



# Induced Activity

FLUKA Beginner's Course

# FLUKA-Implementation – *Main features*

The generation and transport of decay radiation (limited to  $\gamma$ ,  $b^-$ ,  $b^+$ , X-rays, and Conversion Electrons emissions for the time being) 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

# Input options - *Overview*

Input card: **RADDECAY**

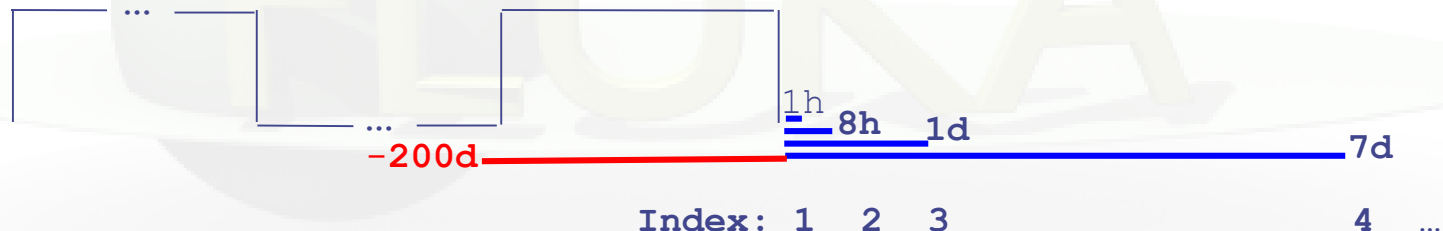
requests simulation of decay of produced radioactive nuclides and allows to modify biasing and transport thresholds (defined with other cards) for the transport of decay radiation

Input card: **IRRPROI**

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 <sup>3</sup>	Activity per unit volume
ACTOMASS	235	Bq/g	Activity per unit mass
SI1MEVNE	236	cm <sup>-2</sup>	Silicon 1 MeV-neutron equivalent flux
HADGT20M	237	cm <sup>-2</sup>	Hadrons with energy > 20 MeV

# Card: RADDECAY [1/2]

\* 1) request radioactive decays

RADDECAY 1.0 0 3.0 0000099999 0

## RADDECAY

h/μ Int: ignore ▼

e-e+ LPB: ignore ▼

Decays: Active ▼

h/μ LPB: ignore ▼

e-e+ WW: ignore ▼

decay cut: 0.0

Patch Isom: ▼

h/μ WW: ignore ▼

Low-n Bias: ignore ▼

prompt cut: 99999.0

Replicas: 3.0

e-e+ Int: ignore ▼

Low-n WW: ignore ▼

Coulomb corr: ▼

## WHAT(1)

Decays:

= 1

Active

**radioactive decays activated for requested cooling times**

“activation study case”: time evolution calculated analytically for *fixed* (cooling) times. Daughter nuclei as well as associated radiation is considered at these (fixed) times

> 1

Semi-Analogue

**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”)

## WHAT(2)

Patch Isom:

> 0

On

**isomer “production” activated**

## WHAT(3)

Replicas:

#

**number of “replicas” of the decay of each individual nucleus**

## Card: RADDECAY [2/2]

### **RADDECAY**

h/μ Int: ignore ▼  
e-e+ LPB: ignore ▼

Decays: Active ▼  
h/μ LPB: ignore ▼  
e-e+ WW: ignore ▼  
decay cut: 0.0

Patch Isom: ▼  
h/μ WW: ignore ▼  
Low-n Bias: ignore ▼  
prompt cut: 99999.0

Replicas: 3.0  
e-e+ Int: ignore ▼  
Low-n WW: ignore ▼  
Coulomb corr: ▼

### WHAT(4)

h/μ Int .. Low-n WW

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

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)

decay cut: #  
prompt cut: #

**multiplication factors to be applied to e+/e-/gamma transport energy cutoffs**

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				$\Delta t$ :	1.5552E7	p/s: 5.9175E5
				$\Delta t$ :	1.5984E7	p/s: 0.0
				$\Delta t$ :	1.5552E7	p/s: 5.9175E5

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

$\Delta t$ : #

**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.

**Example (see above):**

180 days	185 days	180 days
$5.9 \times 10^5$ p/s	0 p/s	$5.9 \times 10^5$ 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

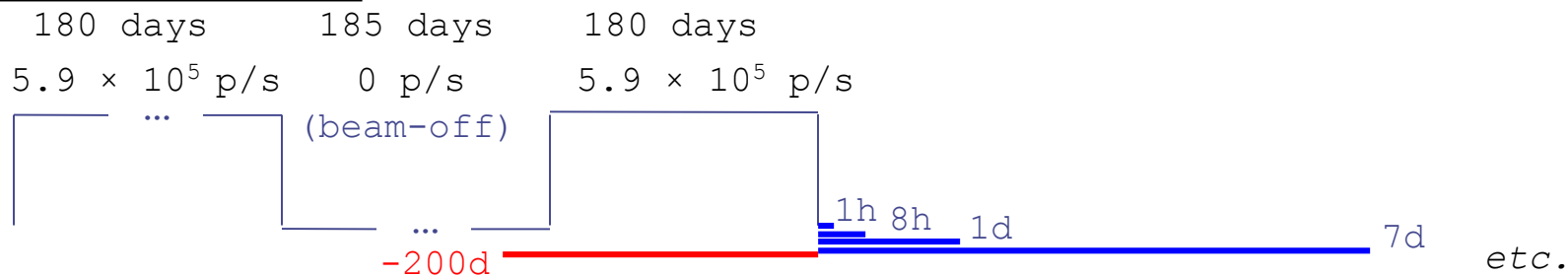
**WHAT(1) – WHAT(6) cooling time (in seconds) after the end of the irradiation**

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			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&

<b>DCYSCORE</b>	Cooling t: 3600. ▼	Kind: USRBIN ▼
	Det: Shielding ▼	to Det: ▼
<b>USRBIN</b>	Unit: 70 BIN ▼	Name: Shielding
Type: X-Y-Z ▼	Xmin: -250.0	NX: 80.0
Part: ALL-PART ▼	Ymin: -200.	NY: 80.0

**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      USBIN PHOTON      Target      EWT74

**AUXSCORE**

Type: USBIN ▼

Part: PHOTON ▼

Set: EWT74 ▼

Det: Target ▼

to Det: ▼

Step:

## WHAT(1)

Type:

## Type of estimator to associate with

drop down list of estimator types (USBIN, USBDX...)

## 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

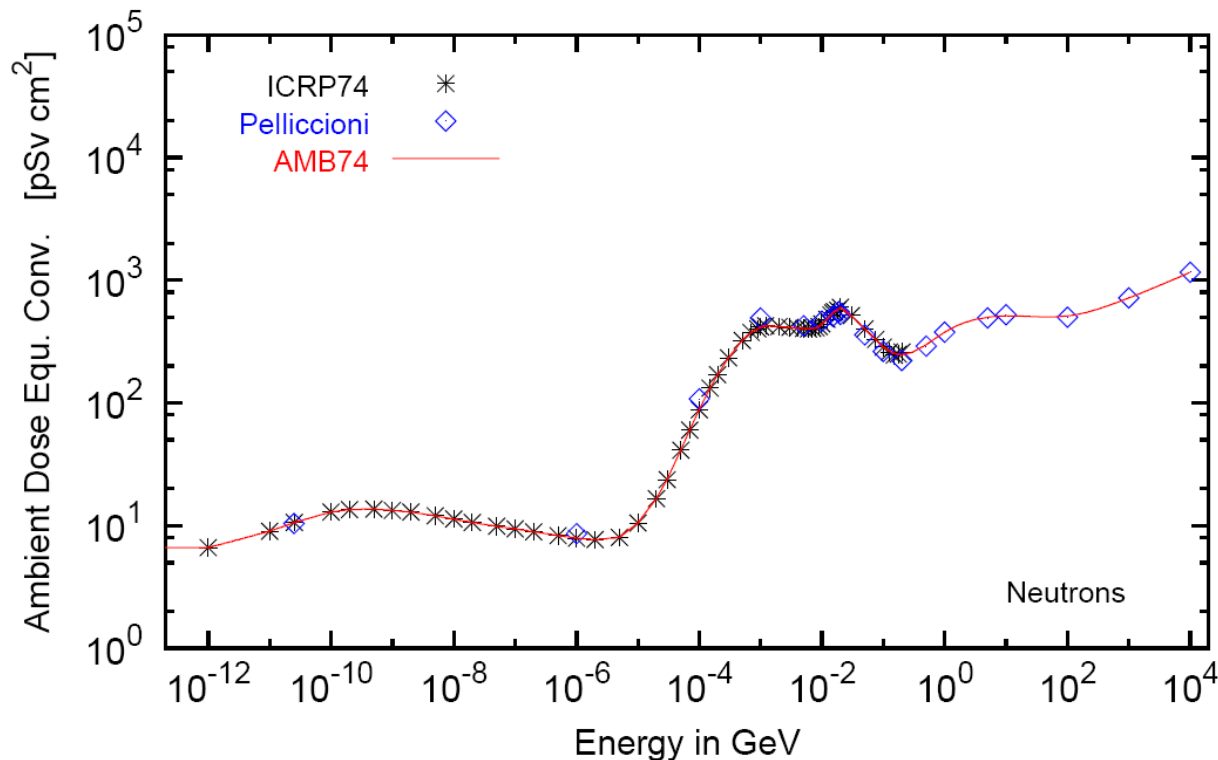
Set:

