# Induced Activity

21st FLUKA Beginners' Course

ALBA – Barcelona, Spain

08 – 12 April 2019

# FLUKA-Implementation – *Main features*

The generation and transport of decay radiation (limited to γ, b-, b+, X-rays, and Conversion Electrons emissions for the time being) is possible during the same simulation which produces the radionuclides (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.

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 arbitrary 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.

  **NOTE:** In future major release branchings for isomers produced by neutrons <20 MeV will be based on JEFF → no more simple 50/50 share
- 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

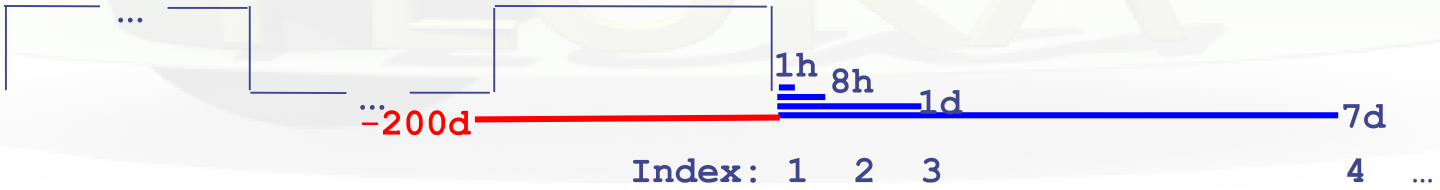
requests simulation of decay of produced radioactive nuclides and allows to modify biasing and transport thresholds (defined with other cards) for the transport of decay radiation

Input card: IRRPROFI

definition of an irradiation profile (irradiation times and intensities)

Input card: DCYTIMES

definition of decay (cooling ) times measured from end of irradiation cycle (t=0)




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 |

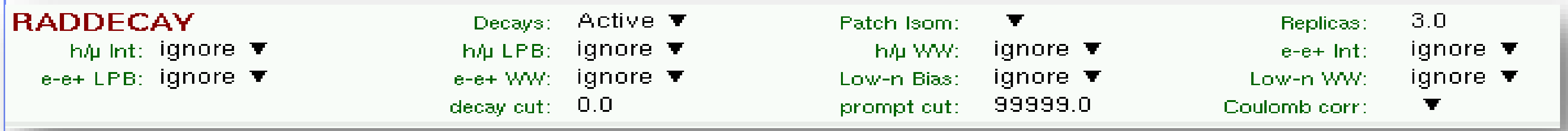
# Card: RADDECAY [1/3]

```
* 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. 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 [2/3]




**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)

# Card: RADDECAY [3/3]


**WHAT(5)** **multiplication factors to be applied to e+/e-/gamma transport energy cutoffs (defined with EMF-CUT cards)**

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

XXXXXYYYYY

10 x Factor for decay radiation

10 x Factor for prompt radiation

e.g.:

0001000200

0.1 x 10 = 1 → decay radiation production and transport thresholds for EMF are not modified

0.1 x 200 = 20 → prompt radiation threshold increased by x 20

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

Notes: Each card has 6 inputs with 3 durations / intensities (intercalated). Several cards can be combined . Sequence order is assumed from first card (top) to last (bottom)

**Example (see above):**

| | | |
|---|---|---|
| 180 days | 185 days | 180 days |
| $5.9 \times 10^5$ p/s | 0 p/s (beam-off) | $5.9 \times 10^5$ 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
```

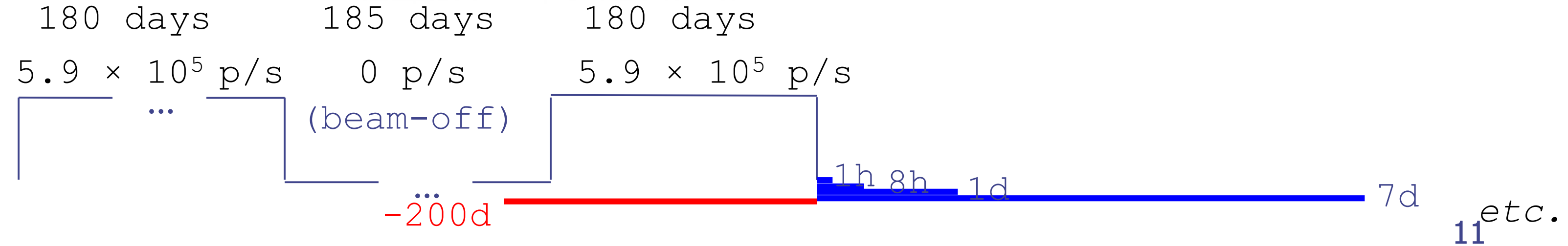
**DCYTIMES** 1hour 8hours 1day 7days 1month 4months

| | | | | | |
|---|---|---|---|---|---|
| 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.

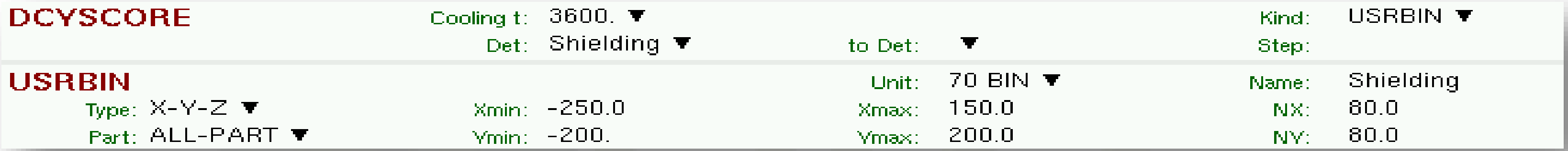
Each cooling time is assigned an index, following the order in which it has been input. This index can be used in option DCYSCORE to assign that particular cooling time to one or more scoring detectors. A negative decay time is admitted: scoring is performed at the chosen time "during irradiation"

*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&
```




**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…

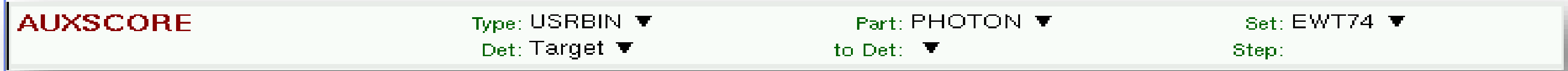
Units: **All quantities are expressed per unit time.** For example
RESNUCLE Bq
USRBIN fluence rate / dose rate

# 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
```




