Heavy ion beams and radioactivity in FLUKA

OMA Monte Carlo school

Heavy ion beams

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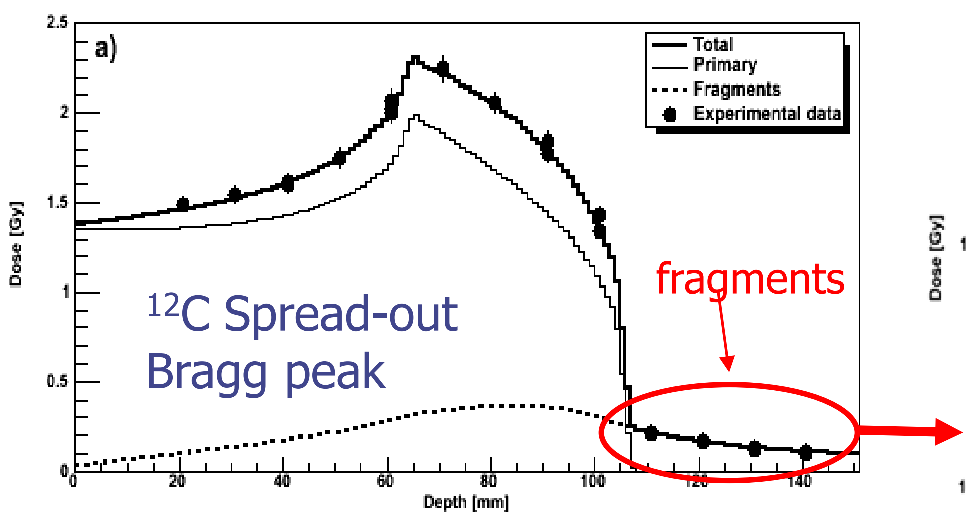
Overview

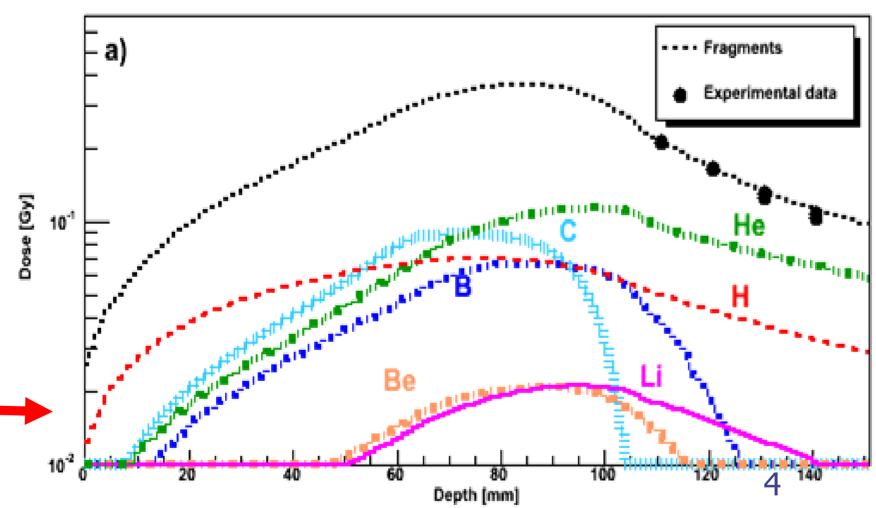
Introduction

The models	DPMJET
	RQMD
	BME
Input options	Beam definition
	Transport thresholds

Introduction

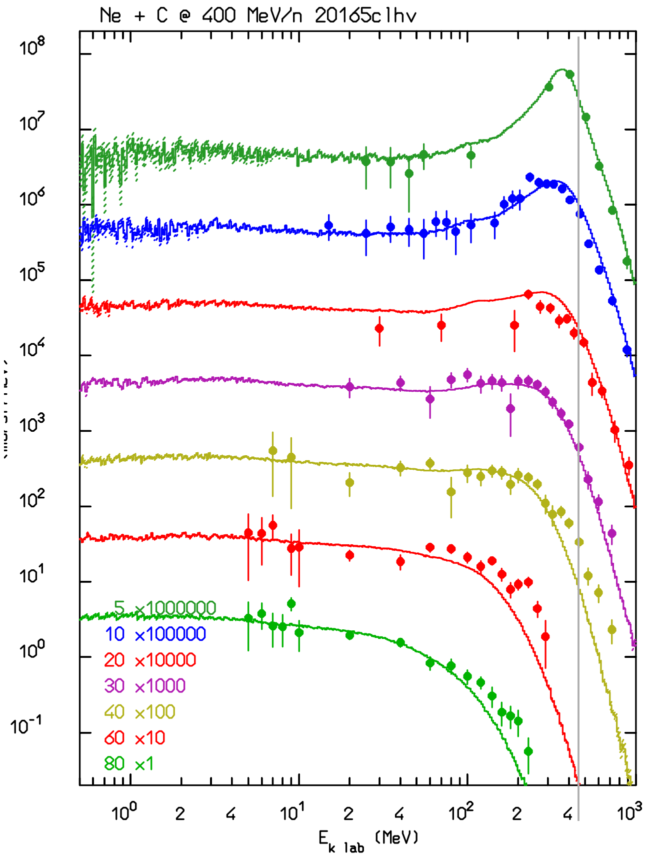
- In hadron – nucleus interactions, reaction products and residuals come mostly from the TARGET nucleus
- In nucleus-nucleus interactions, reaction products and residuals come from both TARGET and PROJECTILE nuclei.
- Indeed, except for complete fusion, one often refers to "projectile-like" and "target-like" fragments
- ➔ projectile-like fragments travel with the projectile speed, thus they can be energetic, and travel longer /shorter than the average projectile range (range $\approx\div A/Z^2$ at given β)