## Conversion set for dose equivalent (DOSE-EQ) scoring

Drop down list of available dose conversion sets

# Conversion Coefficients

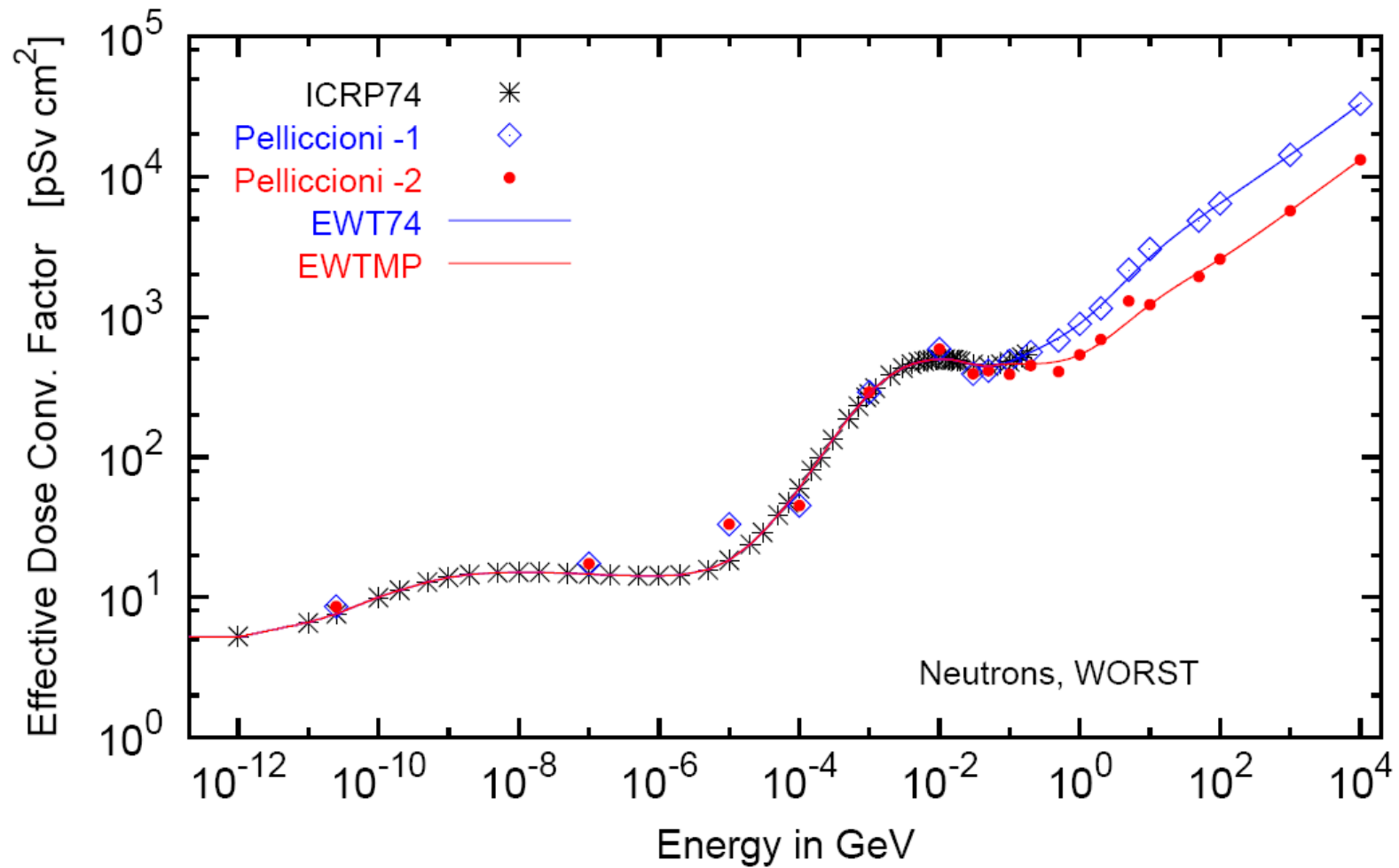
Conversion coefficients from fluence to ambient dose equivalent are based on ICRP74 values and values calculated by M. Pelliccioni. They are implemented for **protons, neutrons, charged pions, muons, photons, electrons** (conversion coefficients for other particles are approximated by these). AMB74 is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



# 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
<b>RESNUCLE</b>	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 [2/3]

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

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

**WHAT(6)**                      volume of the region in cm<sup>3</sup>  
**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 <sup>2</sup>H, <sup>3</sup>H, <sup>3</sup>He, <sup>4</sup>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
PHYSICS	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	PEATHRES

special options for **coalescence** treatment

use **PEANUT model** at all energies

# ISOTOPE 'beam'

## to simulate a radioactive source:

Radioactive source of  $^{60}\text{Co}$  (two main  $\gamma$ -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	0.0	CYLI-VOL

→ request decay by the **RADDECAY** card

# Geometry modifications - 1

120 GeV  
protons

Concrete

Stainless steel target

Concrete

## 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...		

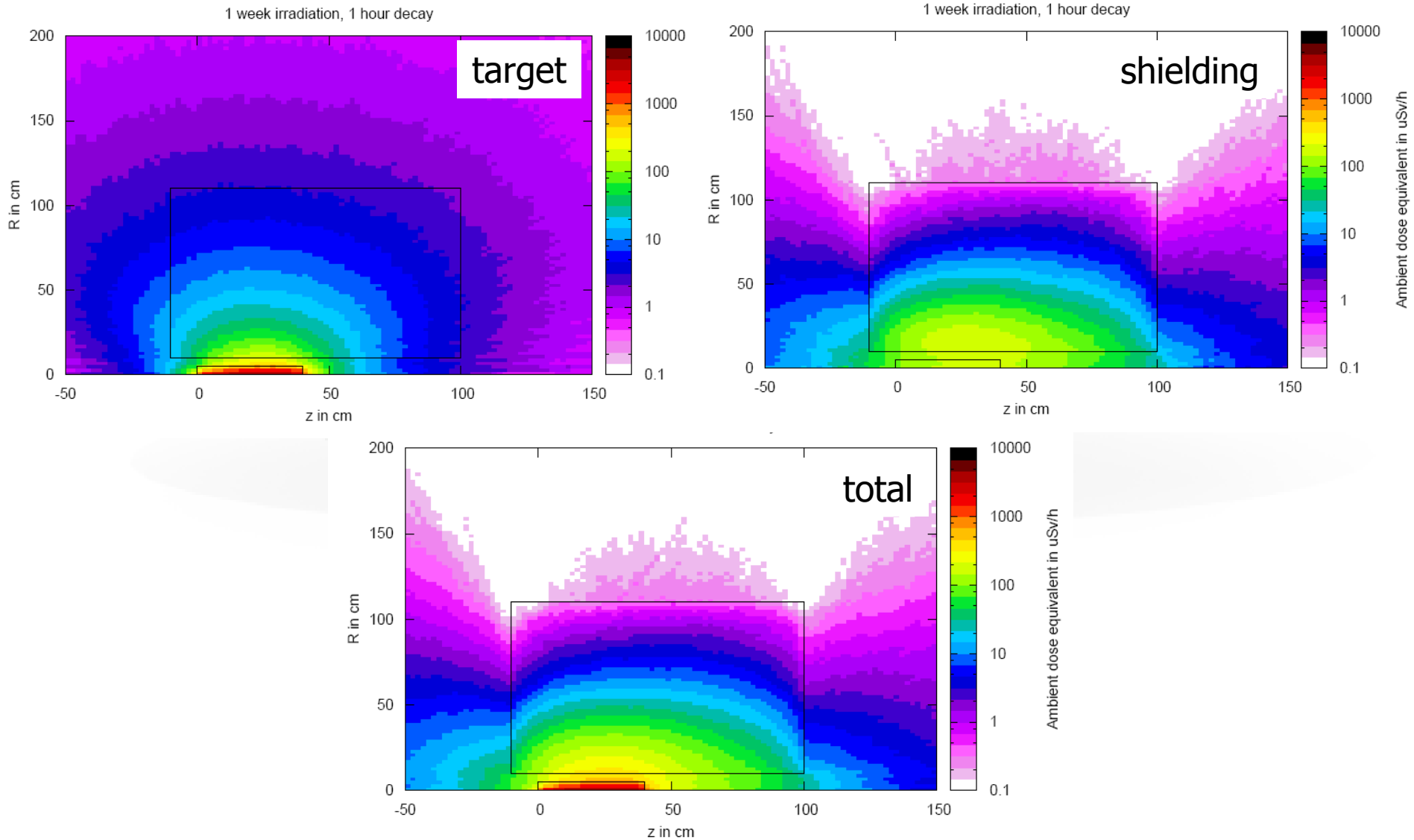
## 2) Shielding only (target set to vacuum)