**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: #

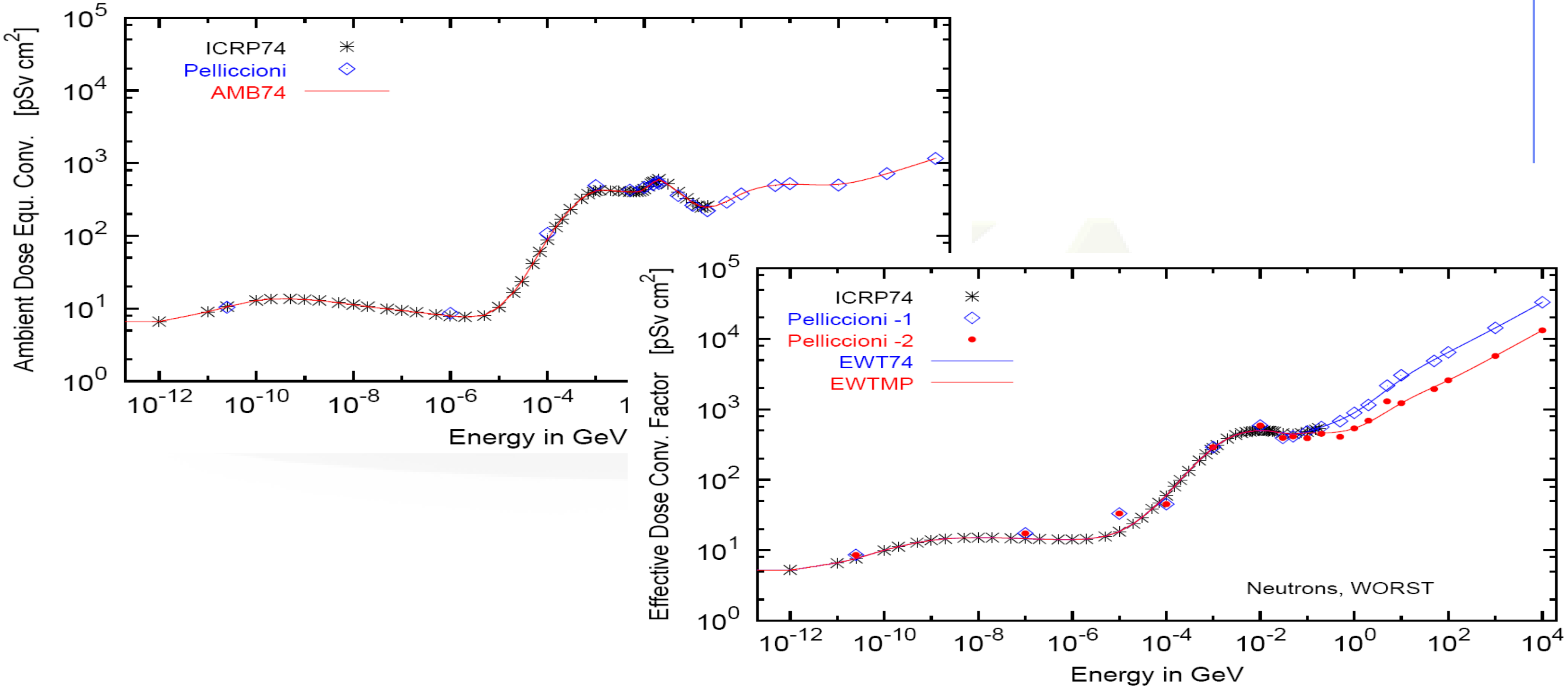
**SDUM** **Conversion set for dose equivalent (DOSE-EQ) scoring**
Set: Drop down list of available dose conversion sets

**NOTE:** This card is NOT just for activation-type scorings. It can be used for prompt radiation.

# Fluence to effective dose coefficients

- AMB74 is the default choice for dose equivalent calculation (scoring DOSE-EQ without AUXSCORE card)
- 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=EWT74) and recommended by M. Pelliccioni (e.g., SDUM=EWTMP).
- 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

# Conversion Coefficients (Examples)




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

# Card: RESNUCLEi [1/3]

```
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 (all inelastic interactions except for low-energy neutron interactions, i.e. with multigroup treatment)
- 2.0 products from low-energy neutron interactions (provided the information is available)
- 3.0 all residual nuclei are scored (if available, see above)
- <= 0.0 resets the default (= 1.0)

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

Unit:

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

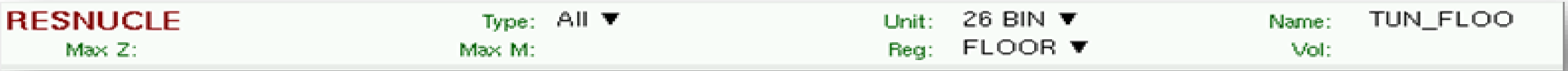
Max Z: Default: according to the Z of the element(s) of the material assigned to the scoring region

**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. Note: also protons are scored (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 evaporation of heavy fragments (up to A=24, CPU expensive)

```
PHYSICS          3.0                                                  EVAPORAT
PHYSICS          1.0                                                  COALESCE
PHYSICS       1000.0    1000.0    1000.0    1000.0    1000.0    1000.0PEATHRES
```

special options for coalescence treatment

use PEANUT model at all energies

# ISOTOPE 'beam'

**to simulate a radioactive source:**

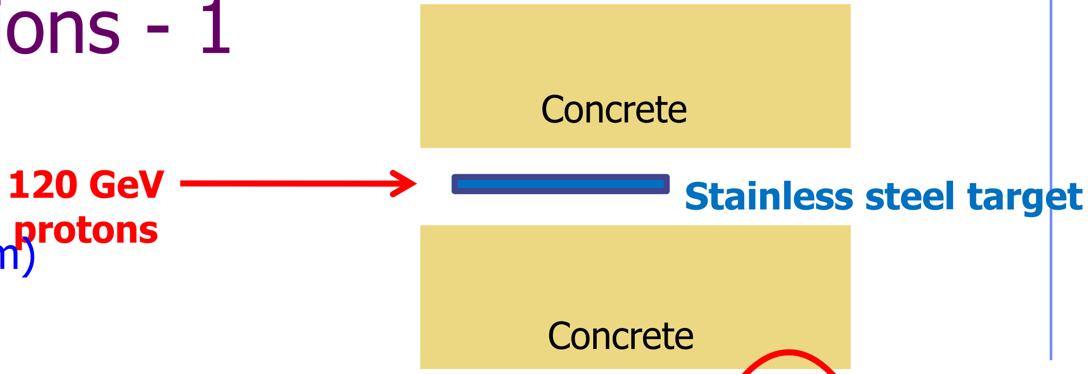
Radioactive source of $^{60}Co$ (two main γ-emissions: 1332.5 keV and 1173.2 keV)
cylindrical shape, 2cm diameter, 2mm height along z, centre of base of cylinder at origin