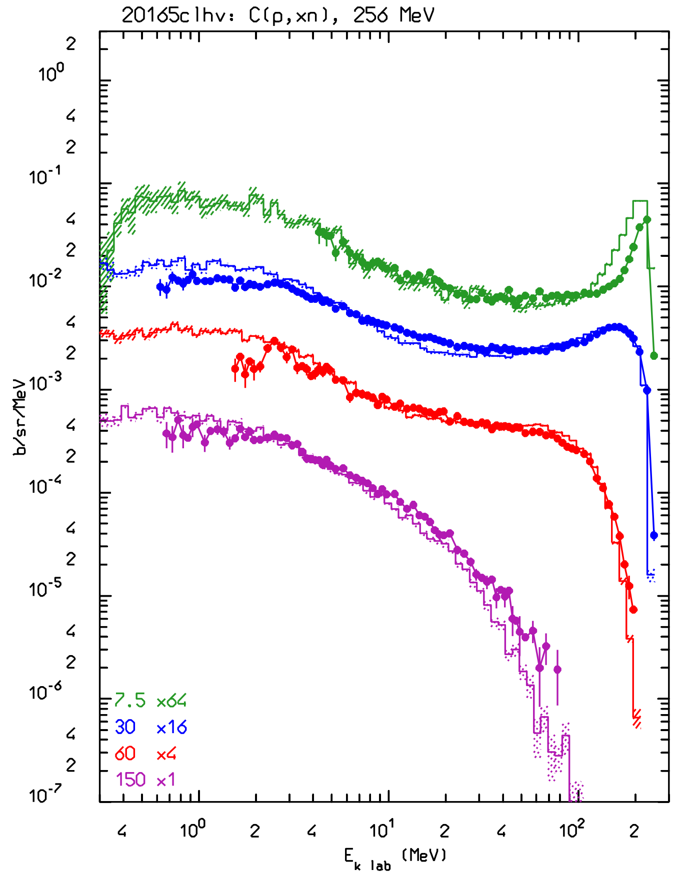




Introduction

Left : Ne+C at 400 MeV/A, right: p+C at 256 MeV, neutron energy spectra at different angles. Note the high energy (>E/A) tails, and the different shape. Also, different "effect"of reaction stages: in A-A, evaporation products can be fast (from proj like)!





Heavy ion interaction models in FLUKA

E > 5 GeV/n

Dual Parton Model (DPM)
DPMJET-III (original code by R.Engel, J.Ranft and S.Roesler,
FLUKA-implementation by T.Empl *et al.*)

~0.1 GeV/n < E < 5 GeV/n

Relativistic Quantum Molecular Dynamics Model (RQMD)
RQMD-2.4 (original code by H.Sorge *et al.*,
FLUKA-implementation by A.Ferrari *et al.*)

E < ~0.1 GeV/n

Boltzmann Master Equation (BME) theory
BME (original code by E.Gadioli *et al.*,
FLUKA-implementation by F.Cerutti *et al.*)

DPMJET

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RQMD - *FLUKA implementation*

- RQMD model adapted to FLUKA: RQMD-2.4

  H. Sorge, Phys. Rev. **C 52**, 3291 (1995);

  H. Sorge, H. Stöcker, and W. Greiner, Ann. Phys. **192**, 266 (1989), Nucl. Phys. **A 498**, 567c (1989)

- QMD: Follows the Time evolution of the combined A+A system, performing n-n interactions and re-calculating the nuclear potentials from sum of two-body fields

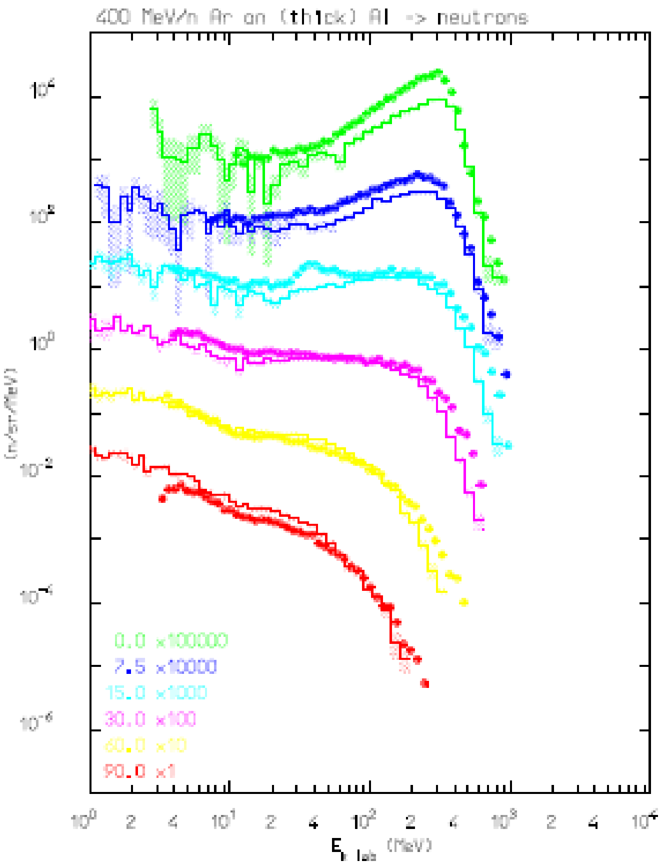
- In FLUKA used in its faster, cascade-like version
- A-posteriori identification of residual fragments (not provided by RQMD)
- Correct energy/momentum conservation