ASSIGNMA	BLCKHOLE	EXTVOID	
ASSIGNMA	VACUUM	VACTRGT	
ASSIGNMA	SS316L	TARGET	
ASSIGNMA	CONCRETE	SHIELDIN	VACUUM
*	..+....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

## **IRRPROI**

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



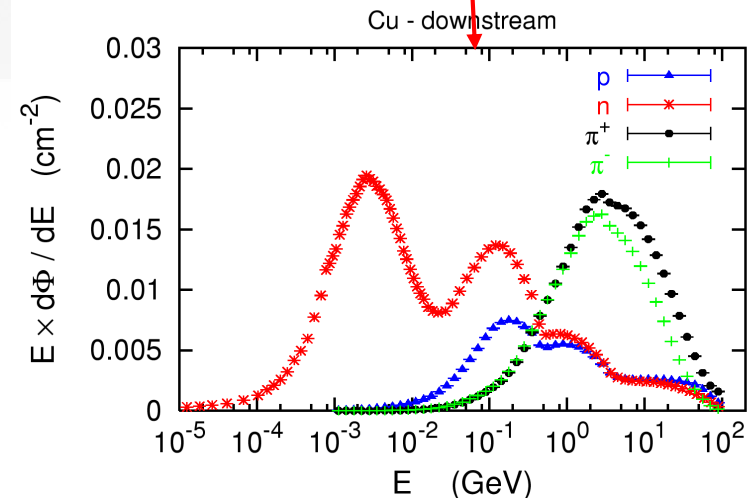
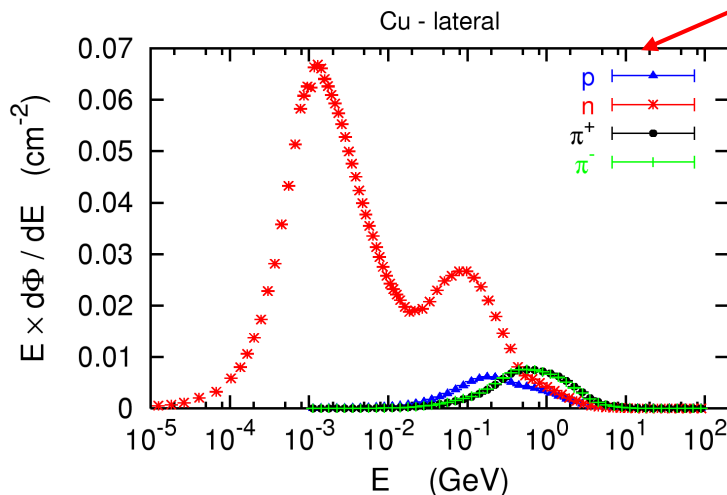
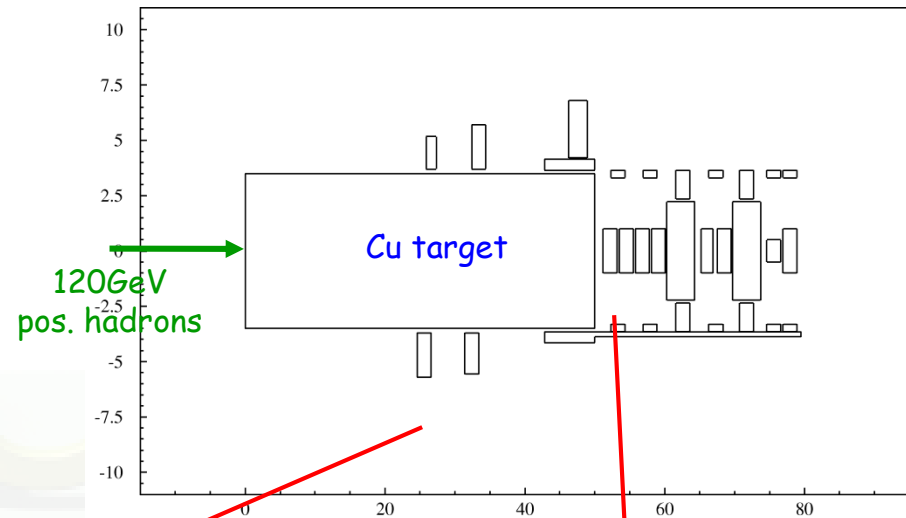


# Benchmarks



# 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<sup>3</sup> 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  $^{22}\text{Na}$  source)
- **physical centre of detector** determined with additional measurements with known sources ( $^{60}\text{Co}$ ,  $^{137}\text{Cs}$ ,  $^{22}\text{Na}$ ) 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		
<sup>7</sup> 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														
<sup>22</sup> 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)	
<sup>24</sup> 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)	
<sup>27</sup> Mg 9.46m							0.79 ± 0.14	M					1.52 ± 0.25	Al,Mg				
<sup>28</sup> 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)	
<sup>28</sup> 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)	
<sup>29</sup> Al 6.56m							0.93 ± 0.25	M										
<sup>38</sup> S 2.84h							0.60 ± 0.12	-										
<sup>m34</sup> Cl 32.00m				0.91 ± 0.19	M		1.19 ± 0.16			0.77 ± 0.15		Fe,Cr,(Mn)				1.25 ± 0.07	Ca	
<sup>38</sup> Cl 37.24m				0.61 ± 0.08			0.60 ± 0.01			0.58 ± 0.07		Fe,Cr,(Mn)						
<sup>39</sup> Cl 55.60m				0.64 ± 0.11	M		0.73 ± 0.08			0.66 ± 0.12		Fe,Cr,(Mn)						
<sup>41</sup> 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	
<sup>38</sup> K 7.64m																1.76 ± 0.20	- Ca	
<sup>42</sup> 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	
<sup>43</sup> 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	
<sup>44</sup> K 22.13m																		
<sup>45</sup> K 17.30m																		
<sup>47</sup> 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	
<sup>43</sup> Sc 3.89h	0.40 ± 0.07	-		1.01 ± 0.14			1.28 ± 0.28	-		0.93 ± 0.15		Fe,Cr,(Mn)						
<sup>44</sup> 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)	
<sup>m44</sup> 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)	
<sup>46</sup> 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)	
<sup>47</sup> 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)	
<sup>48</sup> 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)	
<sup>48</sup> 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	
<sup>48</sup> Cr 21.56h	0.92 ± 0.14			0.97 ± 0.07						1.02 ± 0.08		Fe,(Cr)				1.06 ± 0.23	M Fe	
<sup>49</sup> Cr 42.30m	1.00 ± 0.22	M		1.24 ± 0.12	-					1.06 ± 0.12		Fe,(Cr)						
<sup>51</sup> 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	
<sup>52</sup> 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	
<sup>m52</sup> Mn 21.10m	1.68 ± 0.35			1.24 ± 0.09						1.12 ± 0.10		Fe,(Mn)				1.75 ± 0.79	M Fe	
<sup>54</sup> 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	
<sup>56</sup> 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	
<sup>57</sup> Fe 8.28h				1.09 ± 0.13						0.99 ± 0.19	M	Fe,(Mn)						
<sup>53</sup> Fe 8.51m																		
<sup>58</sup> Fe 44.50d	0.82 ± 0.09																	
<sup>55</sup> Co 17.53h	0.66 ± 0.09			0.76 ± 0.04						1.03 ± 0.05		Fe,Ni						
				1.13 ± 0.10														
<sup>56</sup> 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														
<sup>57</sup> 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				
<sup>58</sup> Co 70.82d	0.91 ± 0.09			0.31 ± 0.08	M					0.98 ± 0.10		Ni	0.82 ± 0.19	Cu,Zn,Ni				
<sup>60</sup> Co 5.27y	0.90 ± 0.08																	
<sup>61</sup> Co 99.00m	0.68 ± 0.08																	
<sup>62</sup> Co 90.00s																		
<sup>57</sup> Ni 35.60h	0.76 ± 0.11									1.44 ± 0.07		Ni						
<sup>65</sup> Ni 2.52h	1.46 ± 0.29																	
<sup>60</sup> Cu 23.70m	0.78 ± 0.08																	
<sup>61</sup> Cu 3.33h	0.87 ± 0.25																	
<sup>64</sup> Cu 12.70h	0.63 ± 0.10																	
<sup>62</sup> Zn 9.19h	1.05 ± 0.23																	
<sup>63</sup> Zn 38.47m																		
<sup>65</sup> 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