```
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
```

| | | | |
|---|---|---|---|
| BEAM | Beam: Momentum | p: | Part: ISOTOPE |
| Δp: Flat | Δp: | Δϕ: Flat | Δϕ: |
| Shape(X): Rectangular | Δx: | Shape(Y): Rectangular | Δy: |
| BEAMPOS | Rin: 0.0 | Rout: 15.0 | Type: SPHE-VOL |
| BEAMPOS | x: 0.0 | y: 0.0 | z: 0.0 |
| | cosx: | cosy: | Type: NEGATIVE |
| HI-PROPE | Z: 39. | A: 90. | Isom: |

→ request decay by the RADDECAY card

# 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

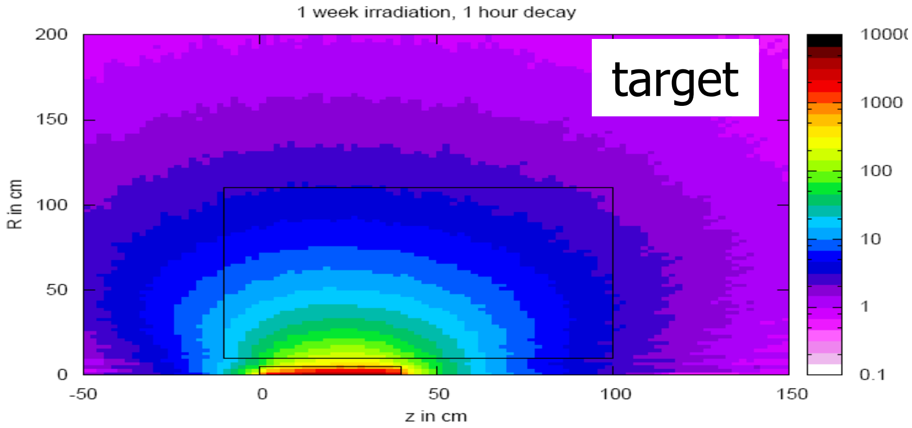
**Material for second step:**

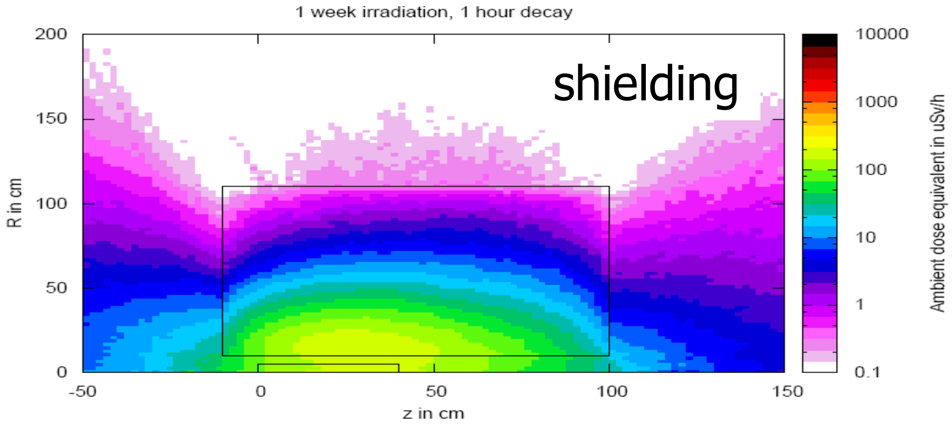
Can only be set to VACUUM or BLCKHOLE, not to AIR or any other material. Otherwise, the following error is obtained:

