Induced Radioactivity

7th FLUKA Course

NEA Paris, Sept.29-Oct.3, 2008

FLUKA-Implementation – *History - 1*

1995 – Offline evolution:

An offline code (usrsuwev.f) is distributed together with FLUKA, which allows the offline computation of the time evolution of a radionuclide inventory obtained with RESNUCLE for arbitrary irradiation profiles and decay times.

2002 – Two step method:

The offline code has been adapted for online use, each time a residual nucleus is produced during a particle cascade. This allows storing information on radio-nuclides for certain irradiation parameter and cooling times into an external file. This information can then be read in order to compute residual dose rates due to induced radioactivity (two-step method). Results were benchmarked in numerous irradiation experiments.

2004 - Online:

This capability has been implemented into FLUKA with an exact analytical solution of the Bateman equations describing activity build-up and decay during irradiation and cooling down, for arbitrary irradiation conditions.

FLUKA-Implementation – *History - 2*

The generation and transport of decay radiation (limited to γ, β^-, and β^+ emissions for the time being) is now possible during the same simulation which produces the radio-nuclides (one-step method). A dedicated database of decay emissions has been written, using 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 now 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% branching
- all beta emission spectra down to 0.1% branching: the sampling of the beta+/- spectra including 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, or in the offline evolution code.

- Different transport thresholds can be set for the prompt and decay radiation parts, as well as some (limited) biasing differentiation (see later)

Input options

Input options - *Overview*

Input card: RADDECAY

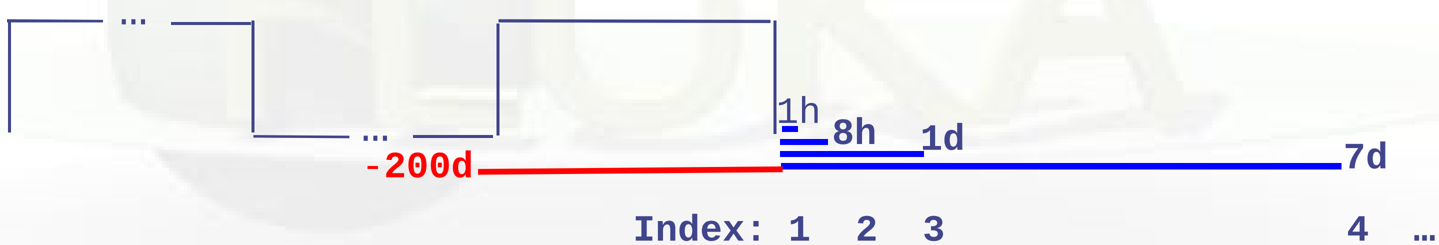
requests simulation of decay of produced radioactive nuclides allows to modify biasing and transport thresholds (defined with other cards) for application to the transport of decay radiation

Input card: IRRPROFI

definition of an irradiation profile (irradiation times and intensities)

Input card: DCYTIMES

definition of decay (cooling) time



Input card: DCYSCORE

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

Input card: AUXSCORE

allows to associate scoring estimators with auxiliary (generalized) particle distributions and dose equivalent conversion factors

Input options - *Overview*

```
* 1) request radioactive decays
RADDECAY         1.0                 3.0         0000099999
*
* 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
*
* 3) definition of cooling times
*              1hour     8hours       1day      7days     1month    4months
DCYTIMES       3600.     28800.     8.64E4   6.048E5   2.592E6  1.0368E7
*
USERWEIG                             1.0
*
* 4) associate scoring with different cooling times
DCYSCORE         1.0                             1.0        1.0         USRBIN
USRBIN          10.0       201.      -70.0      150.0      200.0     5000.0EWT74
USRBIN        -250.0      -200.        0.0       80.0       80.0        1.0&
DCYSCORE         2.0                             2.0        2.0         USRBIN
USRBIN          10.0       201.      -71.0      150.0      200.0     5000.0EWT74
USRBIN        -250.0      -200.        0.0       80.0       80.0        1.0&
RESNUCLE         3.0       -26.                            FLOOR        TUN_FLOO
RESNUCLE         3.0       -27.                             WALL        TUN_WALL
DCYSCORE         1.0                        RESTUBE1   RESTUBE1         RESNUCLE
RESNUCLE         3.0       -75.                             TUBE        RESTUBE1
```

Input options - *Overview*

- request 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:	▼

- definition of irradiation pattern

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

- definition of cooling times

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

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

Input options - *Overview*

Associate scoring with different cooling times

4) associate scoring with different cooling times

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
	Zmin:	0.0	Zmax:	5000.0	NZ:	1.0
DCYSCORE	Cooling t:	28800. ▼			Kind:	USRBIN ▼
	Det:	Target ▼	to Det:	Target ▼	Step:	
AUXSCORE	Type:	USRBIN ▼	Part:	▼	Set:	EWT74 ▼
	Z:	0	A:	0	Isomer:	0
	Det:	Target ▼	to Det:	▼	Step:	
USRBIN			Unit:	71 BIN ▼	Name:	Target
Type: X-Y-Z ▼	Xmin:	-250.0	Xmax:	150.0	NX:	80.0
Part: ALL-PART ▼	Ymin:	-200.	Ymax:	200.0	NY:	80.0
	Zmin:	0.0	Zmax:	5000.0	NZ:	1.0
RESNUCLE	Type:	All ▼	Unit:	26 BIN ▼	Name:	TUN_FLOO
Max Z:	Max M:		Reg:	FLOOR ▼	Vol:	
RESNUCLE	Type:	All ▼	Unit:	27 BIN ▼	Name:	TUN_WALL
Max Z:	Max M:		Reg:	WALL ▼	Vol:	
DCYSCORE	Cooling t:	3600. ▼			Kind:	RESNUCLE ▼
	Det:	RESTUBE1 ▼	to Det:	RESTUBE1 ▼	Step:	
RESNUCLE	Type:	All ▼	Unit:	75 BIN ▼	Name:	RESTUBE1
Max Z:	Max M:		Reg:	TUBE ▼	Vol:	

Particle Types

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

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 for requested cooling times**

Decays: Active — "activation study case": time evolution calculated analytically for *fixed* (cooling) times and daughter nuclei as well as associated radiation is considered at these (fixed) times

> 1 — **radioactive decays activated in semi-analogue mode**

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]

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

h/m 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 transport 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 100 irradiation intervals (subject to change with new releases).

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

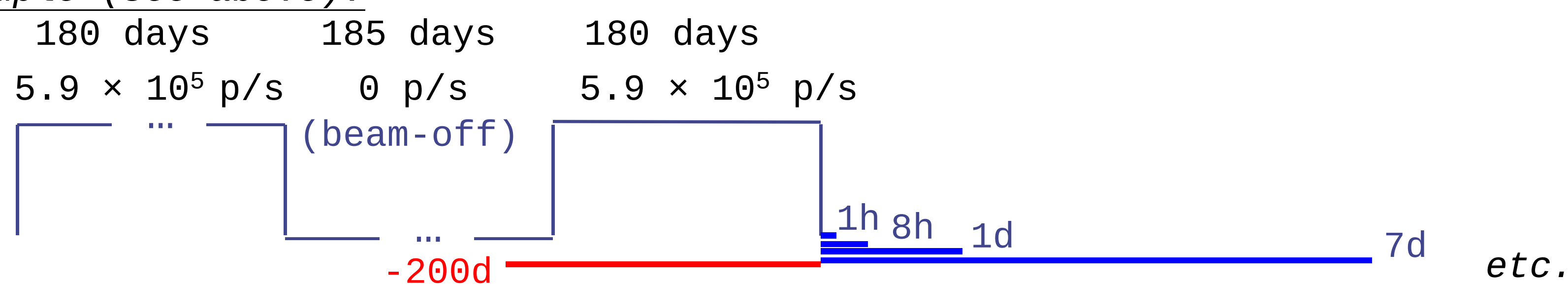
```
* 3) definition of cooling times
*              1hour    8hours     1day     7days    1month   4months
DCYTIMES       3600.    28800.    8.64E4   6.048E5   2.592E6  1.0368E7
```

```
        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.

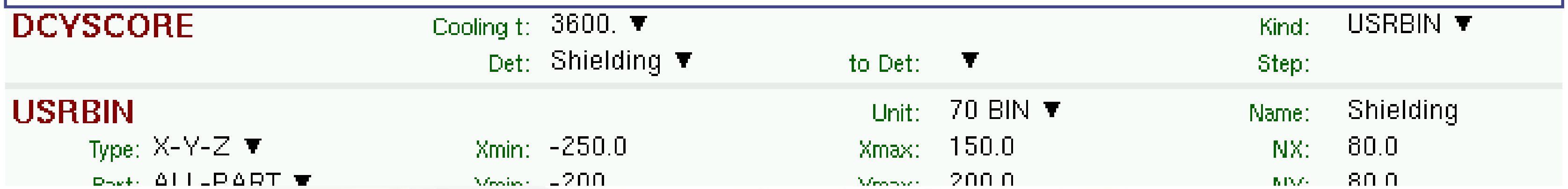
Each cooling time is assigned an index, following the order in which it has been input. This index can be used in option DCYSCORE to assign that particular cooling time to one or more scoring detectors. A negative decay time is admitted: scoring is performed at the chosen time "during irradiation"

Example (see above):



Card: DCYSCORE

```
* Associate scoring with different cooling times
DCYSCORE         1.0                       Target                    USRBIN
USRBIN          10.0      201.     -70.0    150.0     200.0    5000.0Target
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...