- Fragment de-excitation (evaporation etc.) in PEANUT

RQMD – *FLUKA benchmarks*

Double differential neutron yield

Ar ions

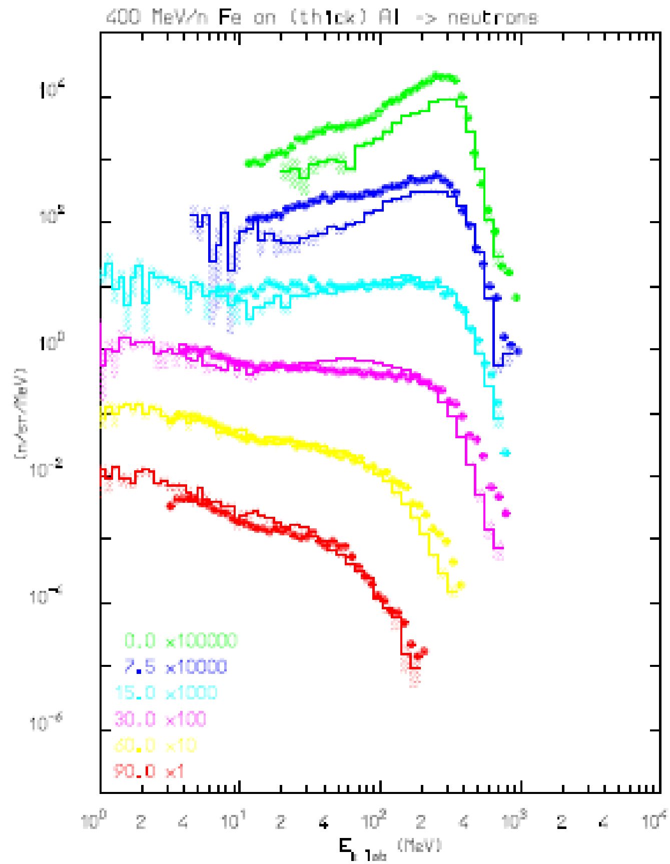


400 MeV/n

on *thick*

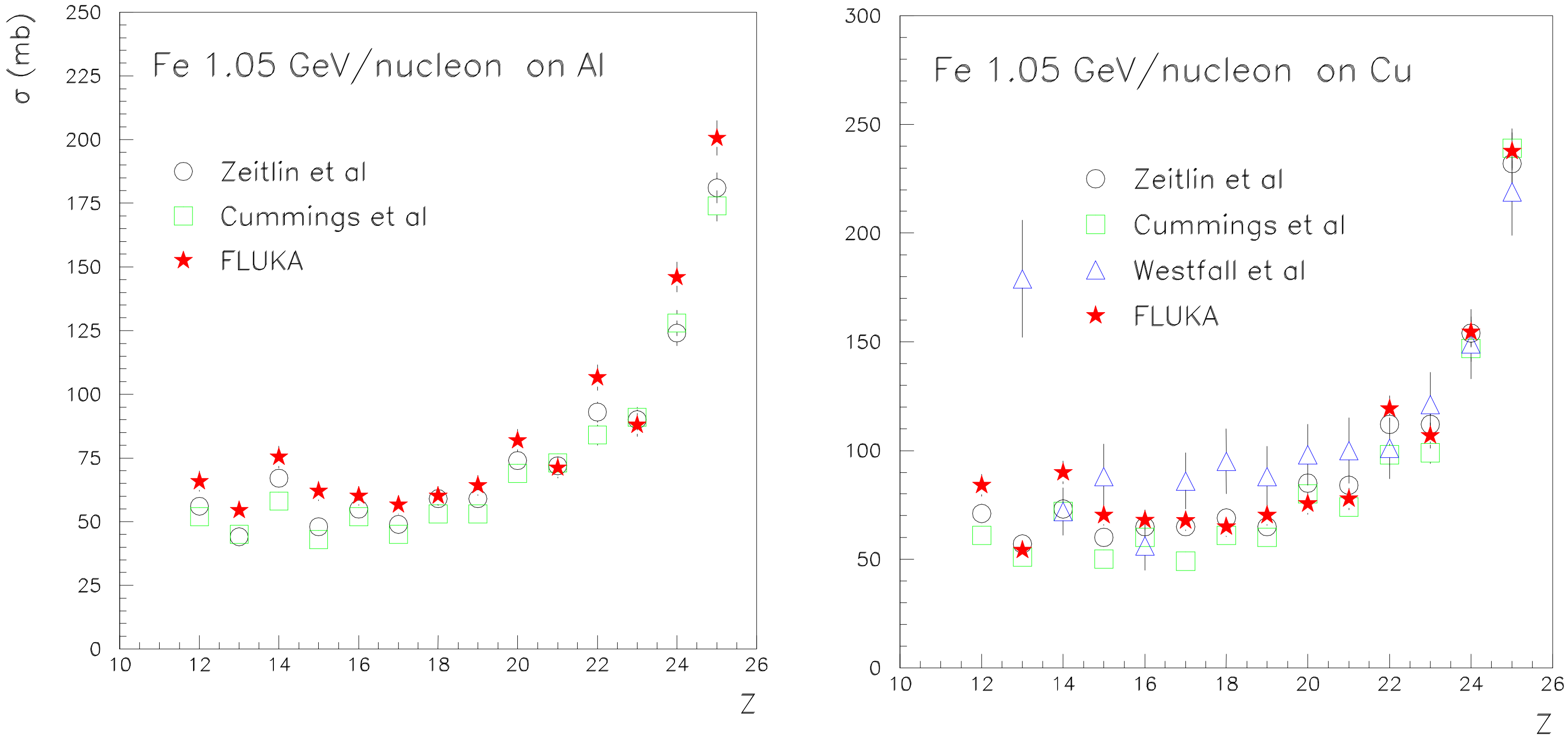
Al targets

Fe ions



exp. data from T. Kurosawa *et al.*, Phys. Rev. **C 62**, 044615 (2000)

RQMD - *FLUKA benchmarks*



Fragment charge cross section for 1.05GeV/n Fe ions on Al (left) and Cu (right).
Exp. data from PRC56, 338 (1996) , PRC42,5208(1990) and PRC19, 1309 (1979)

BME

E > 5 GeV/n

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BME - *References*

interface to a Monte Carlo code

founded on the BME theory (E. Gadioli et al.)

[M. Cavinato *et al.*, Nucl. Phys. **A 679**, 753 (2001),

M. Cavinato *et al.*, Phys. Lett. **B 382**, 1 (1996)]

BME – *The implemented code*

two different main reaction paths have been adopted:

1. COMPLETE FUSION

$P_{CF}=\sigma_{CF}/\sigma_R$

composite nucleus formation

2. PERIPHERAL COLLISION

$P = 1 - P_{CF}$

Only part of nucleons involved, with several topologies:

-three body with possible incomplete fusion

-*one nucleon break-up and possibly transfer*

-pickup/stripping

pre-equilibrium de-excitation of the produced fragment(s)
according to the BME theory (where available)
or the PEANUT exciton model

NB interface to PEANUT pre-eq not yet distributed!

FLUKA evaporation/fission/fragmentation/gamma de-excitation

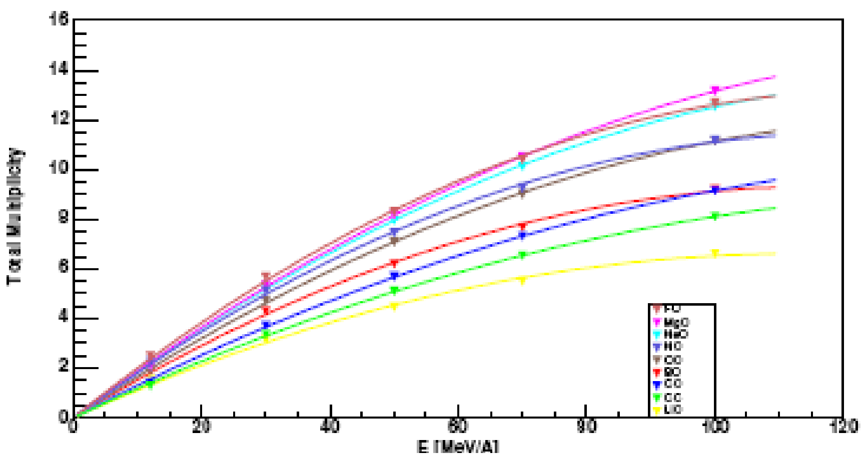
BME – *The database for the pre-equilibrium emissions*

In order to get the multiplicities of the pre-equilibrium particles and their double differential spectra, the BME theory is applied to several representative systems at different bombarding energies and the results are parameterized.