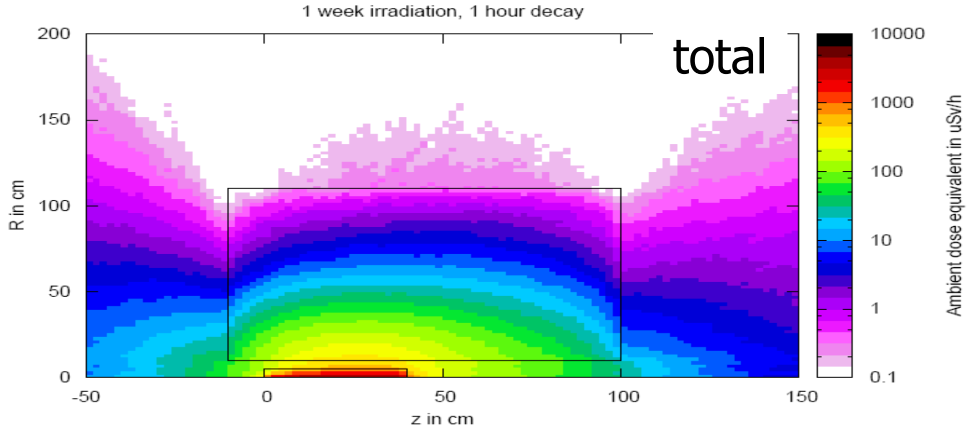
*** Vacuum and Blackhole only permitted as alternate radioactive product material ***
Abort called from ASMCRD reason RAD. DECAY MAT NOT 1/2 Run stopped!
STOP RAD. DECAY MAT NOT ½

Future FLUKA releases will allow setting other materials for second step (e.g. to simulate insertion of 'fresh' shielding for activation). These effects can be currently estimated only with 'third-party' two-step methods

# Geometry modifications - 3



# 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

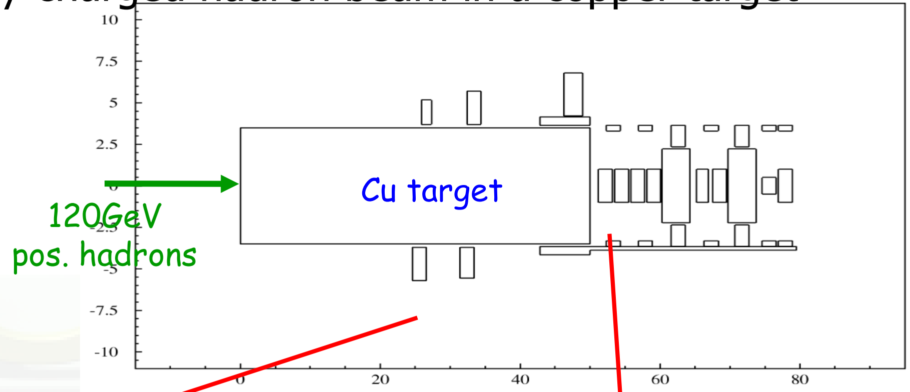
switch to activate the evaporation of heavy fragments (up to A=24) and the simulation of coalescence

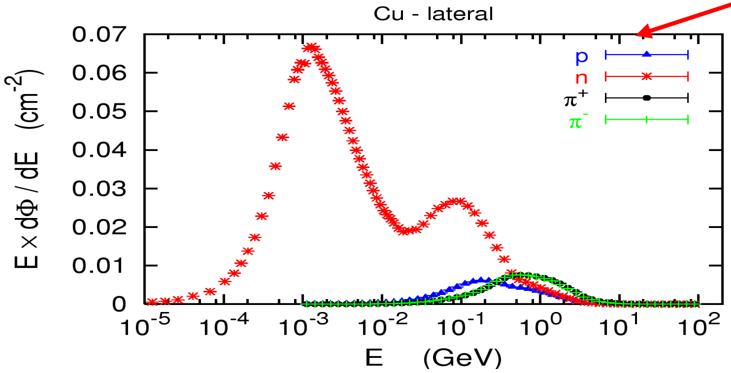