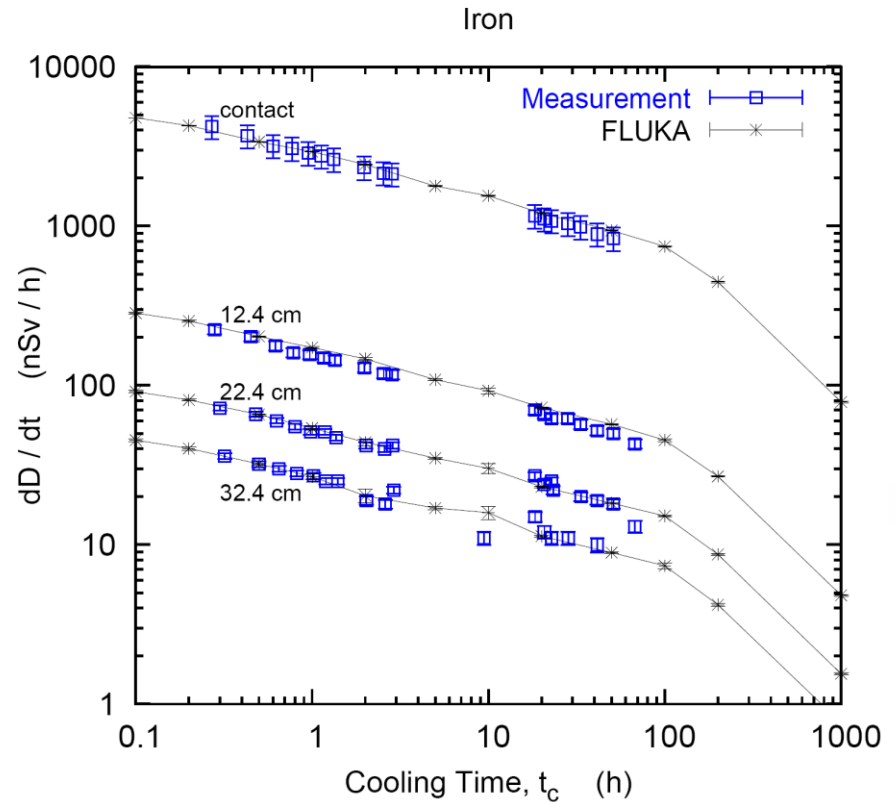
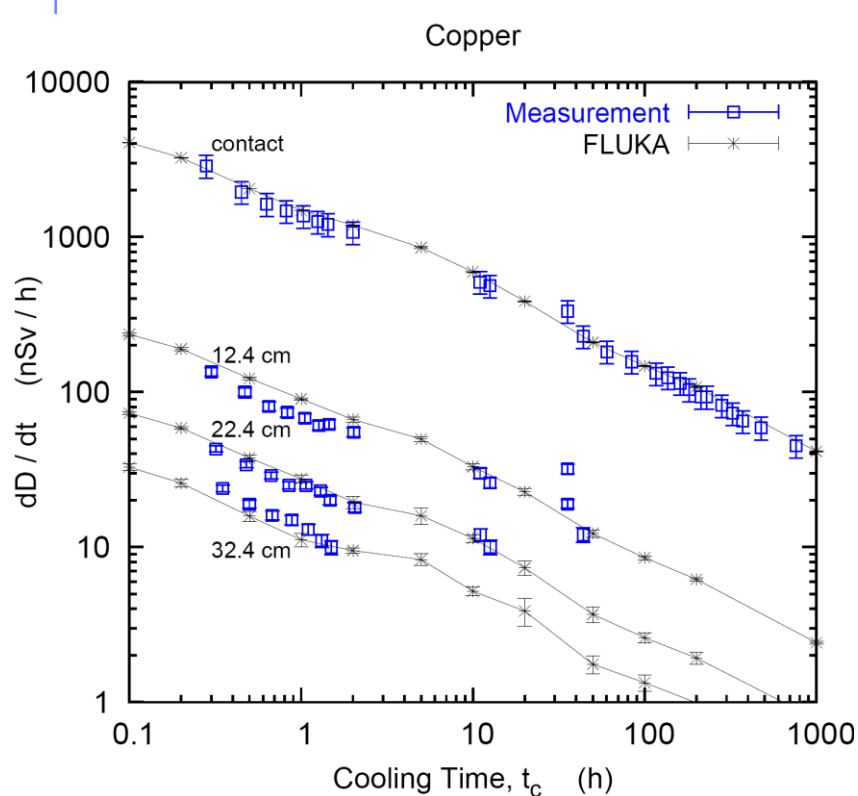
Exp/MDA < 1

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*

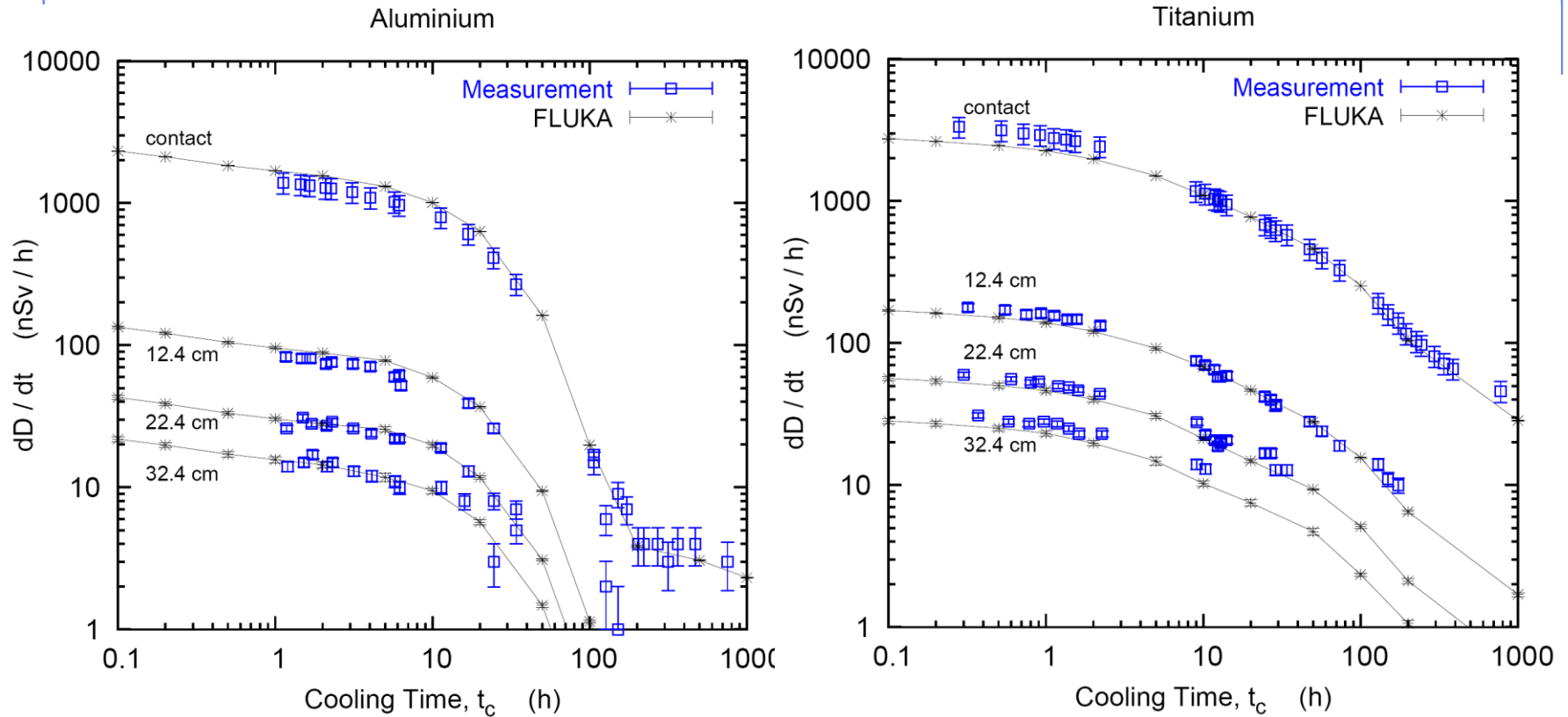
Dose rate as function of cooling time  
for different distances between sample and detector