^{16}**O** + ^{6}Li, ^{8}Li, ^{8}B, ^{10}B, ^{12}C, ^{14}N, ^{16}O, ^{19}F, ^{20}Ne, ^{24}Mg, ^{27}Al, ^{56}Fe, ^{197}Au

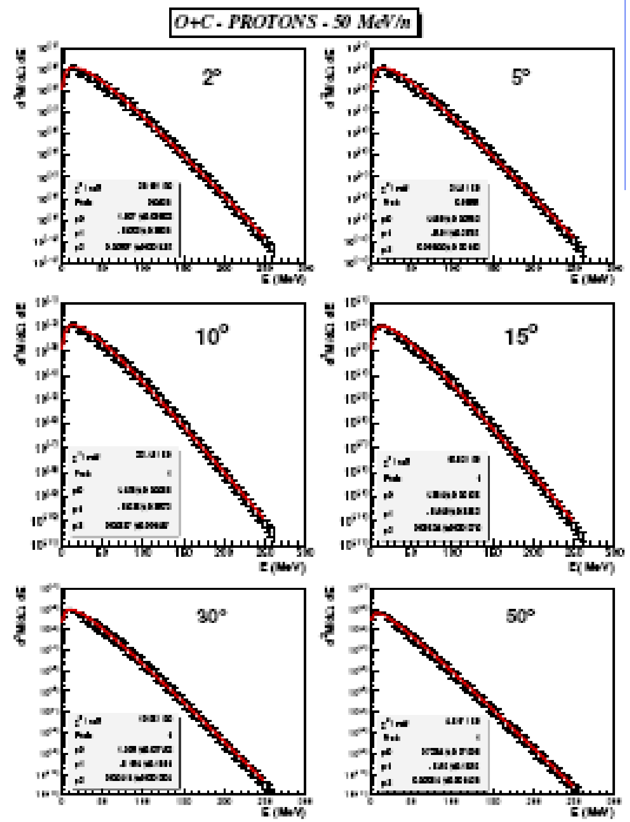
^{12}**C** + ^{8}Li, ^{8}B, ^{12}C, ^{27}Al, ^{40}Ca

@ 12, 30, 50, 70, 100 MeV/n



total multiplicity

$$M = P_1 E_{nucl} - P_2 E_{nucl}^2$$



energy spectra

$$d^2M/(dEd\Omega) = E^{P_0(\theta)} \exp\left(-P_1(\theta) - P_2(\theta)E\right)$$

Work is ongoing to extend it to more massive systems, i.e.

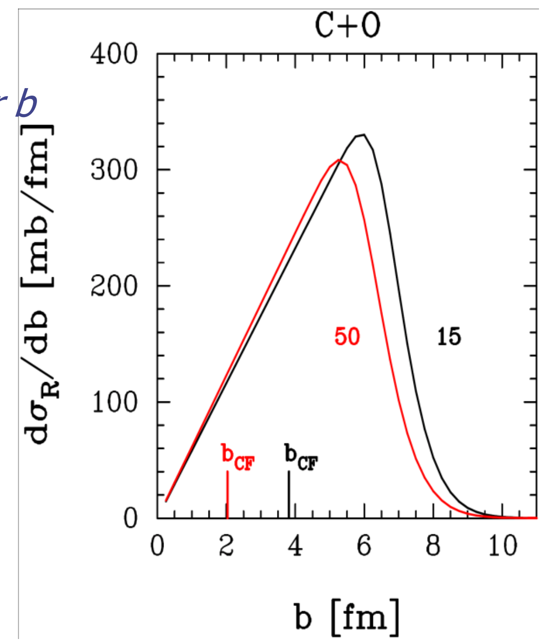
^{40}Ca + ^{120}Sn ^{56}Fe + ^{28}Si, ^{40}Ca, ^{48}Ca, ^{120}Sn

and consequently review the fitting functions
and the extrapolation recipes over a significantly larger mass range

BME – *Peripheral collisions*

We integrate the nuclear densities of the projectile and the target over their overlapping region, as a function of the impact parameter, and obtain a preferentially excited “middle source” and two fragments (projectile- and target-like). The kinematics is suggested by break-up studies.

i. selection of the *impact parameter b*



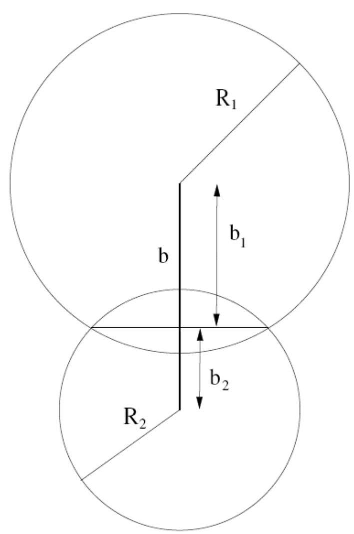
ii. kinematics determination

θ_{PL} , θ_{TL} chosen according to $[d\sigma/d\Omega]_{cm} \sim \exp(-k\theta_{cm})$
θ_{MS} momentum conservation
p_{PL} , p_{TL} chosen according to a given energy loss distribution
p_{MS} momentum conservation
ϕ_{PL} free
ϕ_{TL} , ϕ_{MS} same reaction plane

PL

MS

TL



iii. excitation energy sharing

$$E^\star_{MS} = (A_{MS}/A_{tot})E^\star_{tot} \sum_{n=0}^{k} (1 - A_{MS}/A_{tot})^n$$