# Backup slides

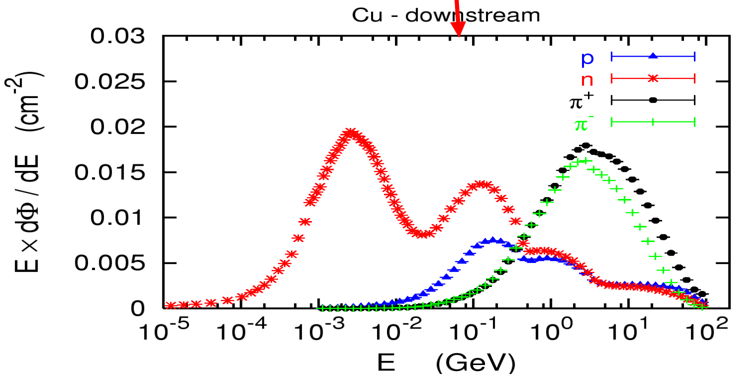
# Benchmarks

# 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

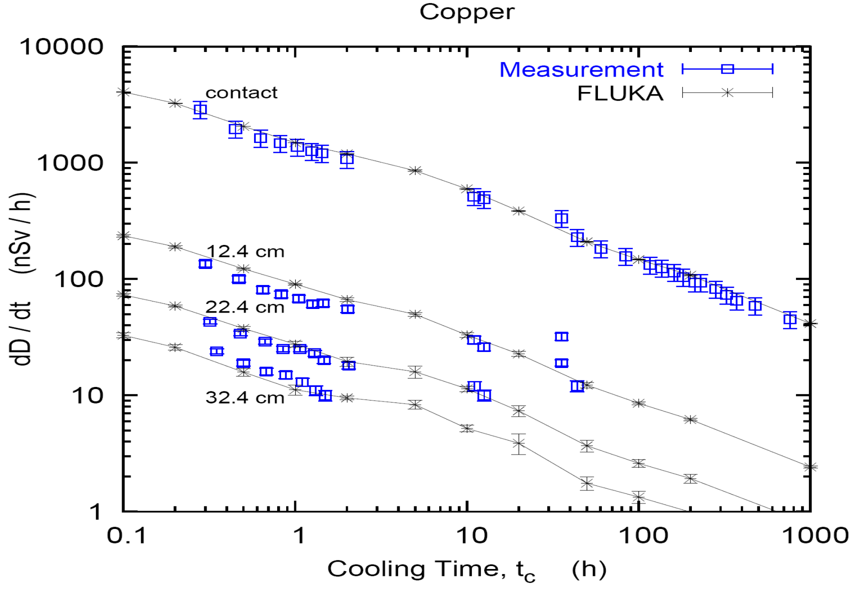
- 0.8 < R < 1.2 (green)
- 0.8 < R ± Error < 1.2 (yellow)
- Exp/MDA < 1 (orange)
- R + Error < 0.8 or R – Error > 1.2 (pink)

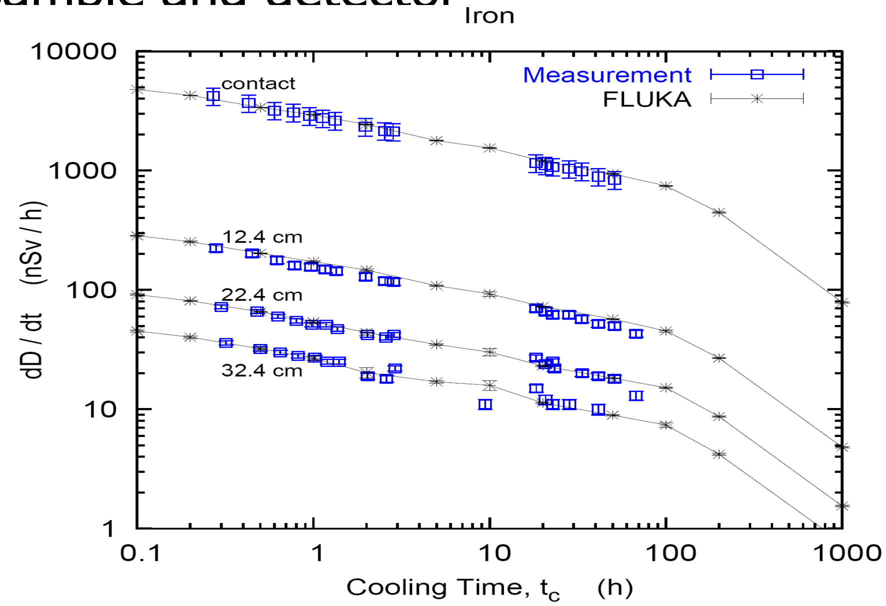

Reference:
M. Brugger, S. Roesler *et al.*, Nuclear Instruments and Methods A 562 (2006) 814-818

# Benchmark experiment – *Results 1*

## Dose rate as function of cooling time

for different distances between sample and detector



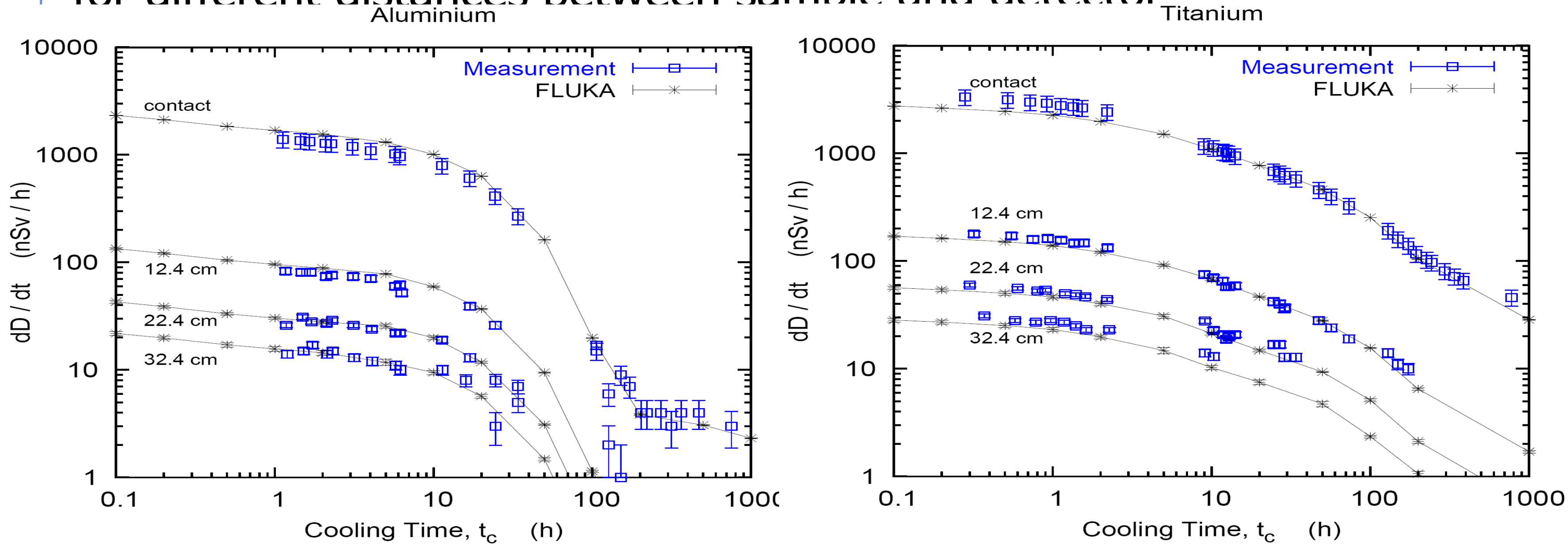




<u>Reference:</u> M. Brugger, S. Roesler *et al.*, Radiat. Prot. Dosim. 116 (2005) 12-15