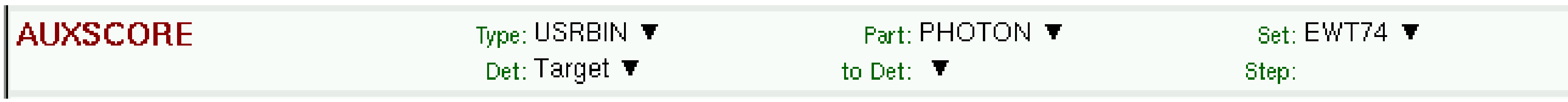
Units: All quantities are expressed per unit time. For example

RESNUCLE Bq

USRBIN fluence rate / dose rate

Card: AUXSCORE

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



WHAT(1) — **Type of estimator to associate with**
Type: — drop down list of estimator types (USRBIN, USRBDX...)

WHAT(2) — **particle or isotope to filter scoring**
Part: # — Particle or particle family list. If empty then flair will prompt for Z, A, and State for filtering on specific isotopes

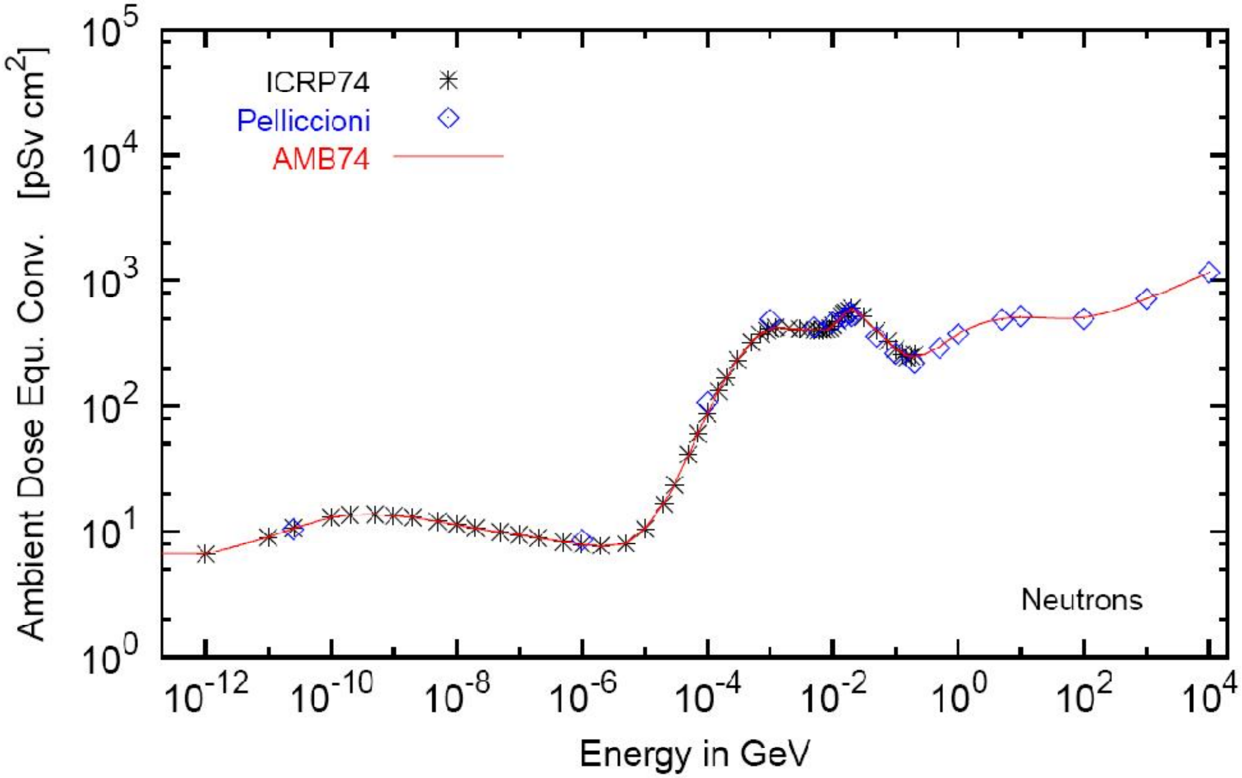
WHAT(4,5) — **Detector range**
Det .. to Det — Drop down list to select detector range of type WHAT(1)

WHAT(6) — **Step in assigning indices of detector range**
Step: #

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

Conversion Coefficients

Conversion coefficients from fluence to ambient dose equivalent are based on ICRP74 values and values calculated by M.Pelliccioni with FLUKA SDUM = AMB74 implemented for protons, neutrons, charged pions, muons, photons, electrons (conversion coefficients for other particles are approximated by these sets)

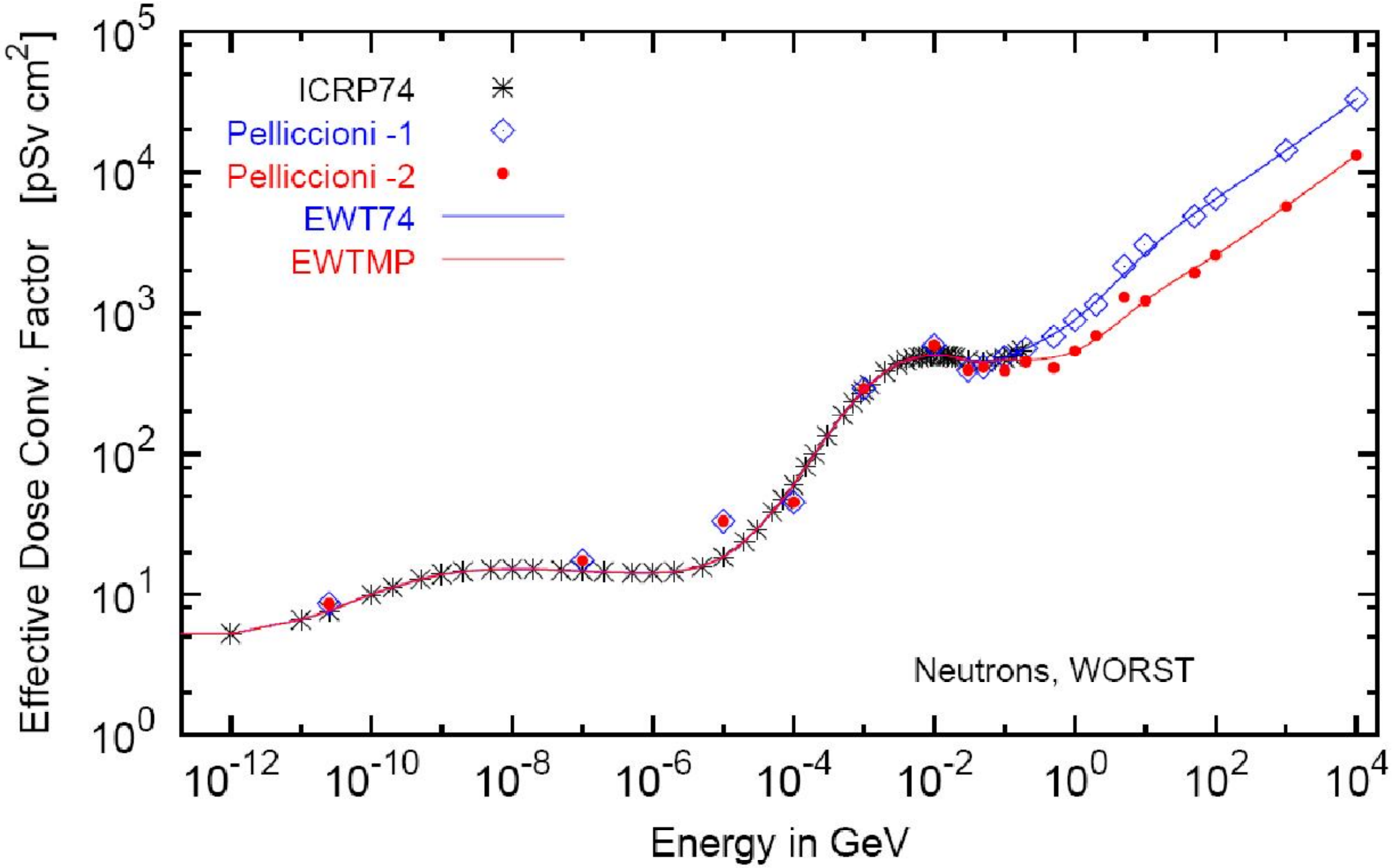


For more info: http://cern.ch/info-fluka-discussion/download/deq2.pdf

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 sets)
- Zero coefficient is applied to all heavy ions

Fluence to effective dose coefficients



Card: RESNUCLEi [1/4]

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

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

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:

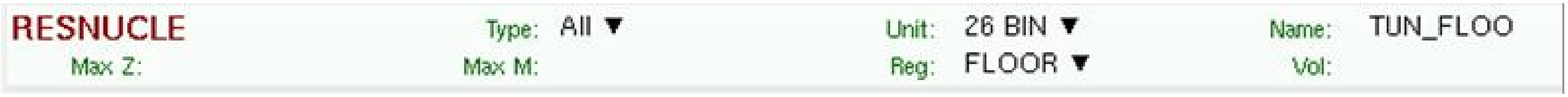
WHAT(3) — **Maximum atomic number Z of the residual nuclei distribution**

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 [2/4]



WHAT(5) scoring region number/name
Floor: (Default 1.0)

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. Starting with Fluka2006.3 protons are scored, together with ^{2}H, ^{3}H, ^{3}He, ^{4}He, at the end of their path, if transported (see option EVENTYPE). This is a change with respect to previous versions where protons were not scored.