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



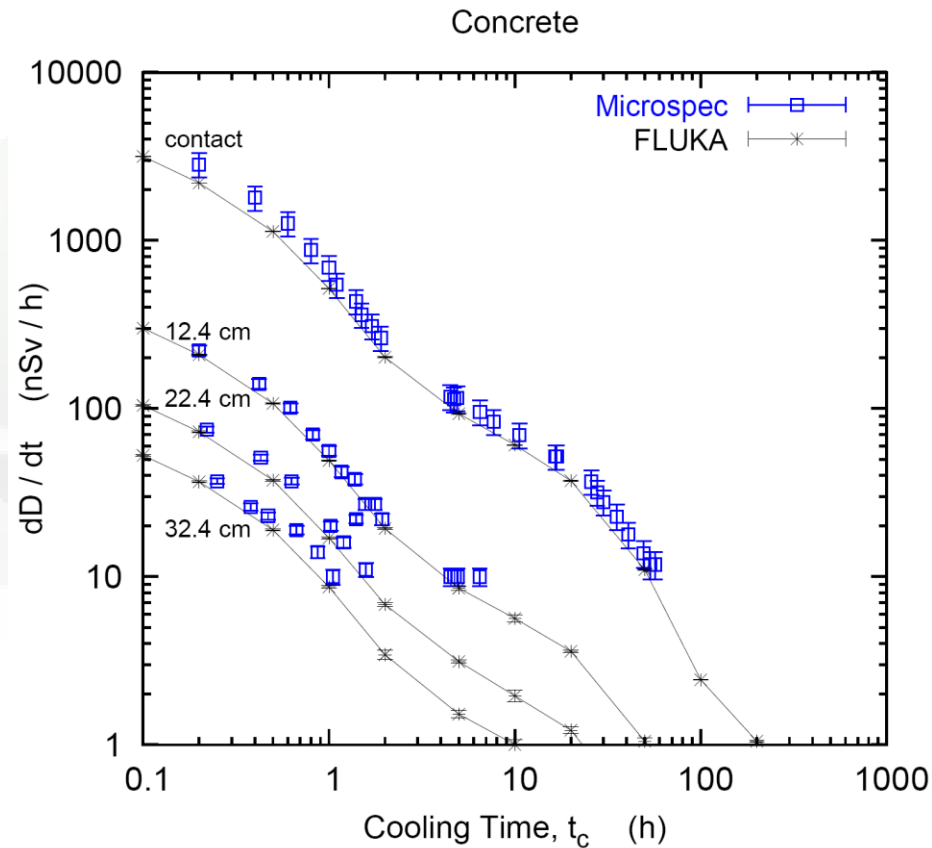
Reference: M. Brugger, S. Roesler *et al.*, Radiat. Prot. Dosim. 116 (2005) 12-15



# 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

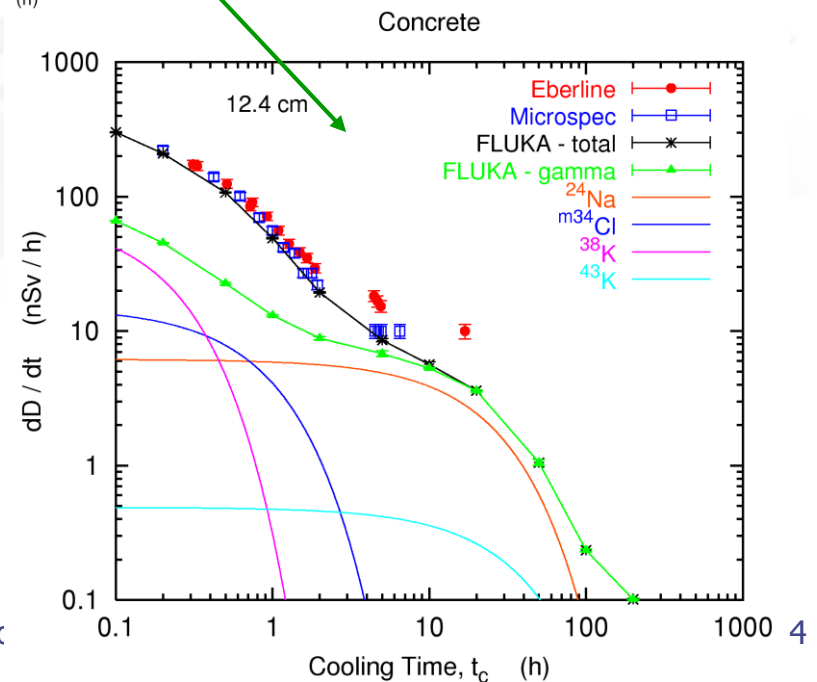
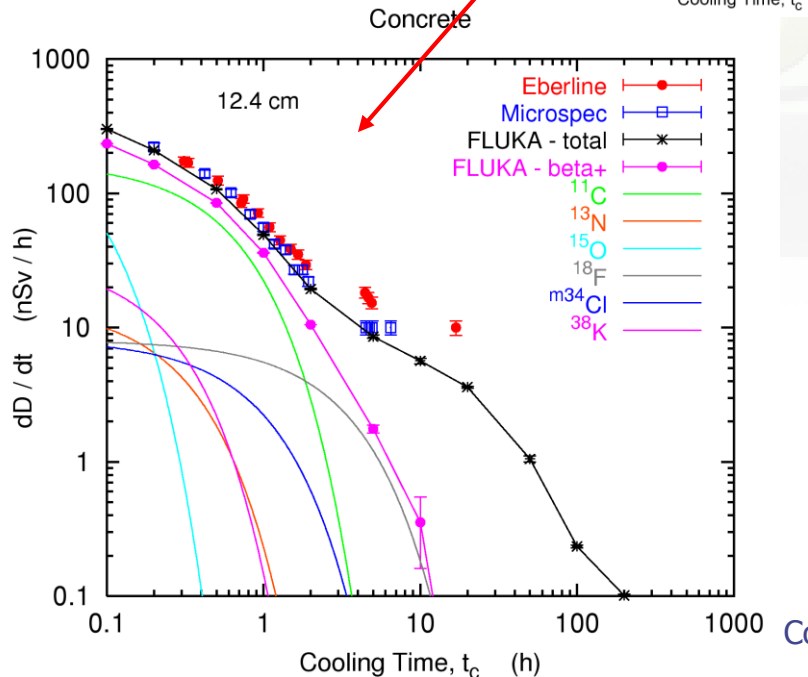
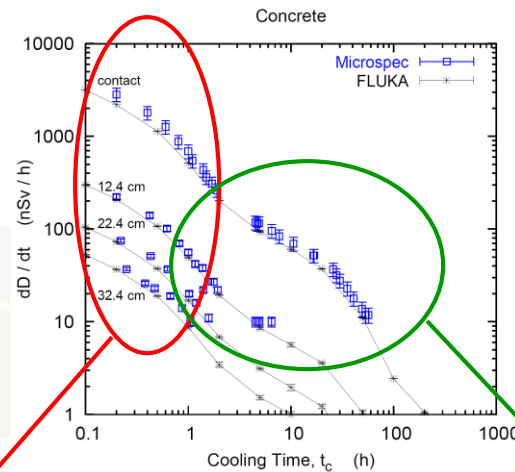
# Benchmark experiment