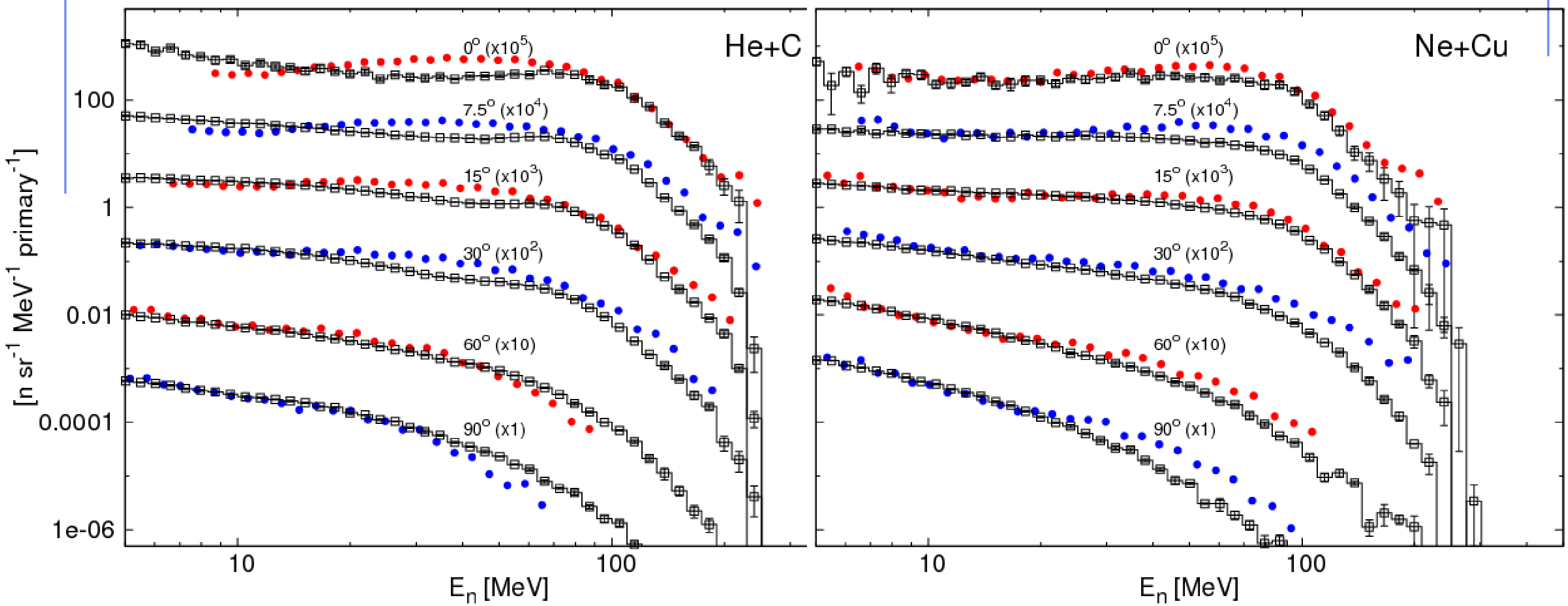
$$E^\star_{PL} = f(A_{PL}, A_{TL}) \left(E^\star_{tot} - E^\star_{MS}\right)$$

forced on the experimental values in the discrete level region

$$E^\star_{TL} = \left(E^\star_{tot} - E^\star_{MS} - E^\star_{PL}\right)$$

BME - *Benchmarking*

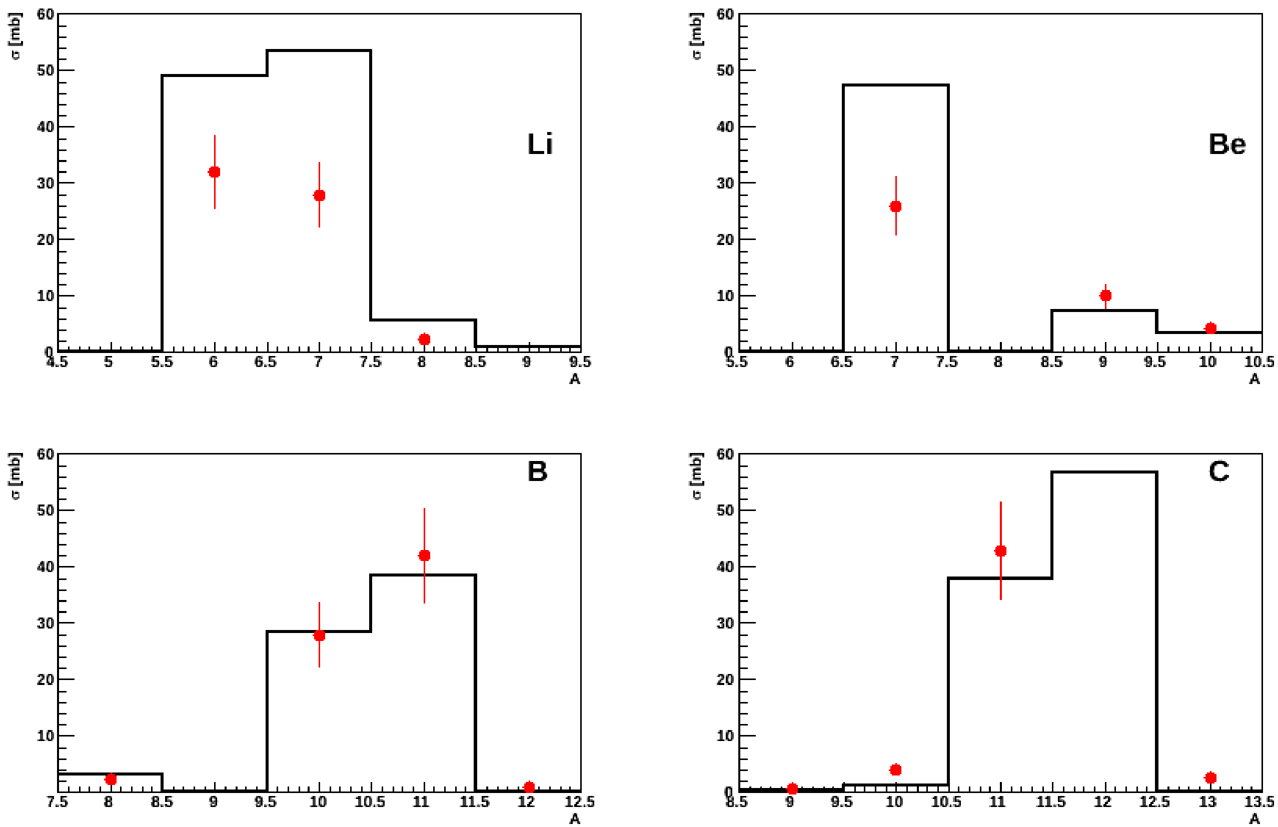
DOUBLE DIFFERENTIAL **NEUTRON** YIELDS
FROM **100 MeV/n** BEAMS ON THICK TARGETS