Card: RESNUCLEi [3/4]

Postprocessing:

- use post-processor **usrsuw.f** to calculate average
- use post-processor **usrsuwev.f** to calculate average *and* perform off-line calculation of radioactive decay (induced radioactivity)

output :

test-resnuc	binary file with average distribution
test-resnuc_sum.lis	ASCII summary file (see below)
test-resnuc_tab.lis	ASCII table for plotting programs

content of test-resnuc_sum.lis :

```
**** test-resnuc ****
    Total primaries run: 132961
    Total weight of the primaries run:  132961.
  Detector n:  1  TDet
     (Region 34 Volume:    8. cmc,
      distr. type  : 3   ,
      Z_max: 78, N-Z_max: 42, N-Z_min: -4)
     Tot. response (n/cmc/pr)  0.000382190832  +/-  99. %
     ( --> Nuclei/pr           0.00305752666  +/-  99. % )
```

Card: RESNUCLEi [4/4]

```
 **** 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+
     +/- 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+
     +/- 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+
     +/- 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+
     +/- 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)

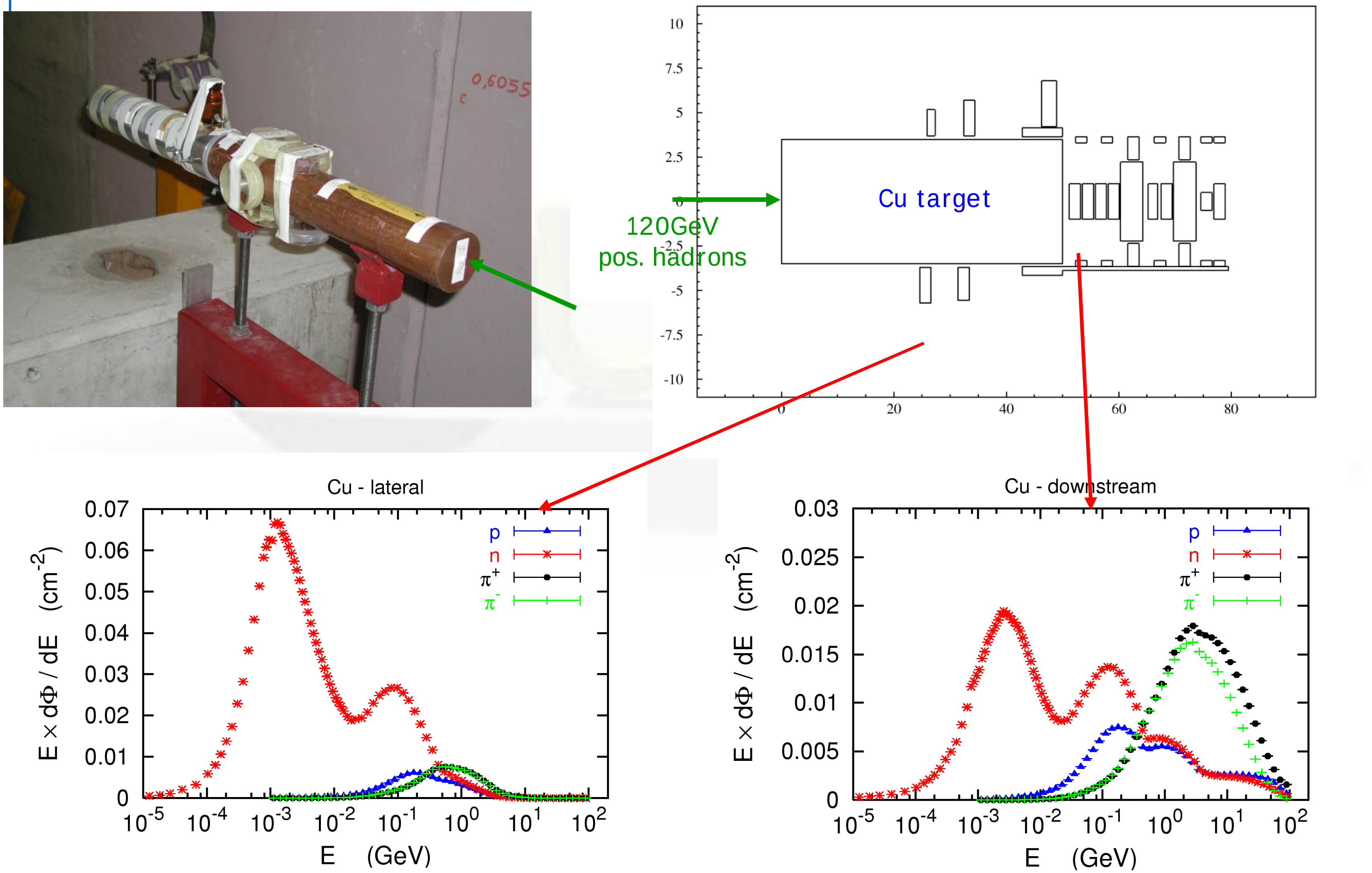
```
PHYSICS       3.0                                                   EVAPORAT
PHYSICS       1.0                                                   COALESCE
```

special options for coalescence treatment

Benchmarks

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



Benchmark Experiment

Measurement and calculation of

1. Specific activities
2. Residual dose equivalent rates

for different cooling times

Benchmark experiment – *Instrumentation 1*

Low-background coaxial High Precision Germanium detector (Canberra)

- use of two different detectors (90 cm^3 sensitive volume, 60% and 40% relative efficiency)

Genie-2000 (Ver. 2.0/2.1) spectroscopy software by Canberra and PROcount-2000 counting procedure software

- include a set of advanced spectrum analysis algorithms, *e.g.,* nuclide identification, interference correction, weighted mean activity, background subtraction and efficiency correction
- comprise well-developed methods for peak identification using standard or user-generated nuclide libraries. HERE: use of user-generated nuclide libraries, based on nuclides expected from the simulation and material composition