$t_{\text{cool}} < 2 \text{ hours} :$

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

$2 \text{ hours} < t_{\text{cool}} < 1 \text{ day} :$

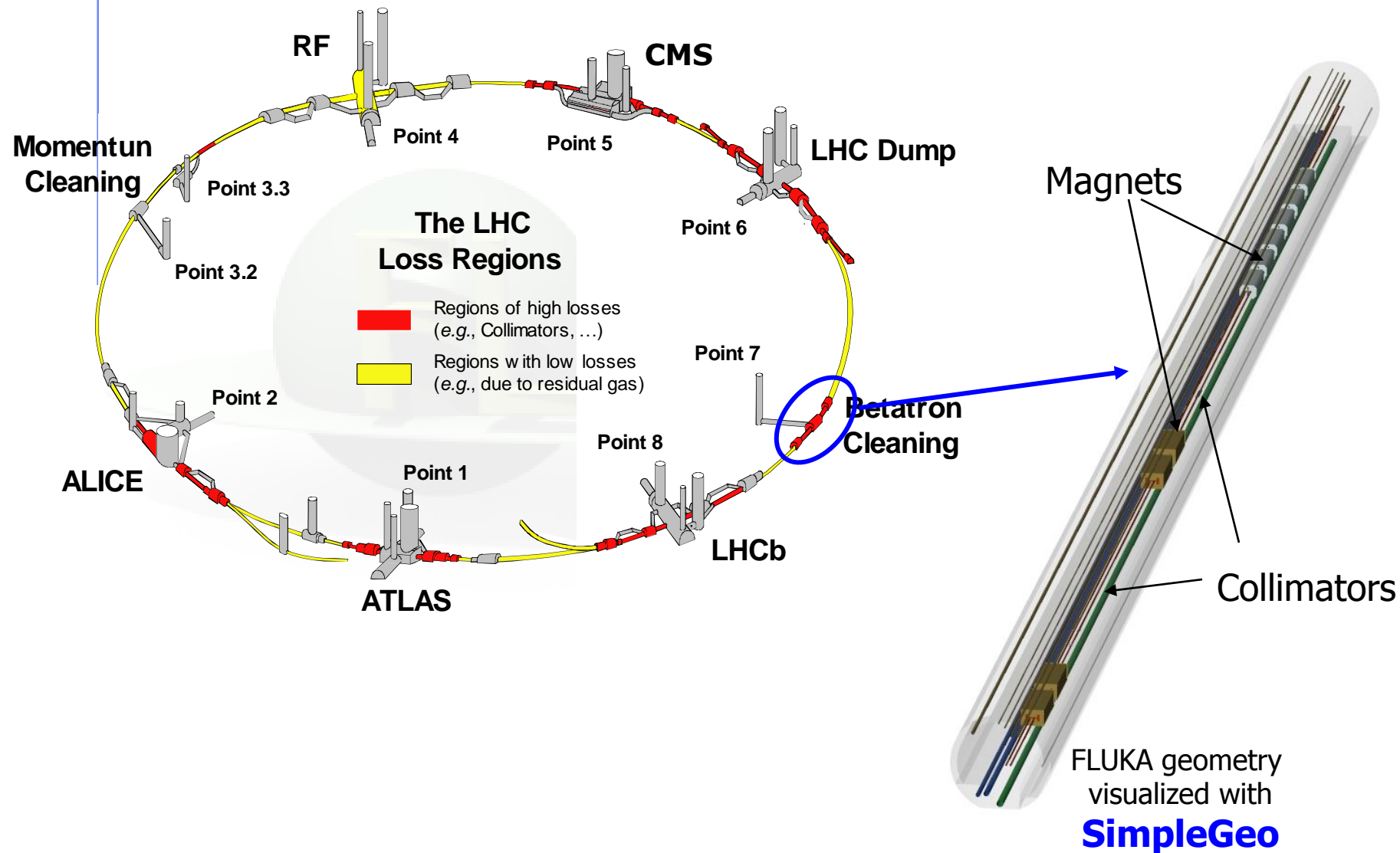
gamma emitter  
( $^{24}\text{Na}$ ,  $t_{1/2} = 14.96\text{hrs}$ )





# Applications

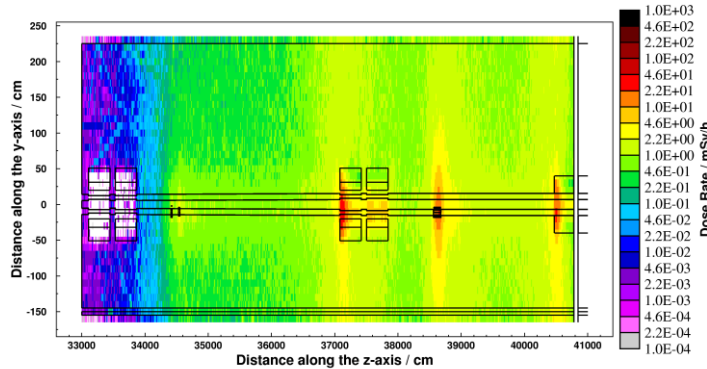
# Applications – *LHC collimation region*



# Applications – *LHC collimation region*

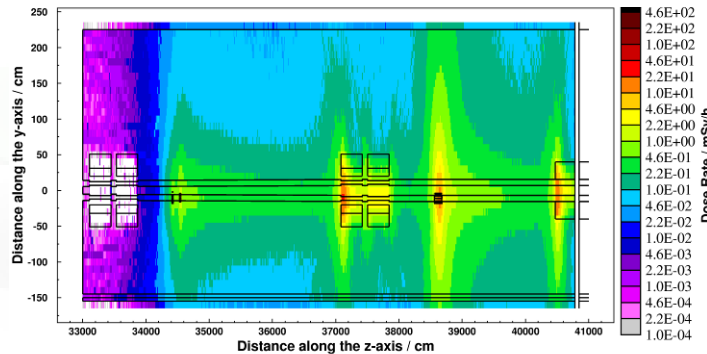
Cooling time

8 hours

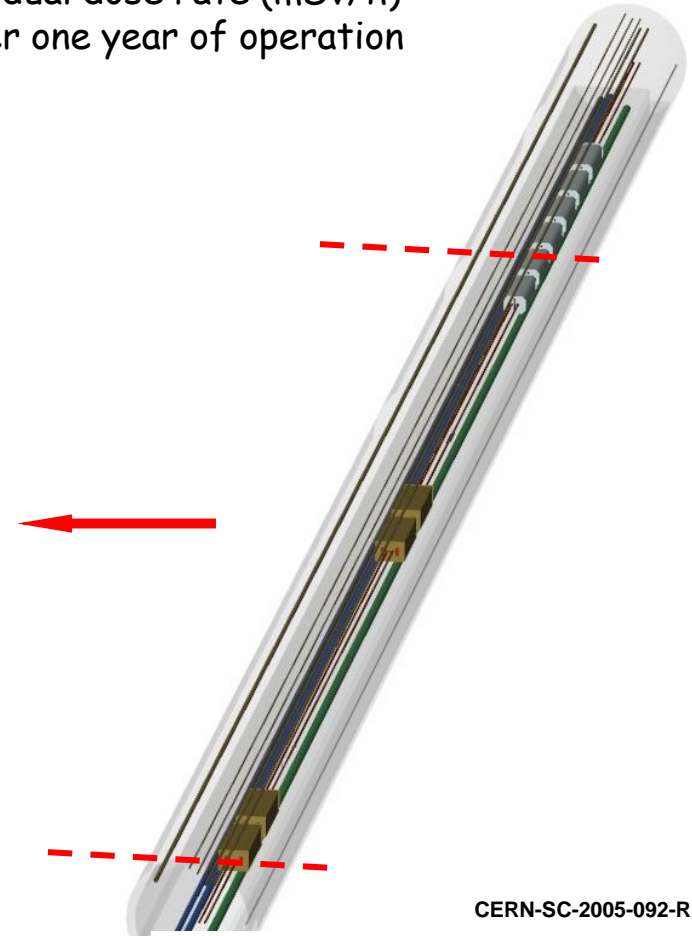
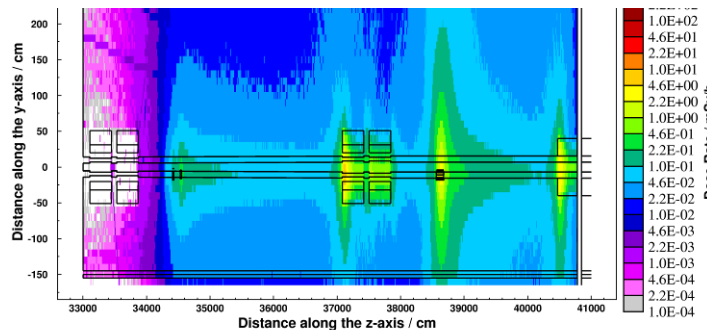