# Benchmark experiment – *Results 2*

## Dose rate as function of cooling time

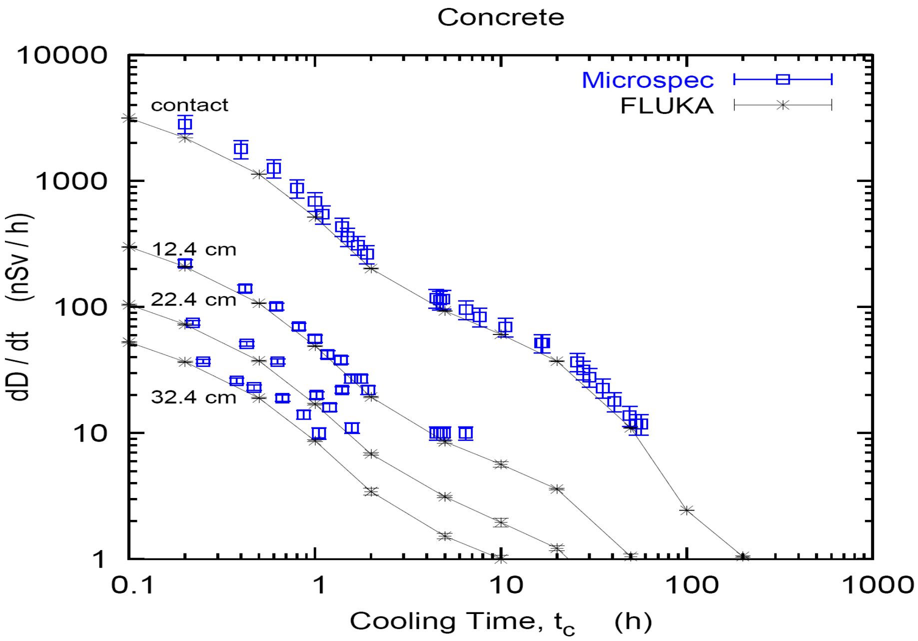
for different distances between sample and detector




<u>Reference:</u> 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

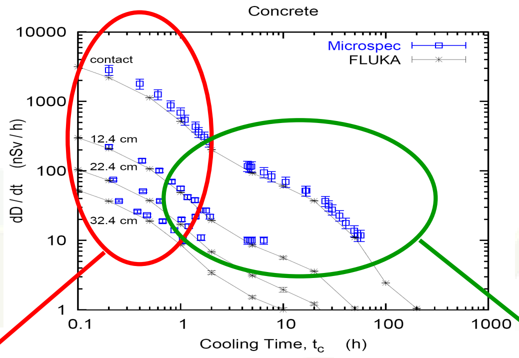



<u>Reference:</u> M. Brugger, S. Roesler *et al.*, Radiat. Prot. Dosim. 116 (2005) 12-15

# Benchmark experiment

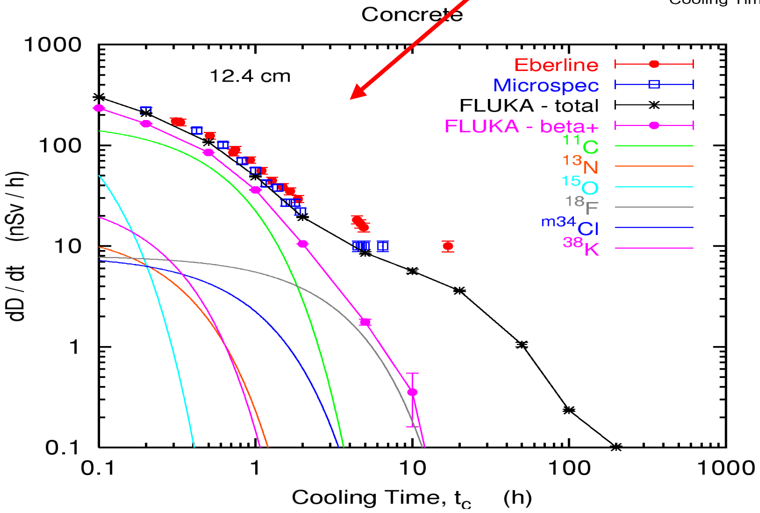
$t_{cool}$ < 2 hours :

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

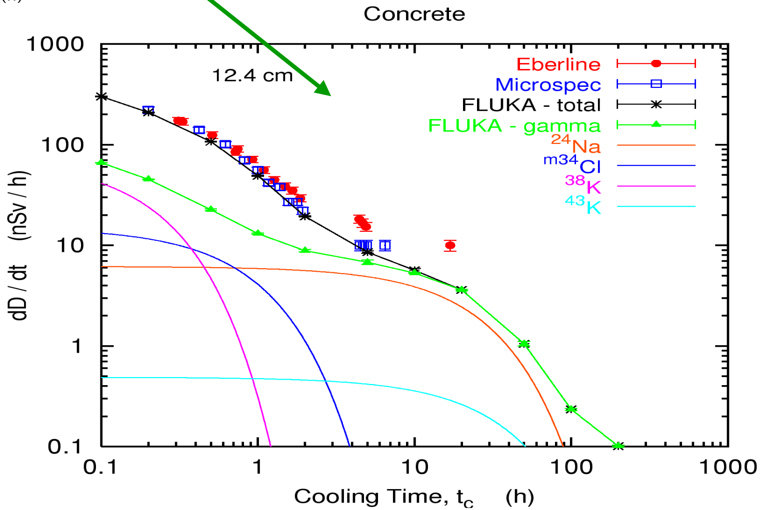



2 hours < $t_{cool}$ < 1 day :

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

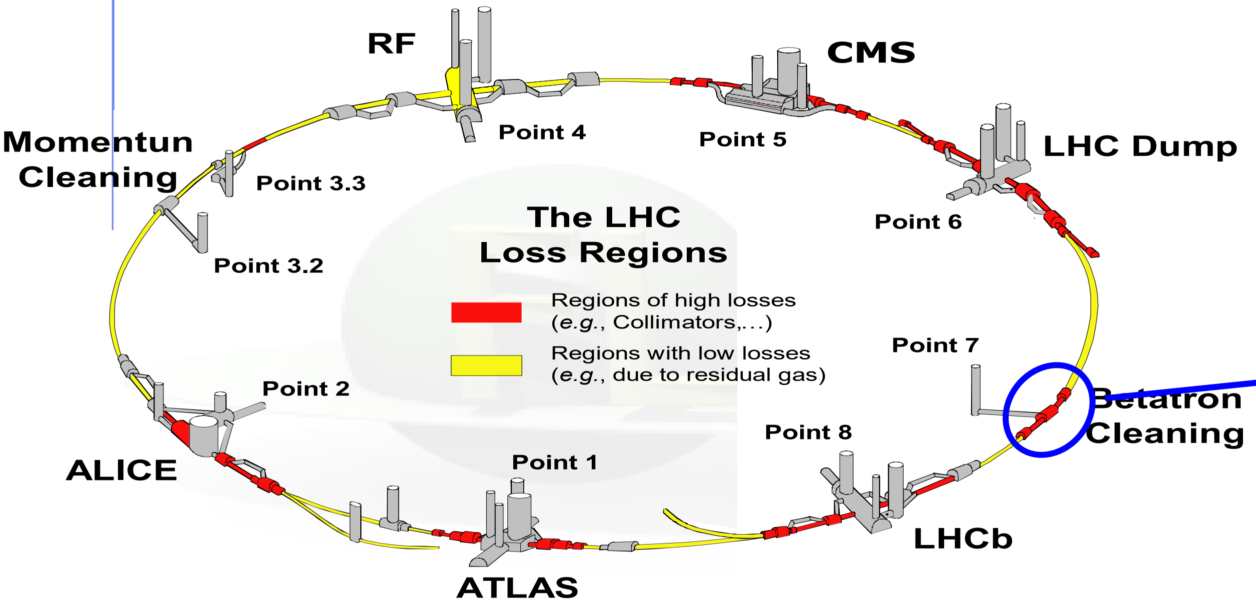


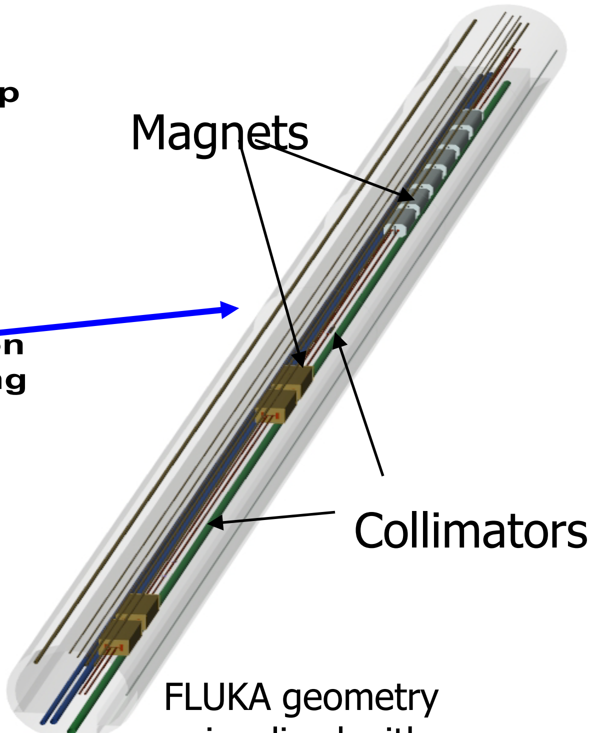