FLUKA vs experimental data from T. Kurosawa, N. Nakao, T. Nakamura et al., Nucl. Sci. Eng. 132, 30 (1999)

BME – *Benchmarking*

ISOTOPE YIELDS
FROM C+C at **86 MeV/n**



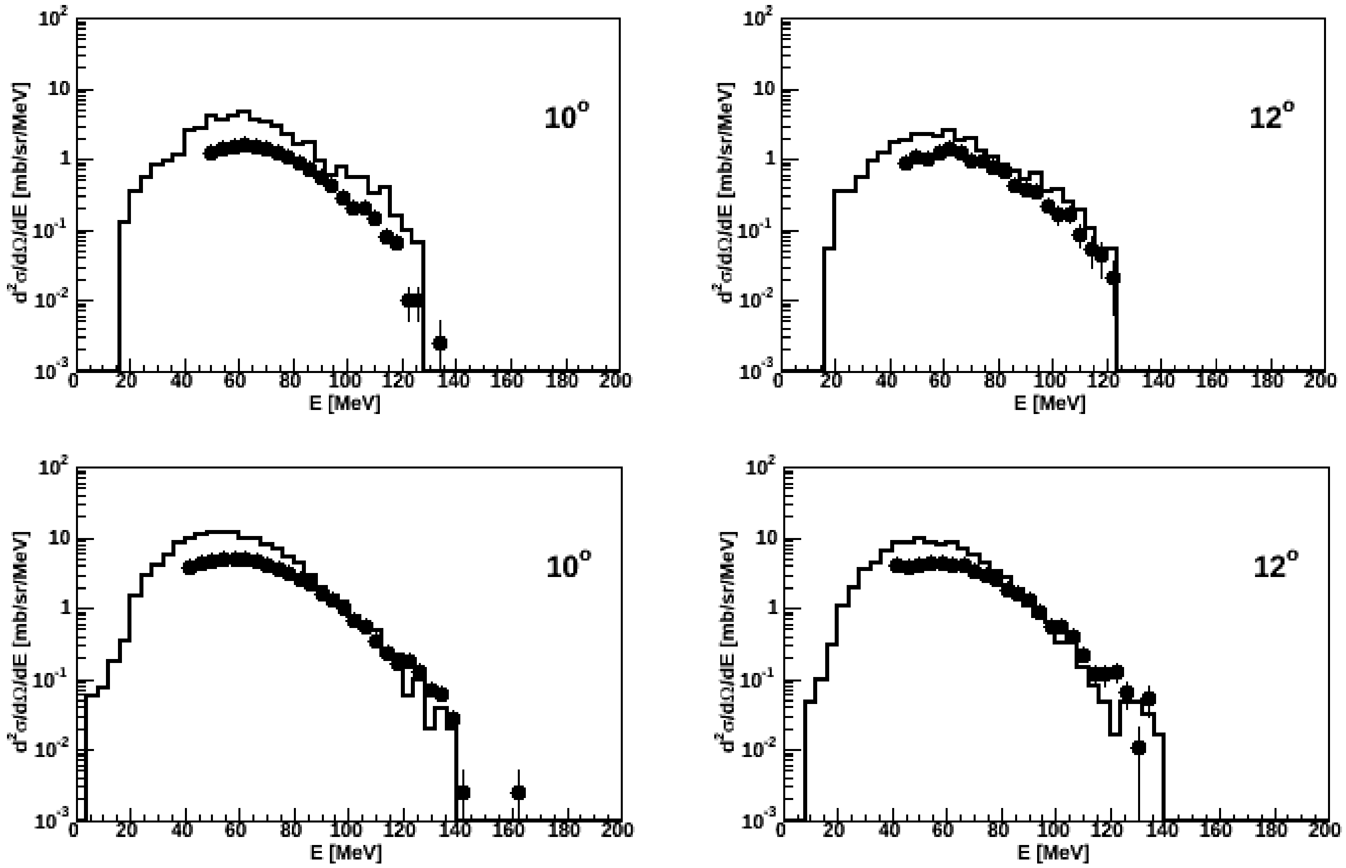
experimental data from H. Ryde, Physica Scripta T5, 114 (1983)

BME – *Benchmarking*

DOUBLE DIFFERENTIAL **FRAGMENT SPECTRA**
FROM C+C at **13 MeV/n**

Fluorine

Oxygen



experimental data by courtesy of S. Fortsch et al., iThemba Labs, South Africa

Input options - 1

a) define momentum / energy

```
BEAM          -10.0      0.0      0.0      0.0      0.0      0.0HEAVYION
```

WHAT(1) > 0.0 : average beam momentum (GeV/*c*)
< 0.0 : average beam kinetic energy (GeV)

Note: **for SDUM = HEAVYION units per nucleon (in fact per *nmu*)**
for SDUM = 4-HELIUM, *etc.* per nucleus

WHAT(2) beam momentum spread (GeV/*c*)

WHAT(3)-WHAT(6) (as for any other particle)

SDUM = HEAVYION

also	**4-HELIUM**	alpha
	3-HELIUM	3-helium
	TRITON	tritium
	DEUTERON	deuterium

Input options - 2

b) define charge and mass *(required for* `BEAM/SDUM=HEAVYION`*)*

```
HI-PROPE          79.0      197.0        0.0        0.0        0.0        0.0
```

HI-PROPE Z: 79.0 A: 197.0 Isom: 0.0

WHAT(1) = Atomic number Z of the heavy ion, Default: 6.0

WHAT(2) = Mass number A of the heavy ion, Default: 12.0

WHAT(3) = if < 0 isomeric state of the heavy ion

c) switch on heavy ion transport and interactions

```
IONTRANS          -2.0
```

(pleonastic in case of ion beams)

IONTRANS Transport: Full transport ▼

IMPORTANT:

- **the** DPMJET/RQMD event generators are EXTERNAL, they are distributed with FLUKA but not included in the main library neither in the standard executable

- **Don't forget** to **link** the DPMJET/RQMD event generators for enabling **ion-ion interactions above 125MeV/n**
  either using FLAIR or