Efficiency calibration with LABSOCS

- allows the creation of a corrected efficiency calibration by modelling the sample taking into account self-absorption inside the sample and the correct detector geometry

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

Benchmark experiment – *Instrumentation 2*

Portable spectrometer Microspec

- NaI detector, cylindrical shape, 5 x 5 cm
- folds spectrum with detector response ("calibrated" with ^{22}Na source)
- physical centre of detector determined with additional measurements with known sources (^{60}Co, ^{137}Cs, ^{22}Na) to be 2.4 cm

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

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

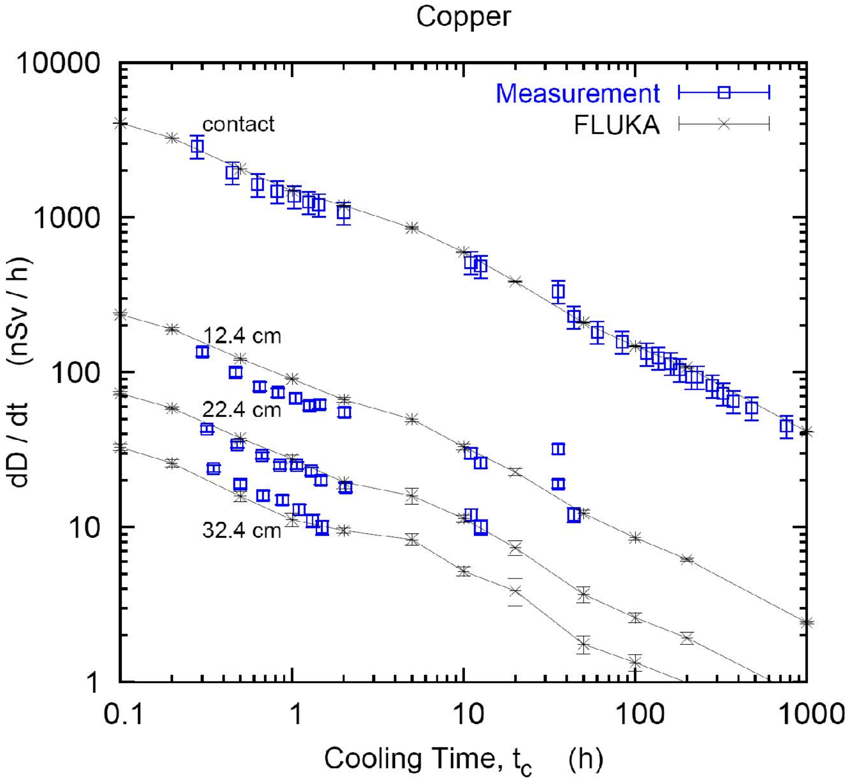
Exp/MDA < 1

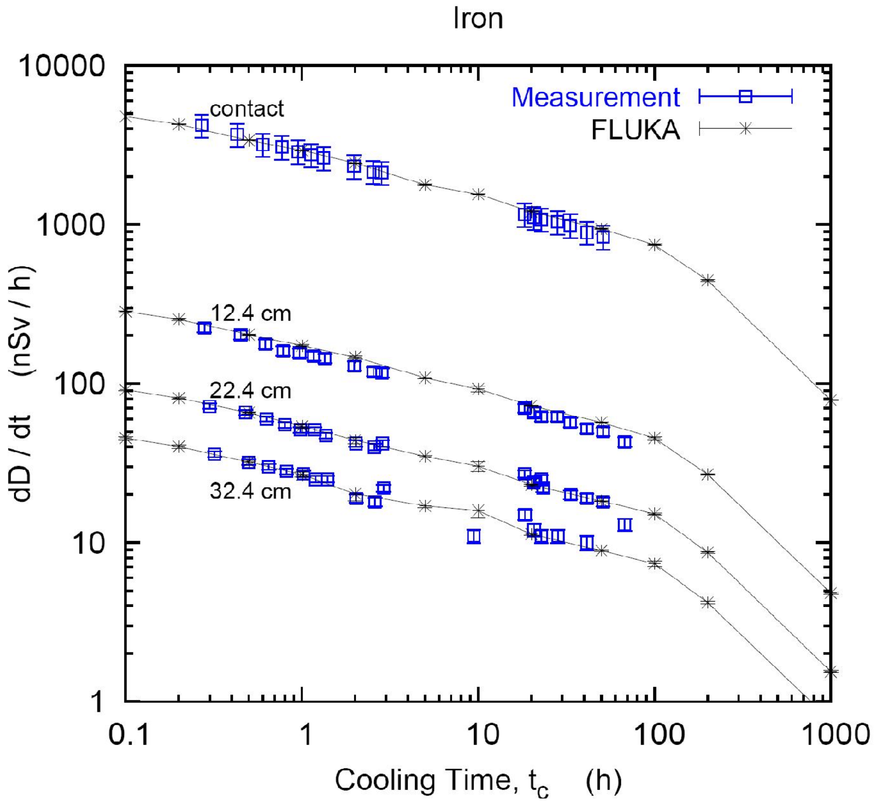
R + Error < 0.8 or
R – Error > 1.2

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

Benchmark experiment – *Results 1*

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

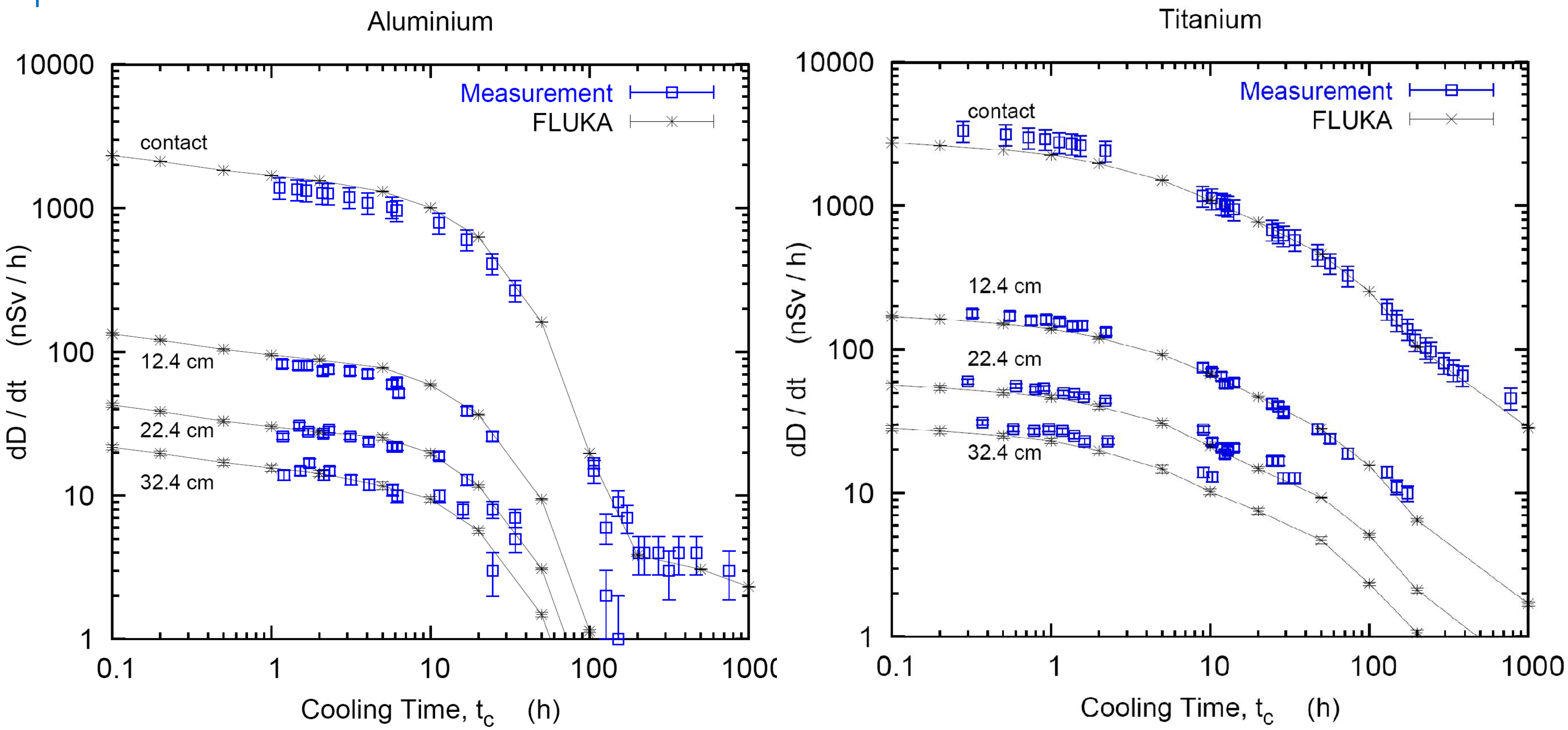




Reference: M. Brugger, S. Roesler *et al.,* Radiat. Prot. Dosim. 116 (2005) 12-15