Residual dose rate (mSv/h)  
after one year of operation

1 week



4 months



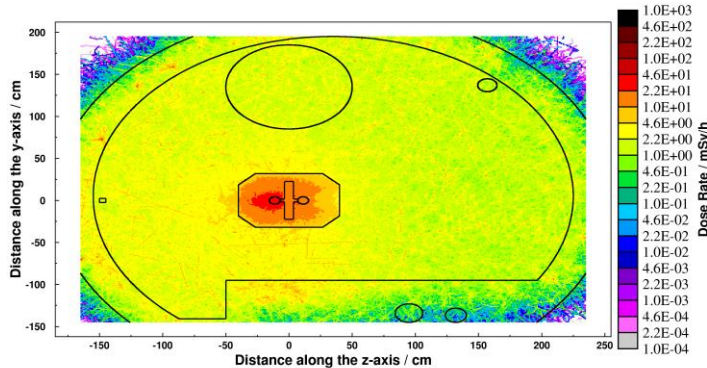
CERN-SC-2005-092-RP-TN  
REMANENT DOSE RATE MAPS  
OF THE LHC BETATRON CLEANING INSERTION (IR7)

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

# Applications – *LHC collimation region*

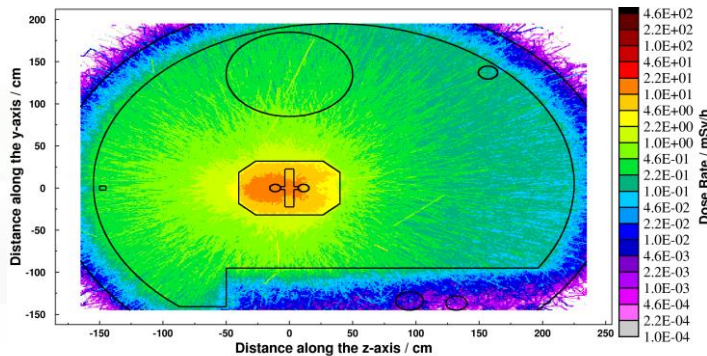
Cooling time

8 hours

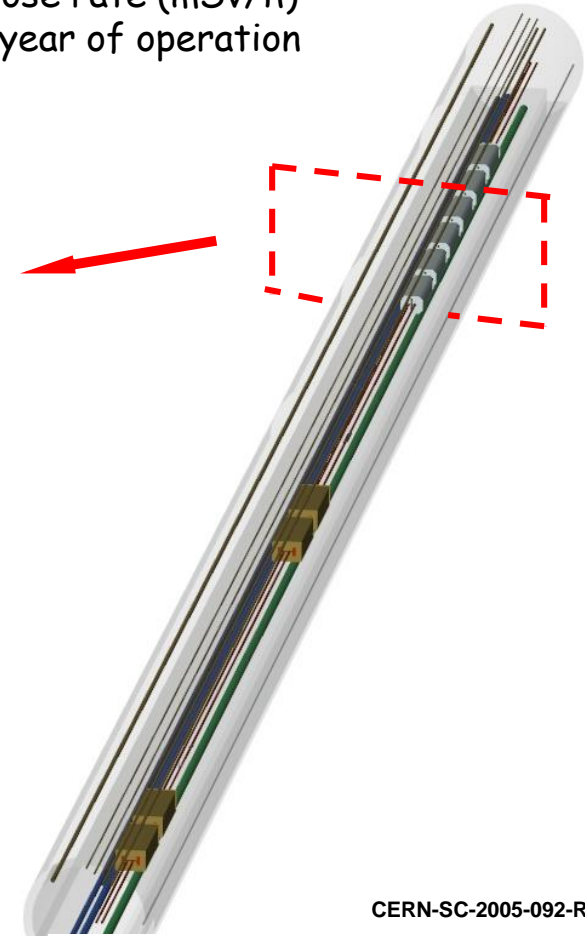
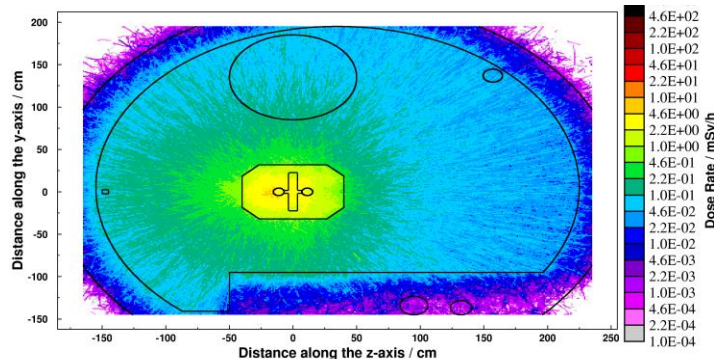


Residual dose rate (mSv/h)  
after one year of operation

1 week



4 months



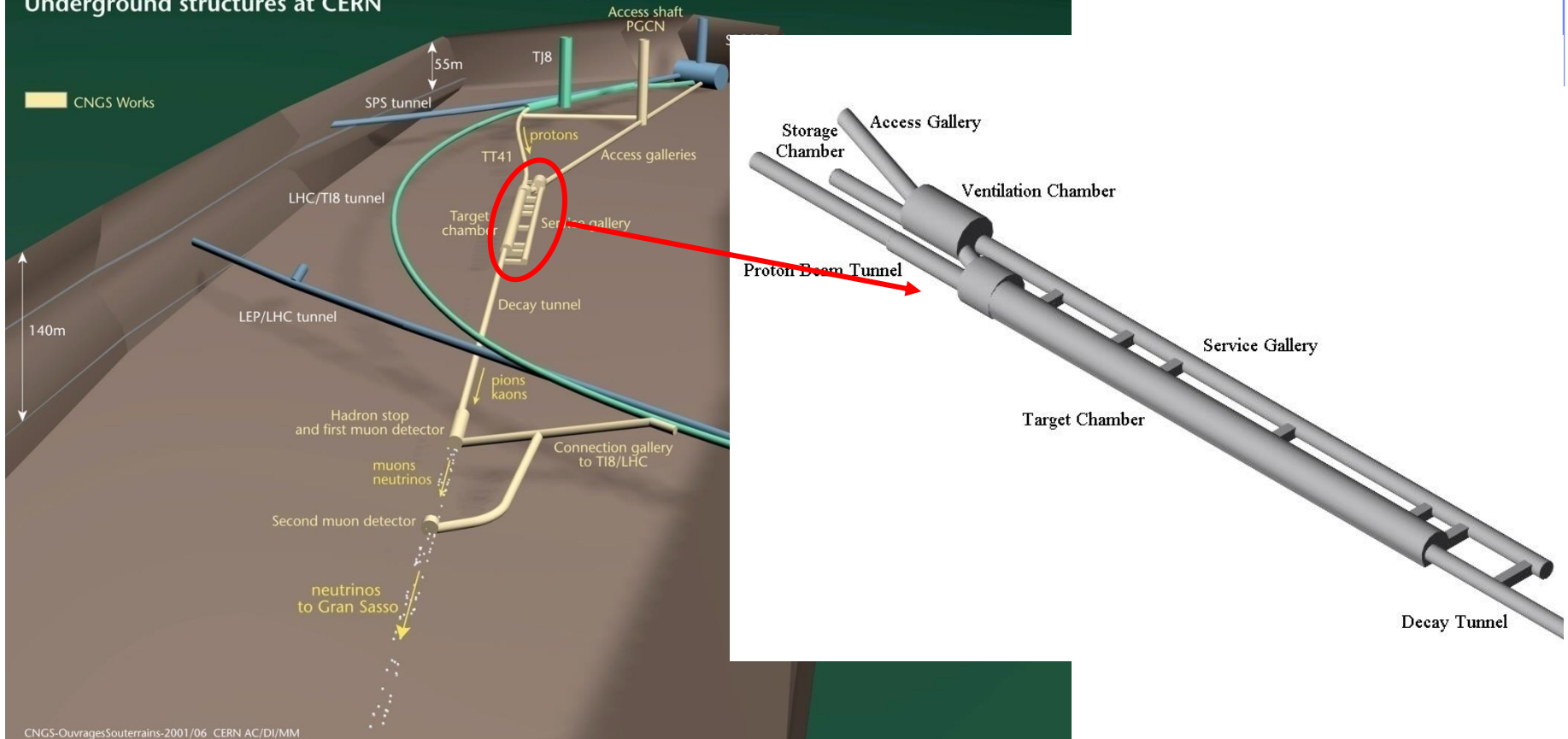
CERN-SC-2005-092-RP-TN  
REMANENT DOSE RATE MAPS  
OF THE LHC BETATRON CLEANING INSERTION (IR7)