  `$FLUPRO/flutil/ldpmqmd`

- The BME event generator, covering the low energy range up to 150MeV/n does not need to be linked since it's already embedded in the main FLUKA library

Warning: deuterons

- Deuteron interactions are NOT modelled in BME, therefore

** NO DEUTERON interactions are available in FLUKA below a few hundreds MeV ***

- RQMD performs the interaction, however reliability is not ensured due to the “special” nature of deuteron interactions

Transport thresholds

- The transport momentum threshold for ions ($p_{th,HI}$) is linked to that of alphas ($p_{th,\alpha}$)

$$p_{th,HI} = p_{th,\alpha} \times m_{HI}/m_{\alpha} \quad (GeV/c)$$

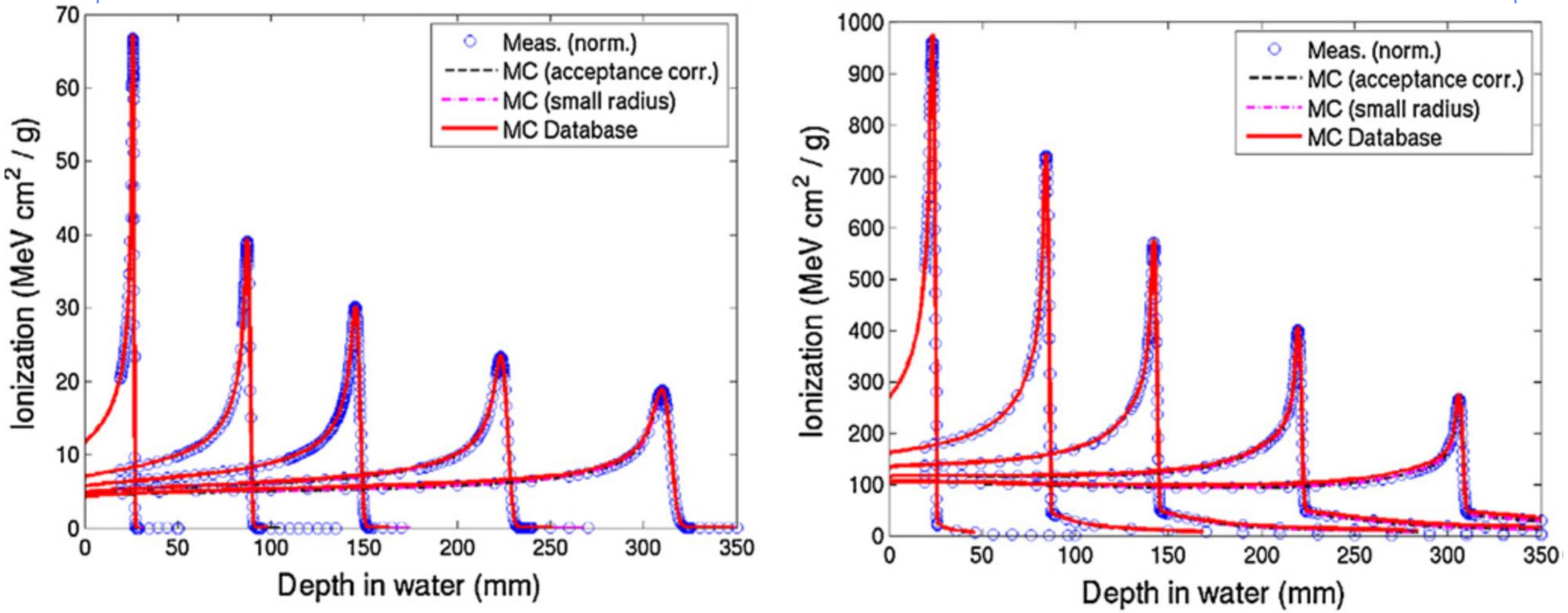
- The transport threshold for light ions (alpha, He-3, t, d) is set equal to total kinetic energy = 10 MeV (100 keV) if DEFAULTS=NEW-DEFA (PRECISIO).
- To change the transport threshold use the PART-THR card (requiring GeV and not GeV per nucleon)
- When the energy of an ion becomes lower than the transport threshold, and if such threshold is lower than 100 MeV/n, the ion is not stopped, but it is ranged out to rest

Benchmarks

Comparison against Bragg curve experimental data

Depth-dose distributions for p (left panel) and carbon ions (right panel)

p **^{12}C**



K. Parodi, A. Mairani, et al Physics in Medicine and Biology 2012, 57, 3759-3784

Radioactivity

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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 radio-nuclides (one-step method). For that, a dedicated database of decay emissions is used, based mostly on information obtained from NNDC, sometimes supplemented with other data and checked for consistency.

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.

  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

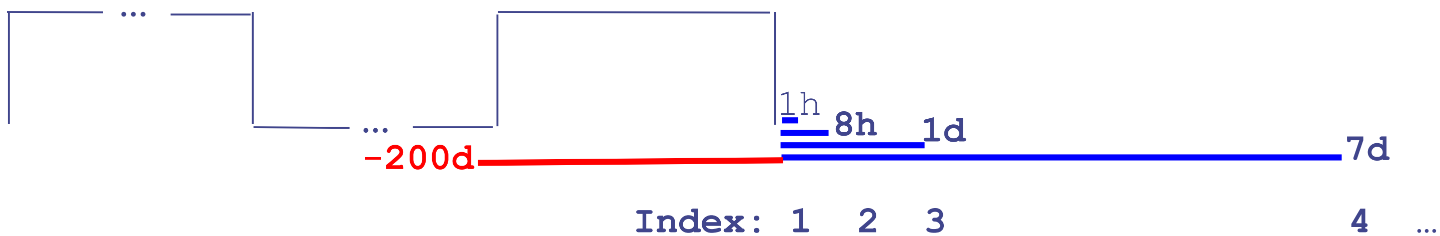
requests simulation of decay of produced radioactive nuclides and allows to modify biasing and transport thresholds (defined with other cards) for the transport of decay radiation

