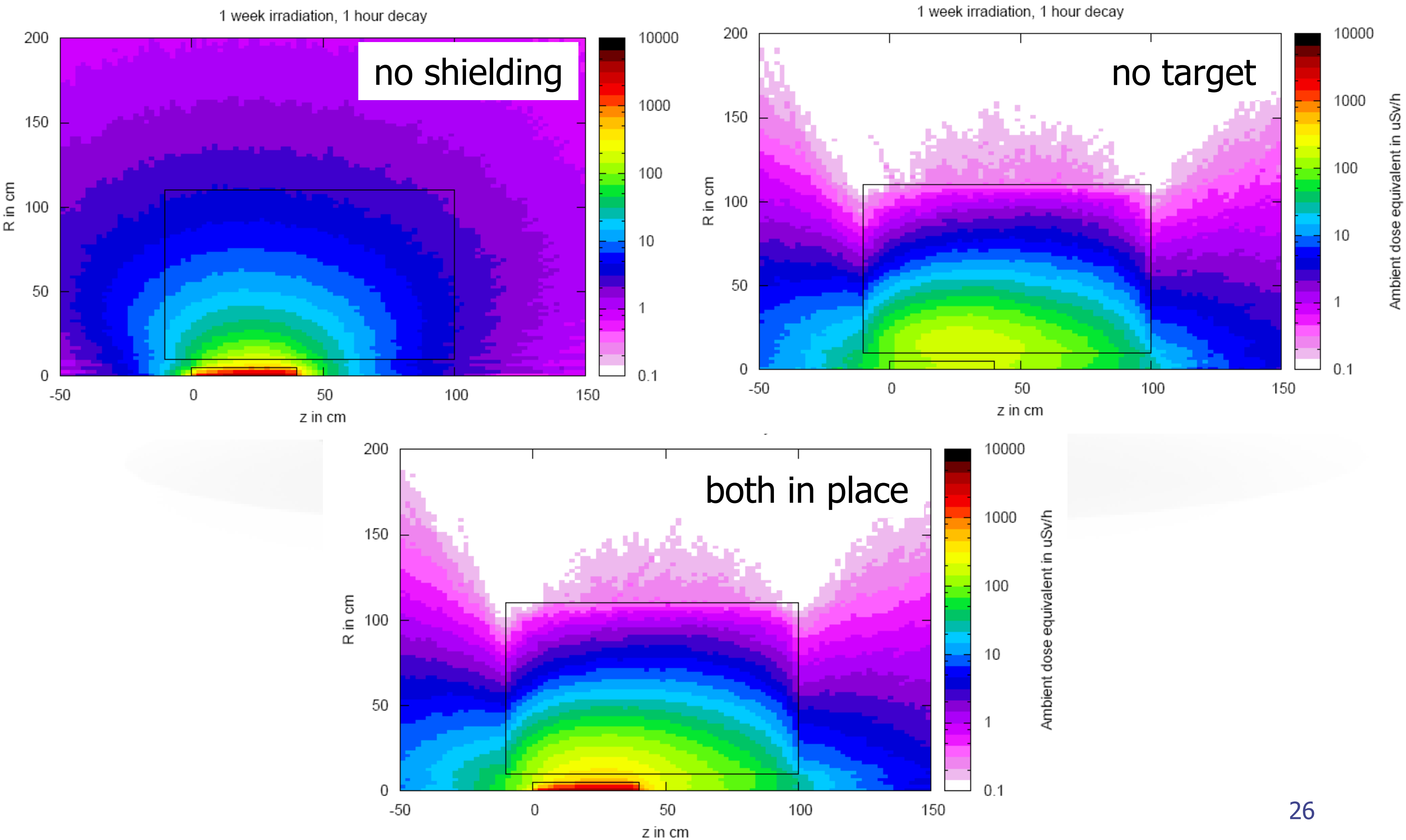
2) Shielding only (target set to vacuum)

```
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



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