Benchmark experiment – *Results 2*

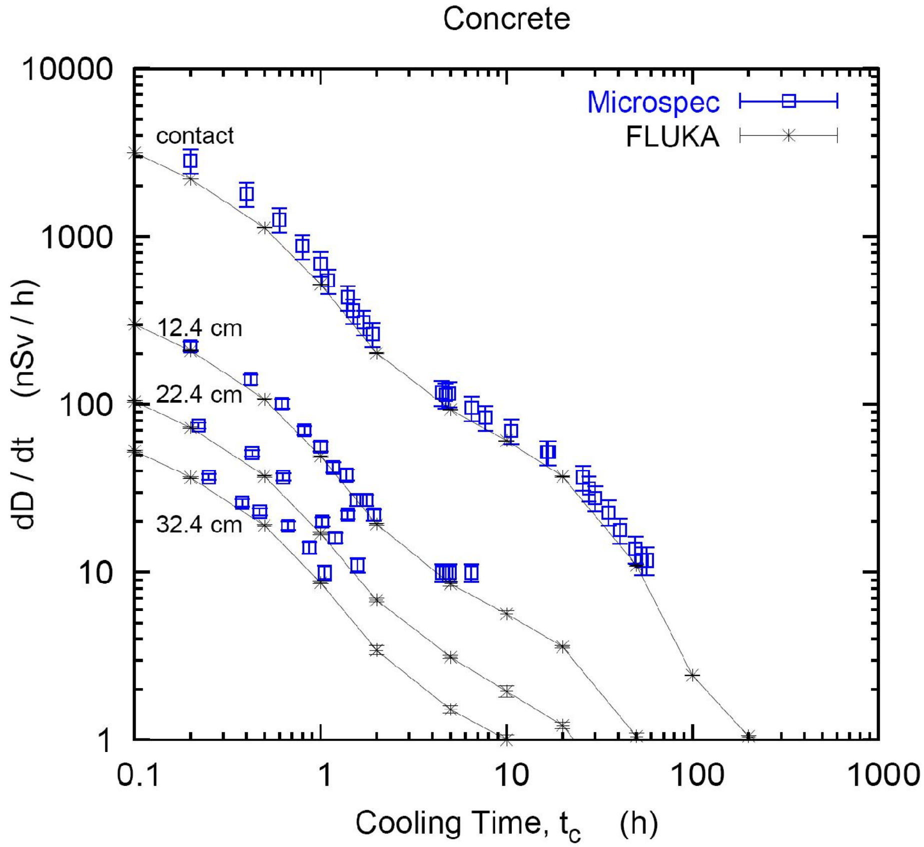
Dose rate as function of cooling time
for different distances between sample and detector



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

Benchmark experiment – *Results 3*

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

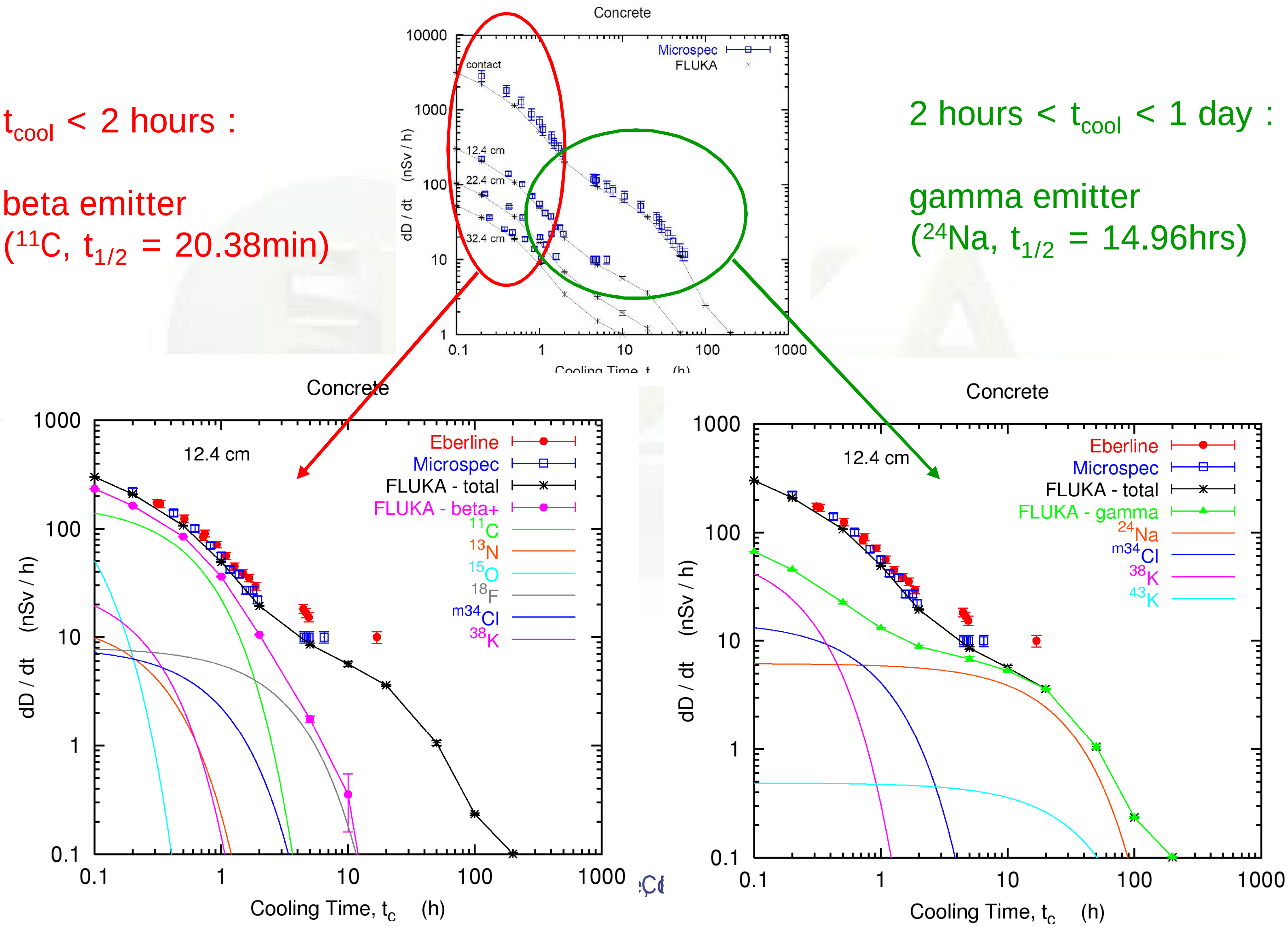
Benchmark experiment

t_{cool} < 2 hours :

beta emitter
(^{11}C, $t_{1/2}$ = 20.38min)

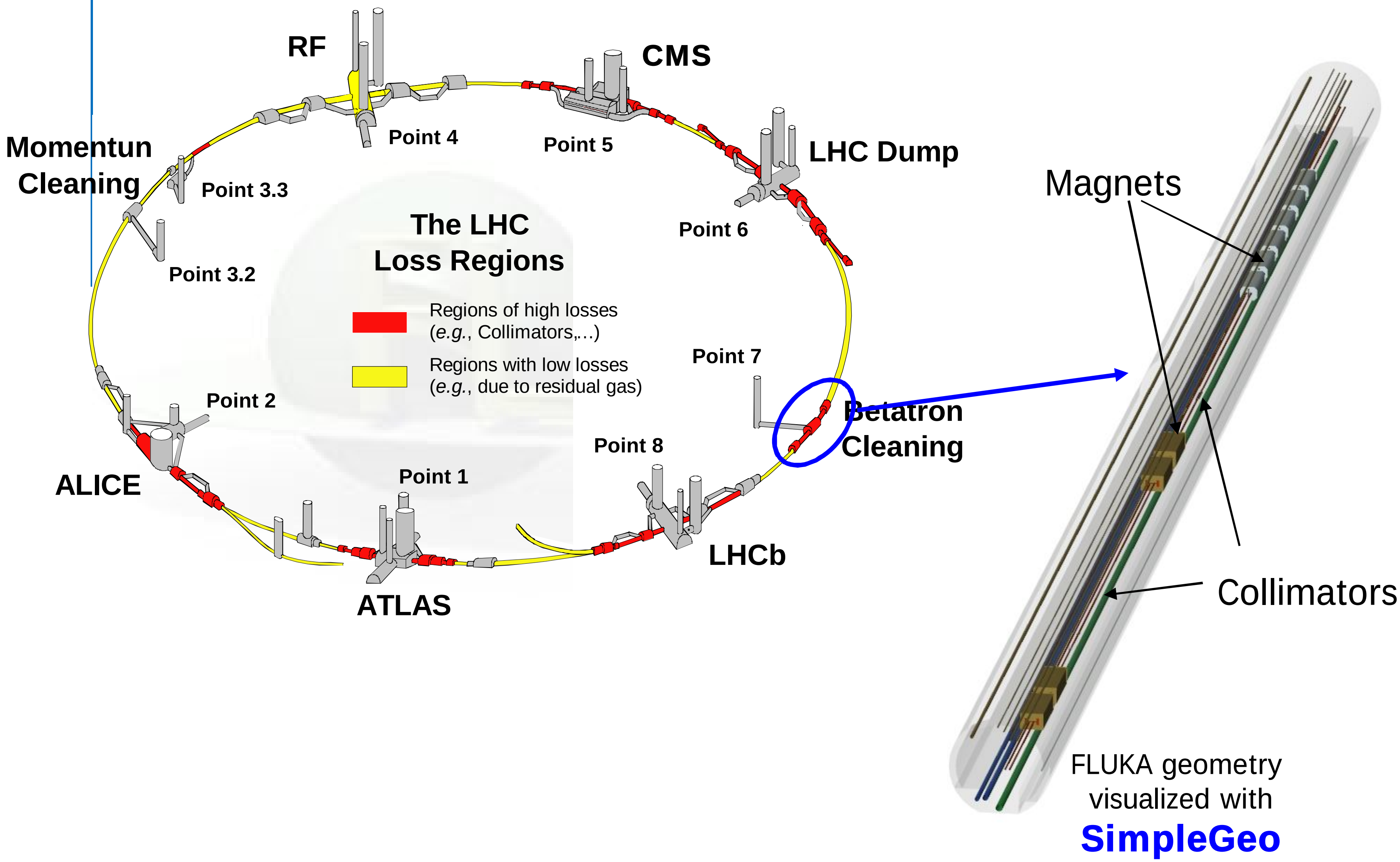
2 hours < t_{cool} < 1 day :

gamma emitter
(^{24}Na, $t_{1/2}$ = 14.96hrs)



Applications

Applications – *LHC collimation region*

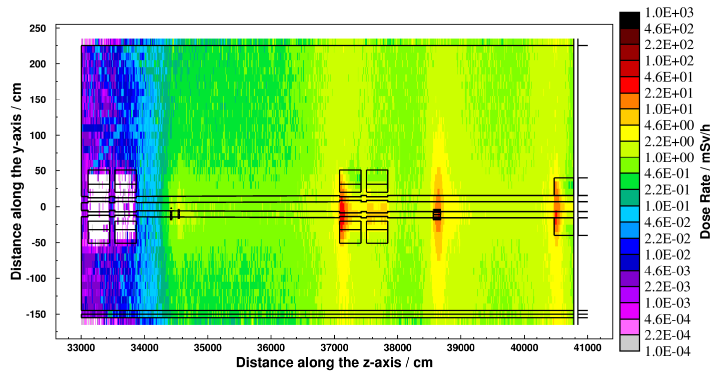


Applications – *LHC collimation region*

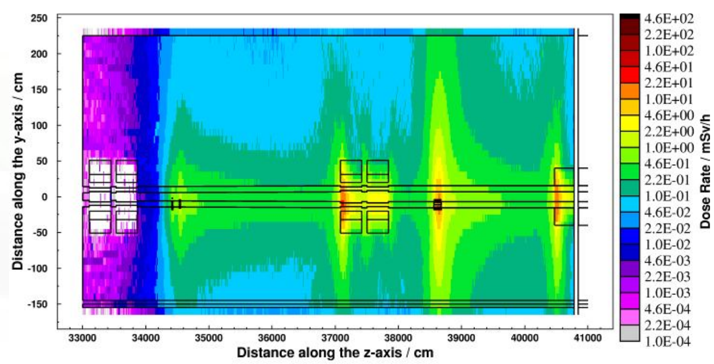
Cooling time

Residual dose rate (mSv/h) after one year of operation

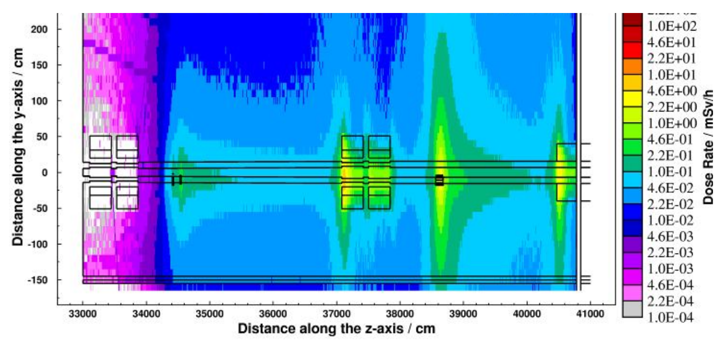
8 hours

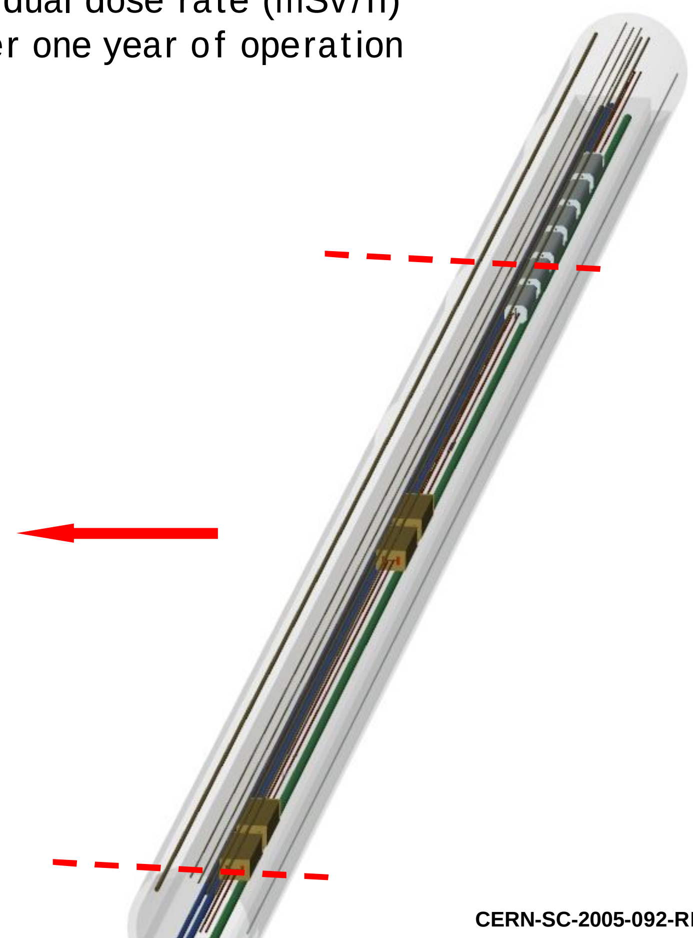


1 week



4 months





CERN-SC-2005-092-RP-TN

REMANENT DOSE RATE MAPS
OF THE LHC BETATRON CLEANING INSERTION (IR7)

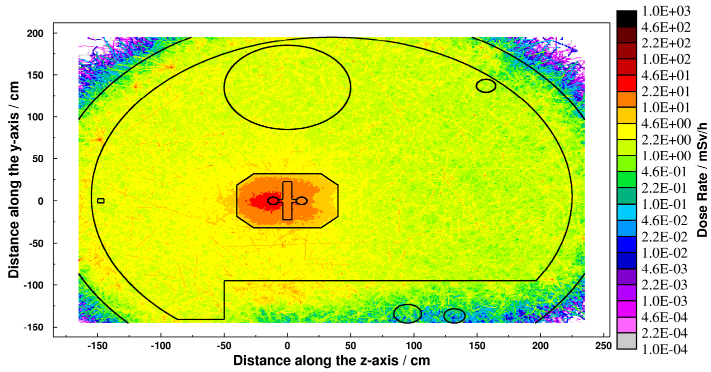
M. Brugger, D. Forkel-Wirth, S. Roesler