Cc



# Applications

# Applications – *LHC collimation region*




FLUKA geometry
visualized with
**SimpleGeo**

# Applications – *LHC collimation region*

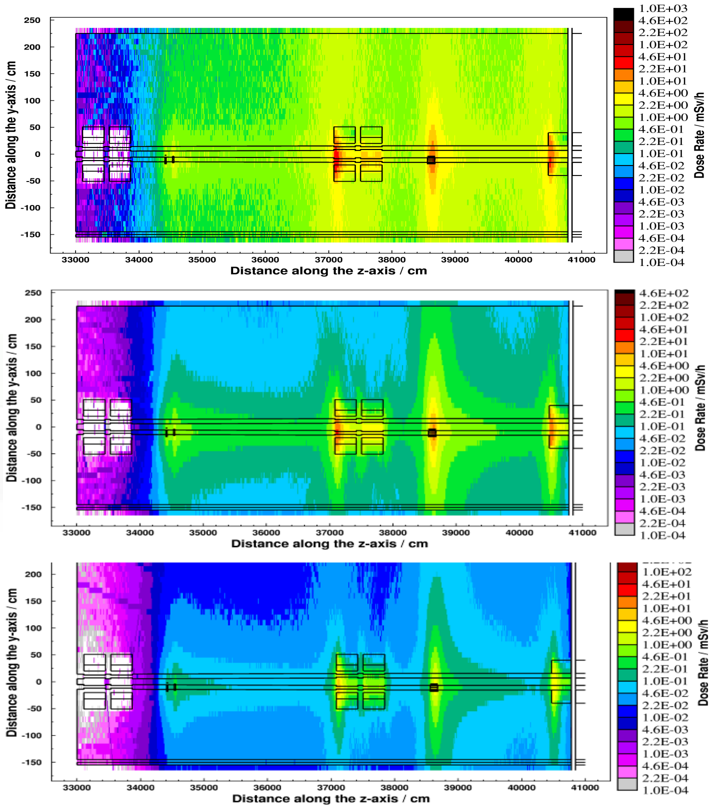
Cooling time

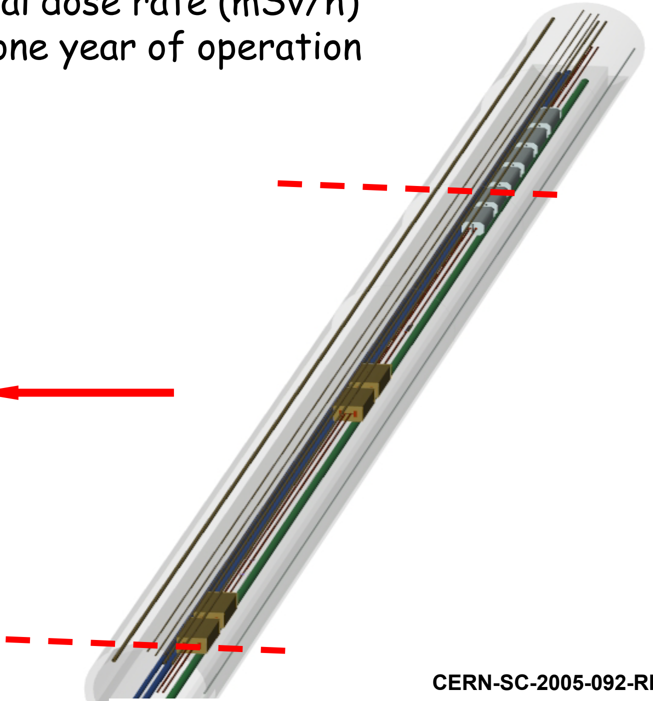
Residual dose rate (mSv/h) after one year of operation

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*

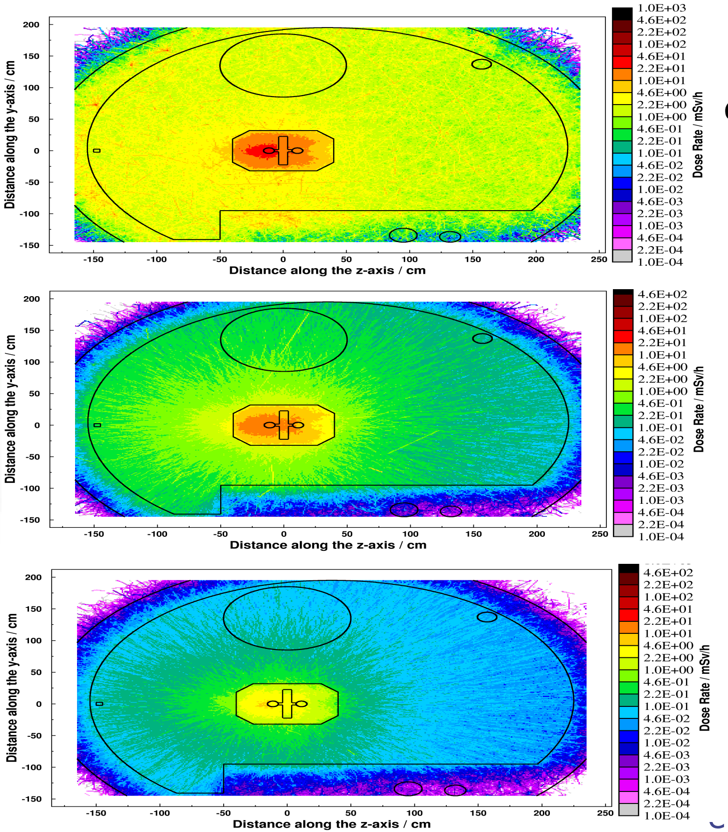
Cooling time

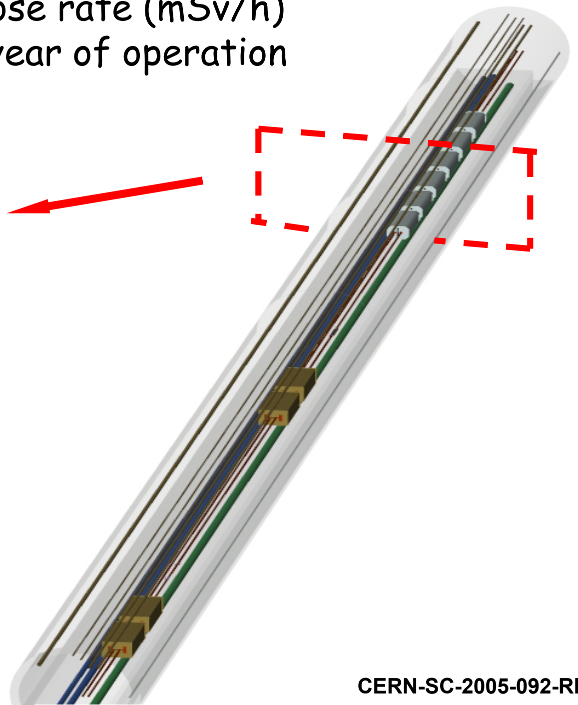
Residual dose rate (mSv/h) after one year of operation

8 hours

1 week

4 months



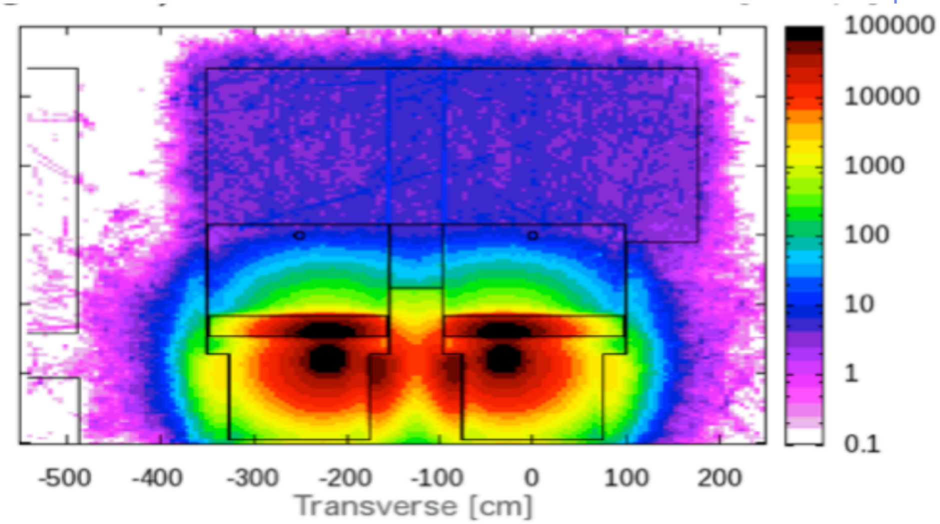
CERN-SC-2005-092-RP-TN

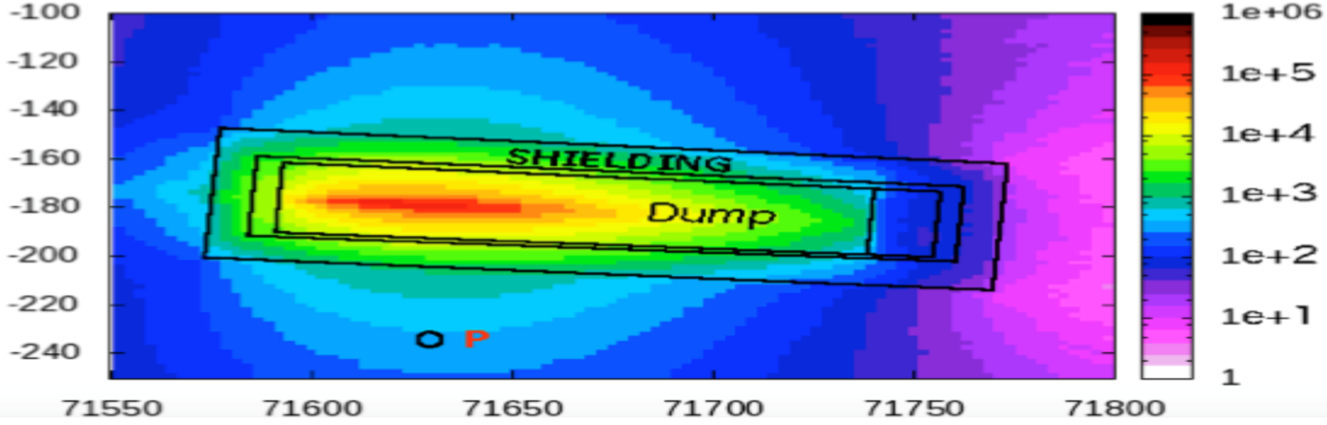
REMANENT DOSE RATE MAPS OF THE LHC BETATRON CLEANING INSERTION (IR7)