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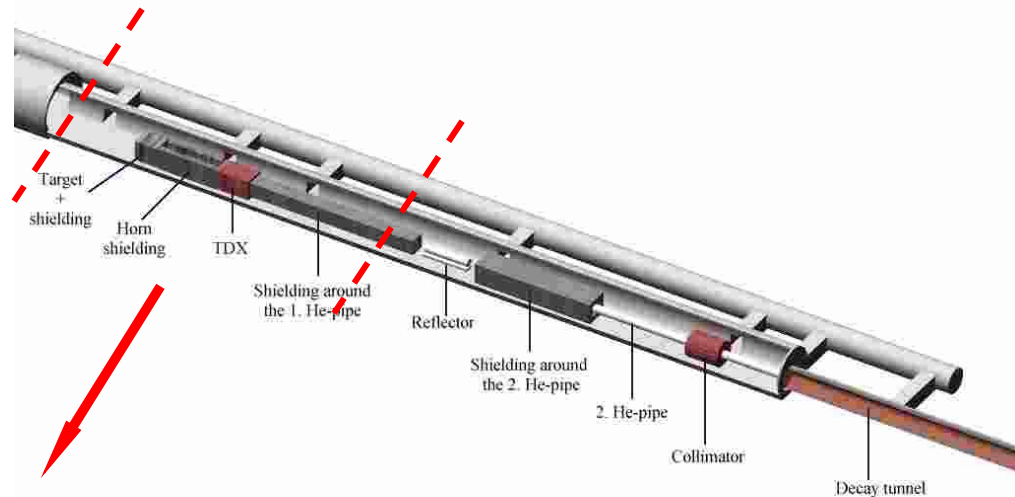


# Applications – *CNGS*

## CERN NEUTRINOS TO GRAN SASSO Underground structures at CERN

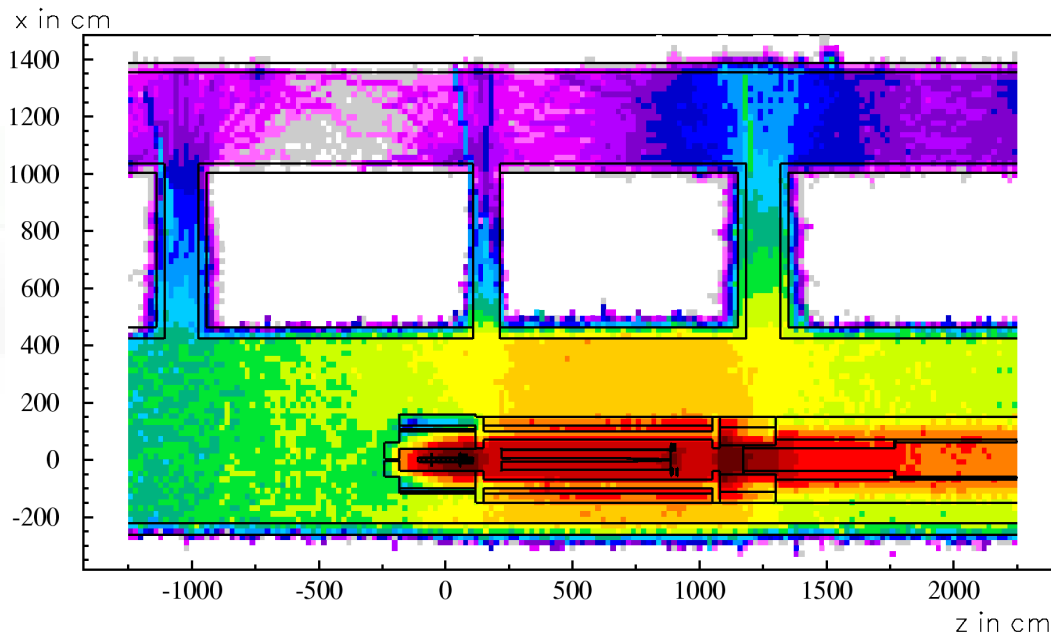


# Applications – CNGS

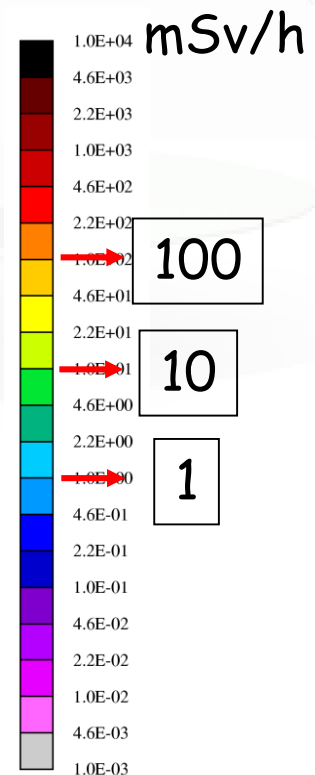


Example:

$t_{\text{cool}} = 1 \text{ day}$

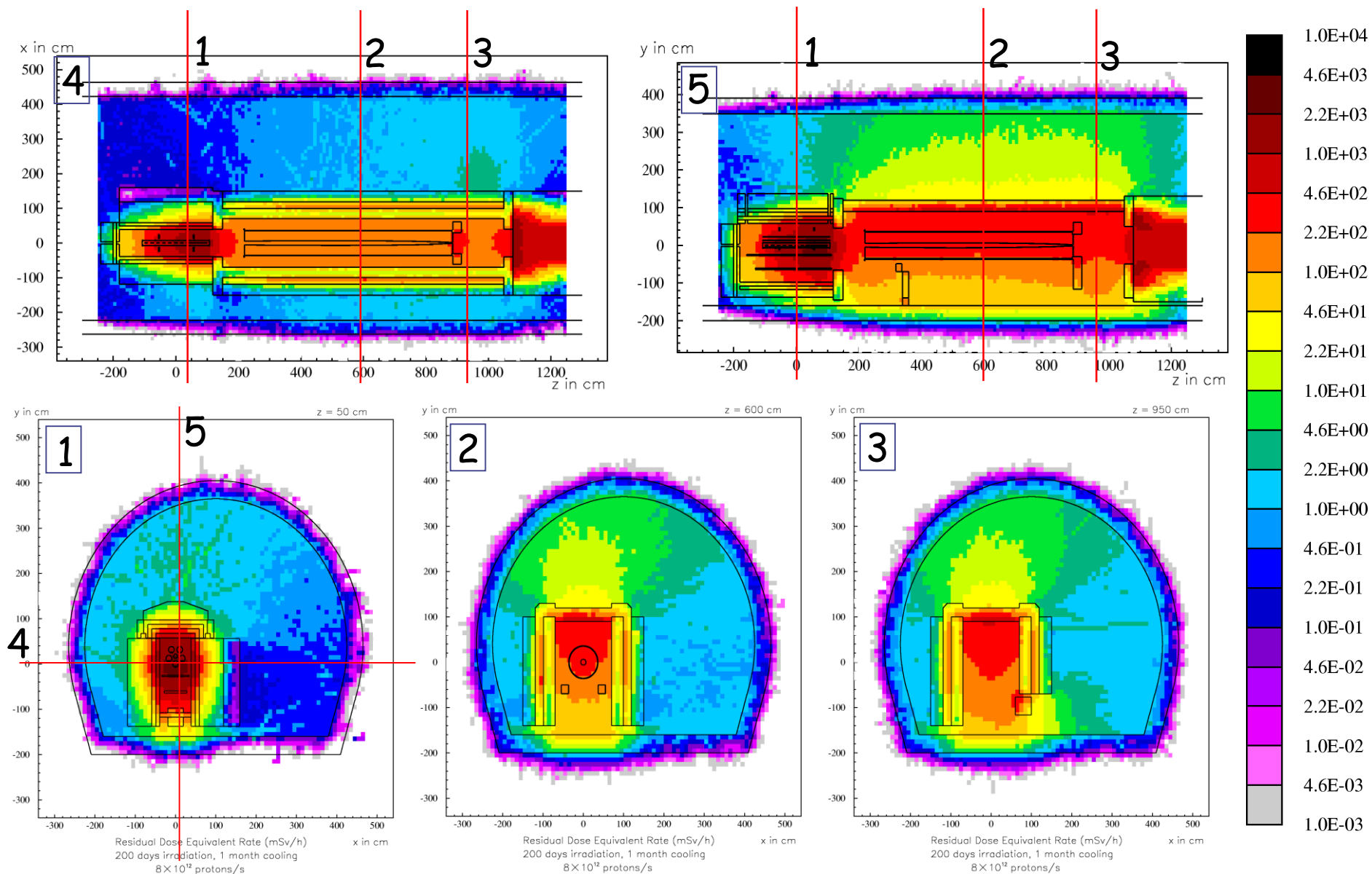


Residual Dose Equivalent Rate (mSv/h)  
200 days irradiation, 1 day cooling  
 $8 \times 10^{12} \text{ protons/s}$





# Applications – *CNGS*





# Miscellaneous

# 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 radionuclides for certain irradiation parameters 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.