Applications – *LHC collimation region*

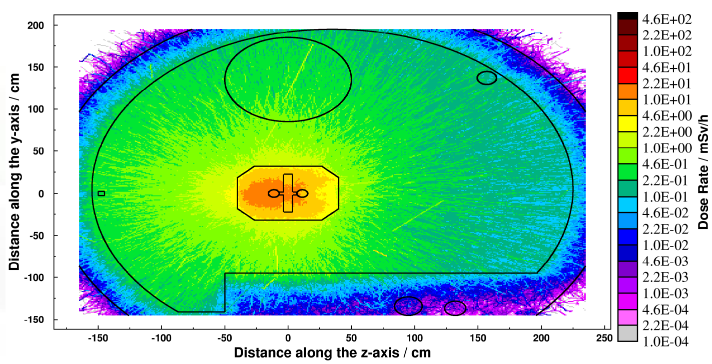
Cooling time

Residual dose rate (mSv/h)
after one year of operation

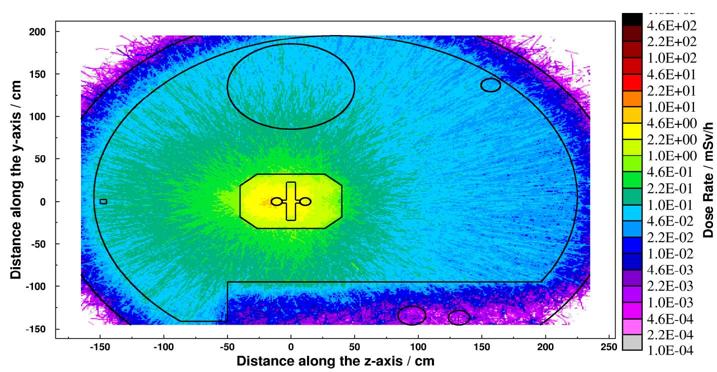
8 hours

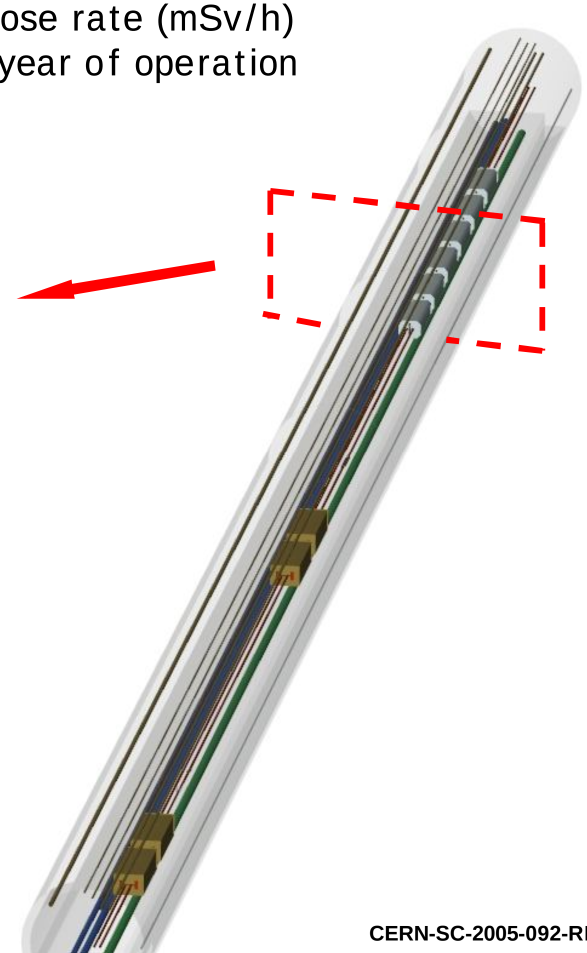


1 week



4 months





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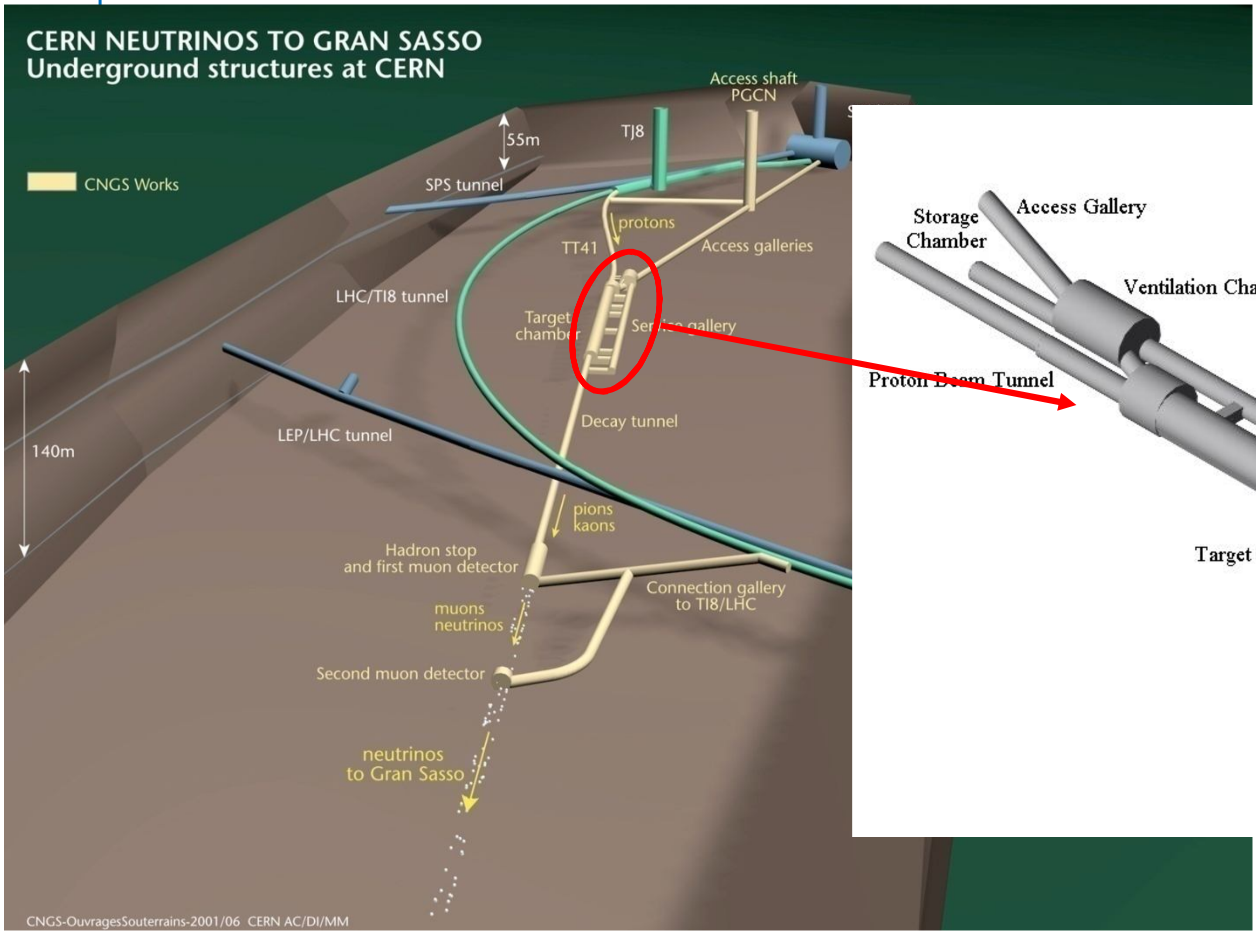
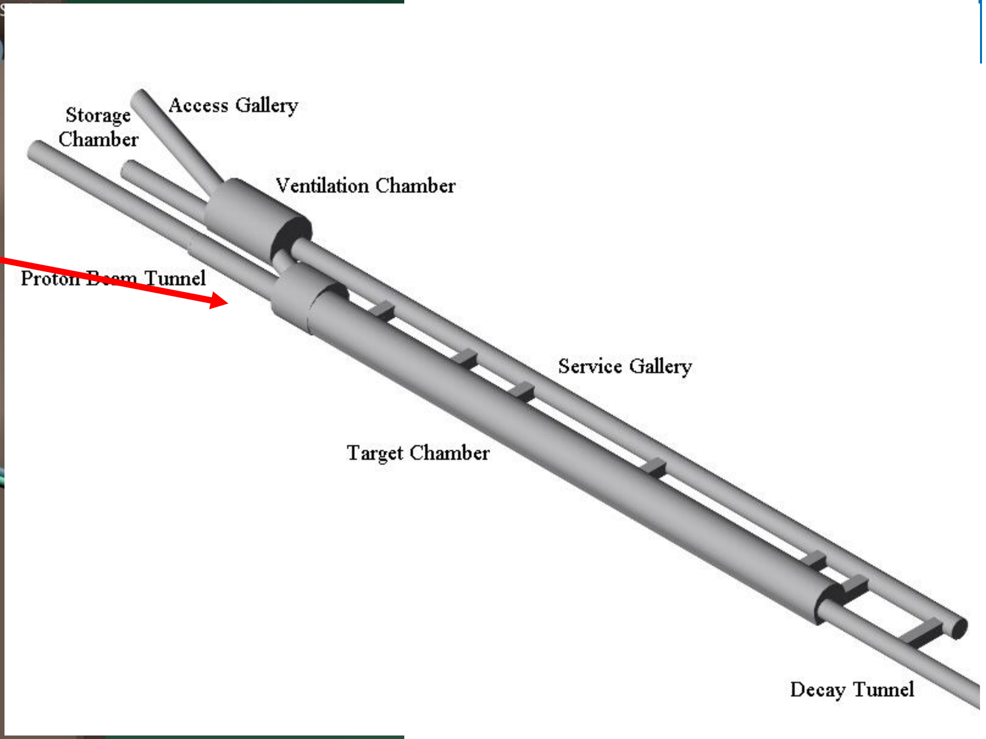
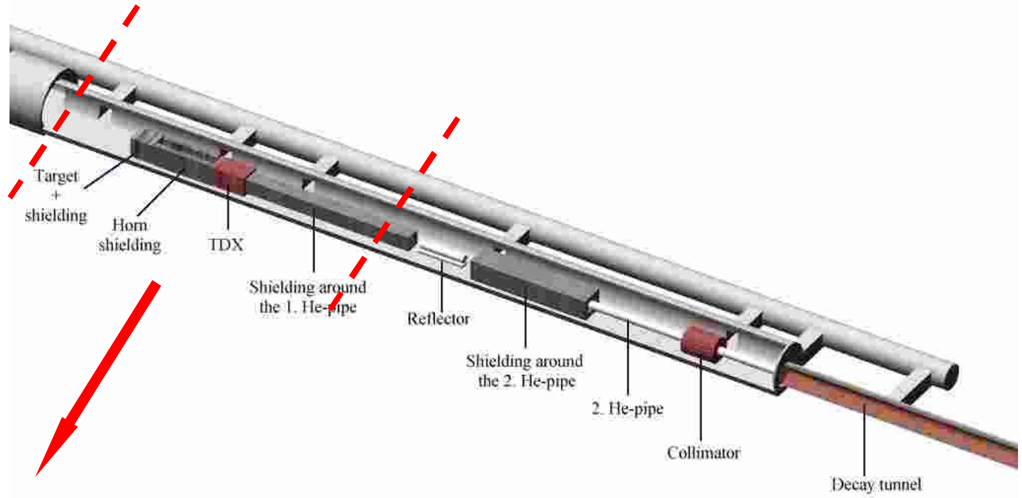
Applications – *CNGS*



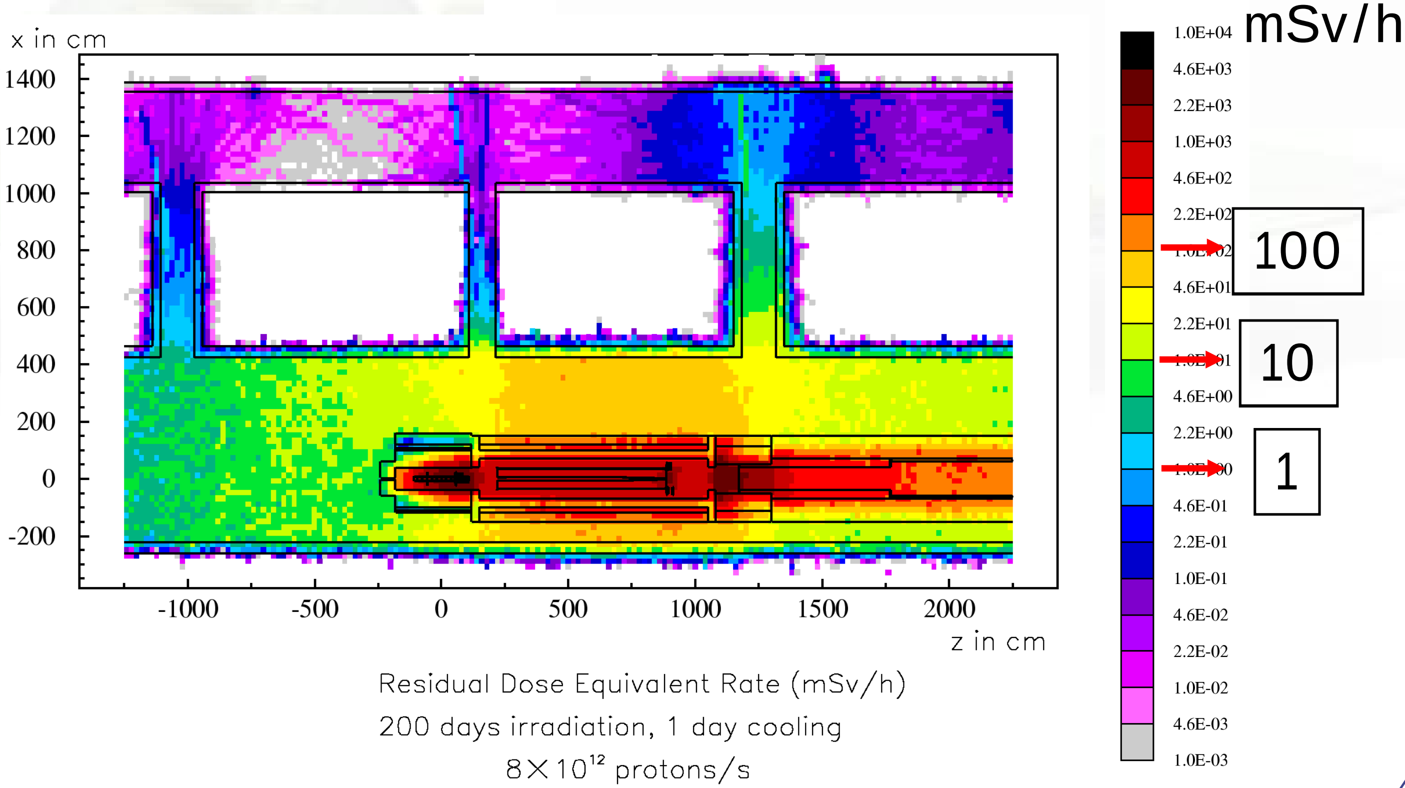


Applications – *CNGS*

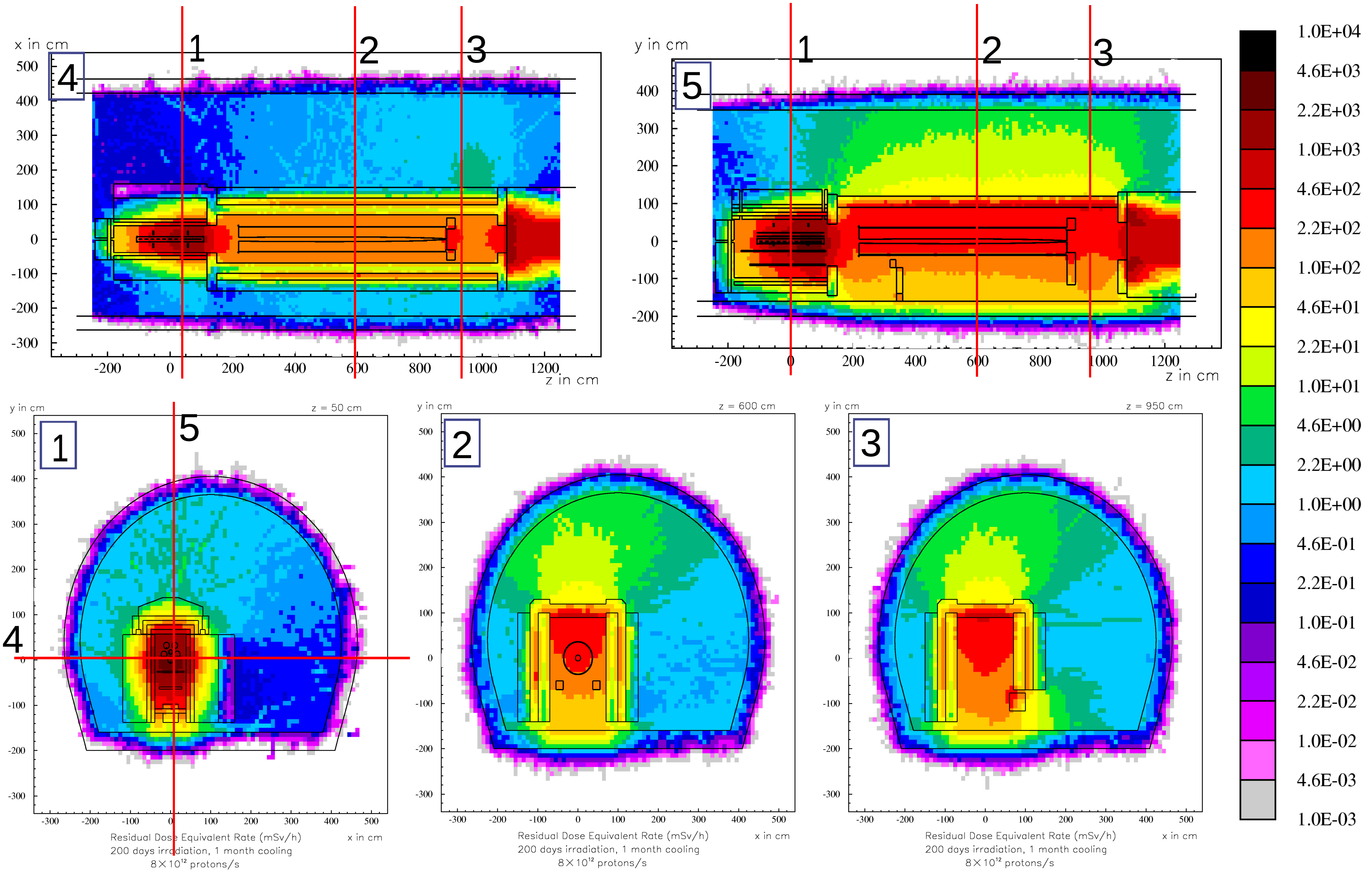


Example:

t_{cool} = 1 day



Applications – *CNGS*



Two-step method

- not part of the standard FLUKA distribution
- all routines and data-files are available on request from Stefan.Roesler@cern.ch

Overview

Two separate FLUKA simulations:

1st step

- simulation of production of radioactive nuclides and of their build-up and decay for a certain irradiation pattern and different cooling times
- write-out of all information on produced radio-nuclides at each cooling time into external file via user-routine usrrnc.f
- uses the analytical solution of the Bateman equation in FLUKA (i.e., radioactive build-up and decay identical to 1-step method)

2nd step

- simulation(s) of radioactive decay and transport of decay radiation
- information on radio-nuclides read in from file created in 1st step via user-routine source.f
- individual simulations for each requested cooling time

Advantages and disadvantages

Advantages

- geometry for 1^{st} and 2^{nd} step can be different, *e.g.,*
  - * simulation of dose rate only from a certain activated component in a different environment (*e.g.,* taken out from accelerator and brought into laboratory)
  - * investigation of relative contributions to the dose rate at a certain locations (e.g., beam-line components and tunnel wall)
  - * contributions from gamma, beta+ and beta- emitter can be studied separately
- complex irradiation pattern can be read-in from external data file (*e.g.,* exact treatment of several hundred beam-spills)

Disadvantages

- several simulations needed: for 1^{st} step and for 2^{nd} step for each individual cooling time
- dedicated user-routines have to be linked and a number of data-files are needed during execution