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

# Application SLAC

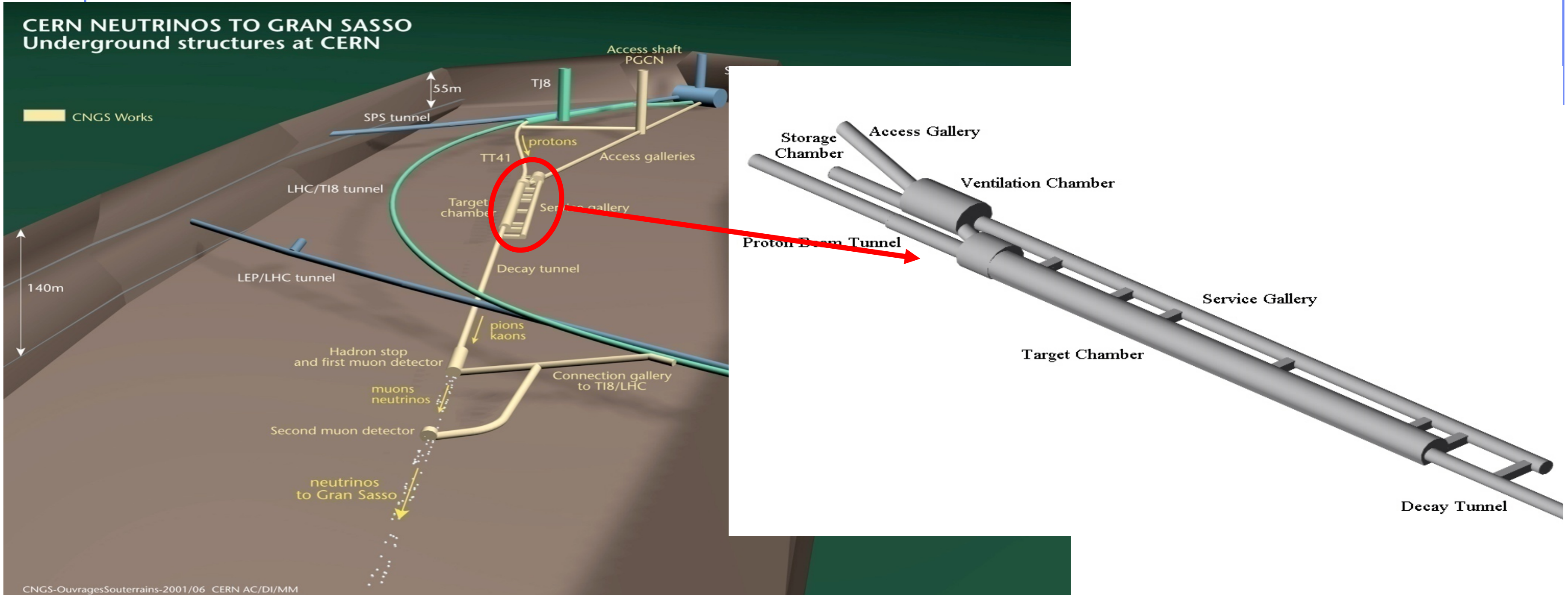
Residual dose rate (mrem/h)
After 10 year of operation at
120 kW 4 GeV e- on each of
the two dumps



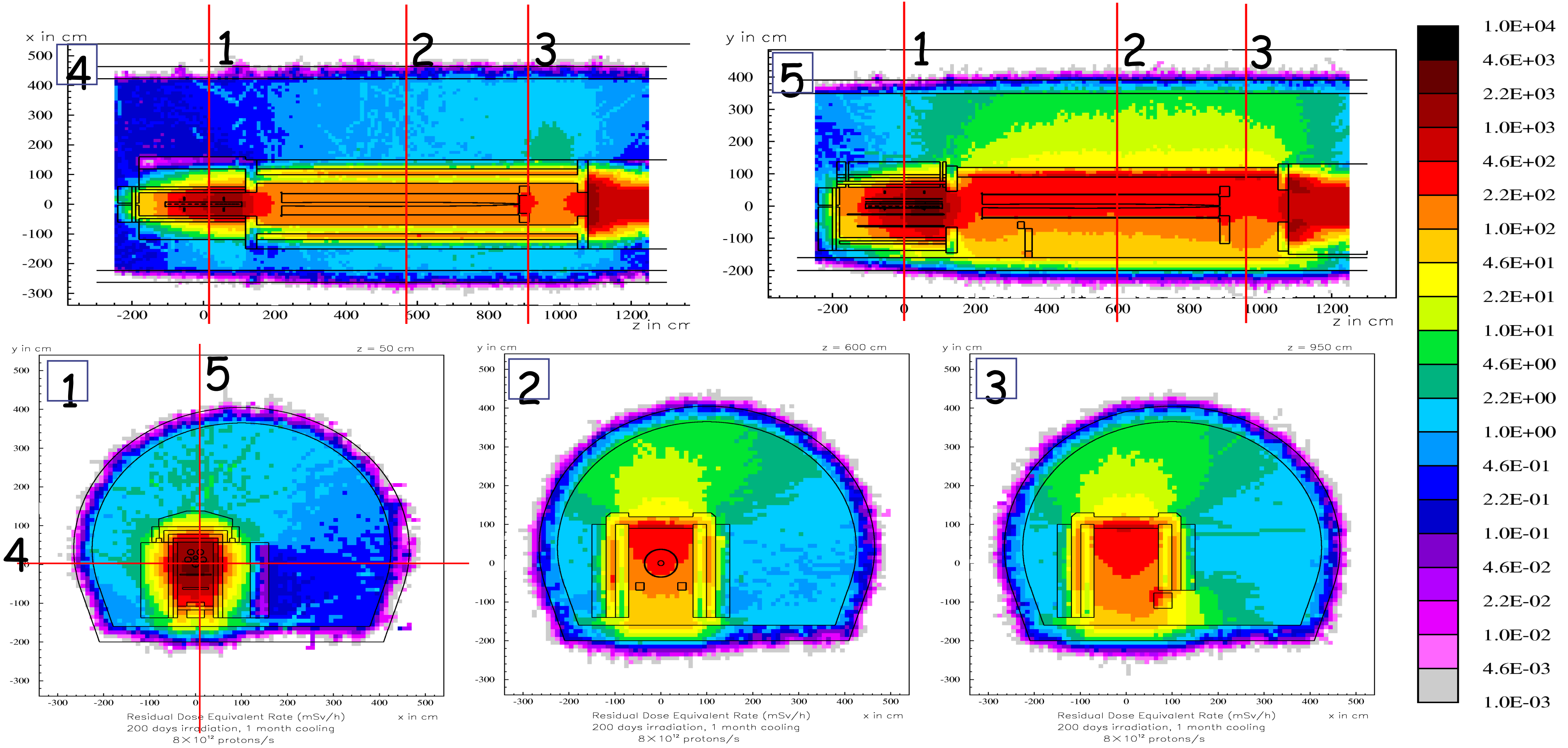




Residual dose of the extracted dump inside a fresh (not-irradiated) steel coffin

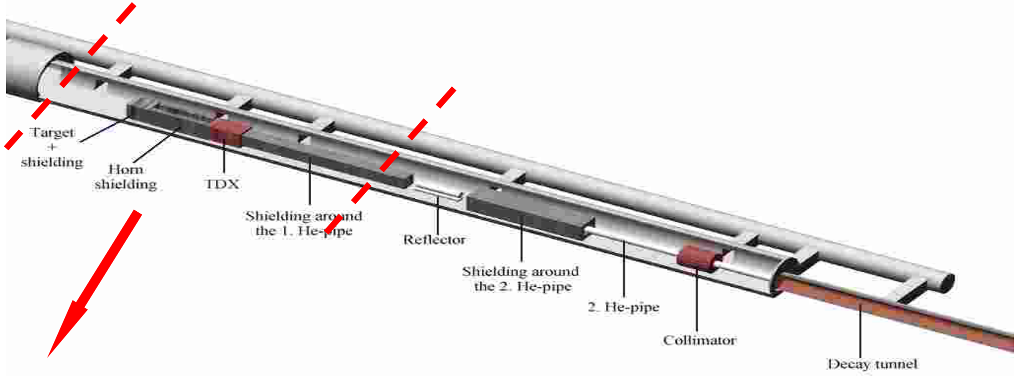
# Applications – *CNGS*



# Applications – *CNGS*

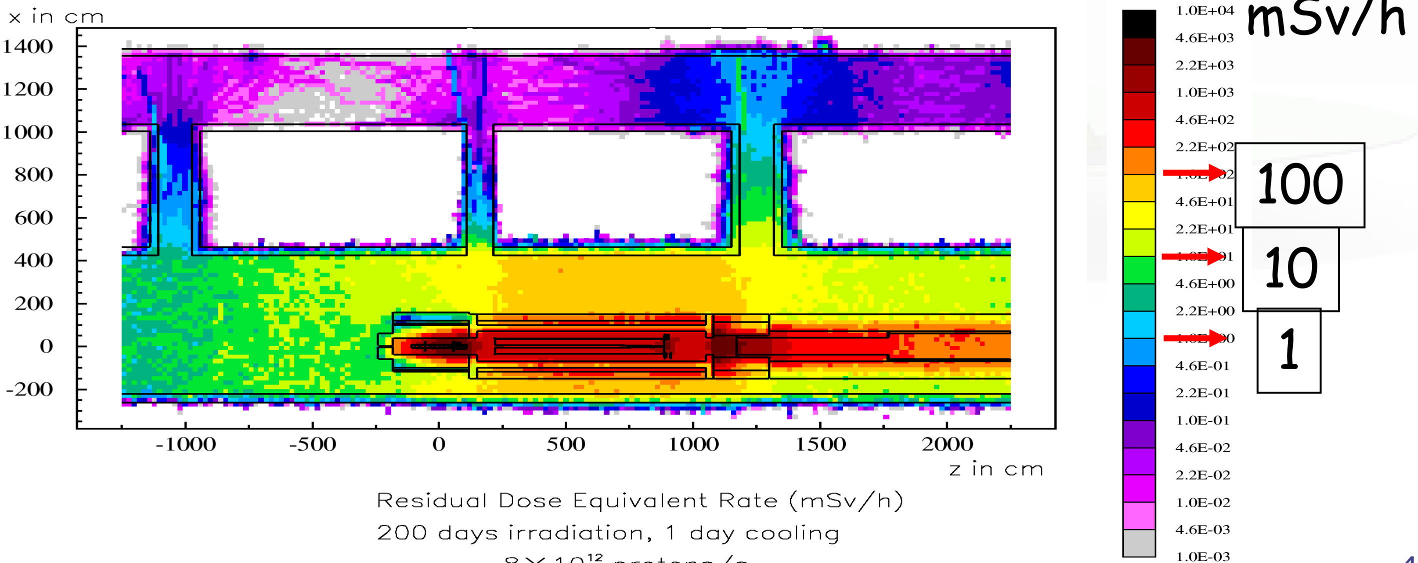


# Applications – *CNGS*




<u>*Example:*</u>

$t_{cool}$ = 1 day




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

# 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 radio-nuclides 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.