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

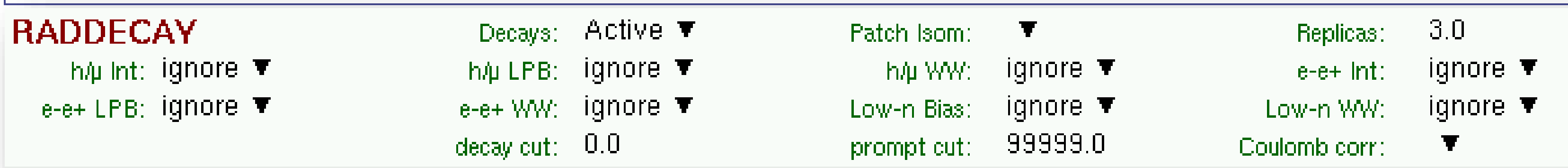
allows to associate scoring estimators with dose equivalent conversion factors or/and to filter them according to (generalized) particle identity

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

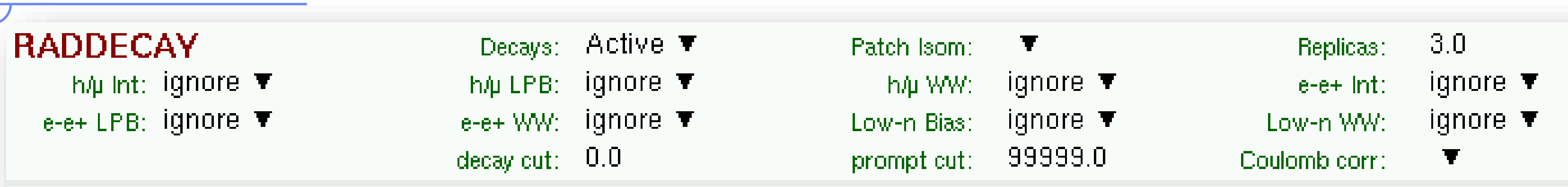
Card: RADDECAY [1/3]

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



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

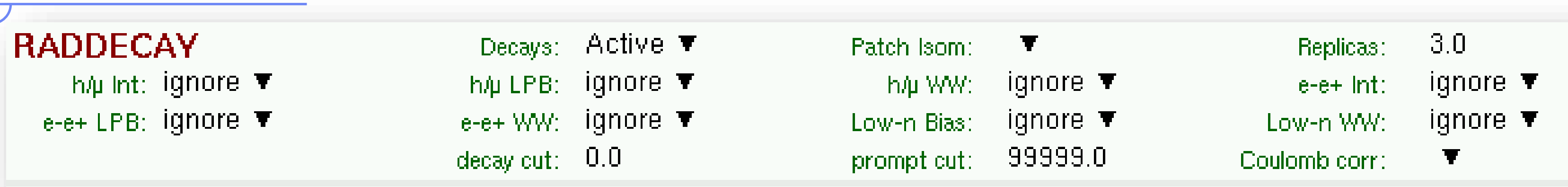
000010000 to prompt radiation only

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: #
prompt cut: #

10 digits, first five for decay radiation, second five for prompt 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
5.9×10^5 p/s	0 p/s (beam-off)	5.9×10^5 p/s

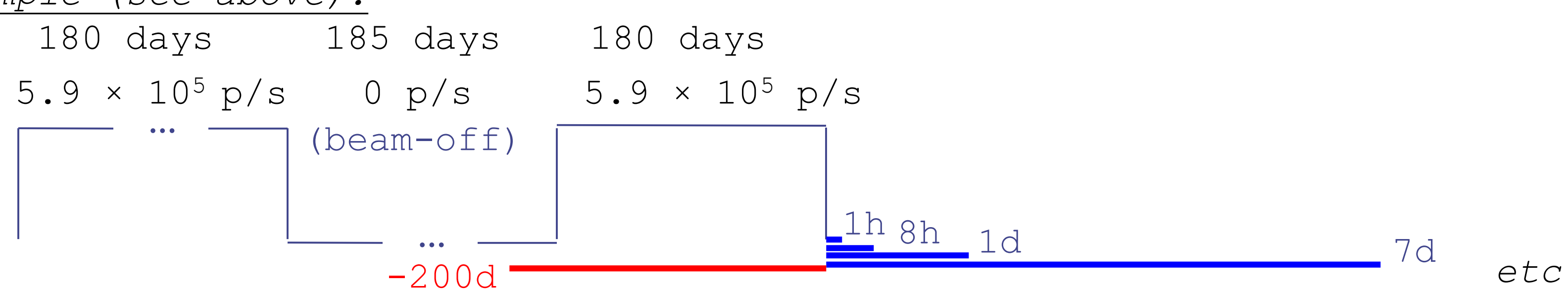
Card: DCYTIMES

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

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

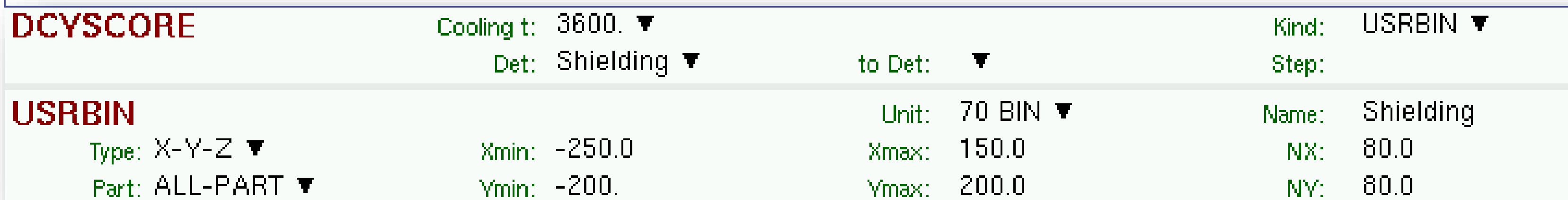
Each cooling time is assigned an index, following the order in which it has been input. This index can be used in option DCYSCORE to assign that particular cooling time to one or more scoring detectors. A negative decay time is admitted: scoring is performed at the chosen time "during irradiation"

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

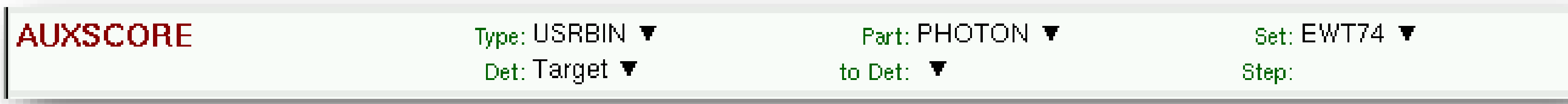
RESNUCLE Bq
USRBIN fluence rate / dose rate

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
```



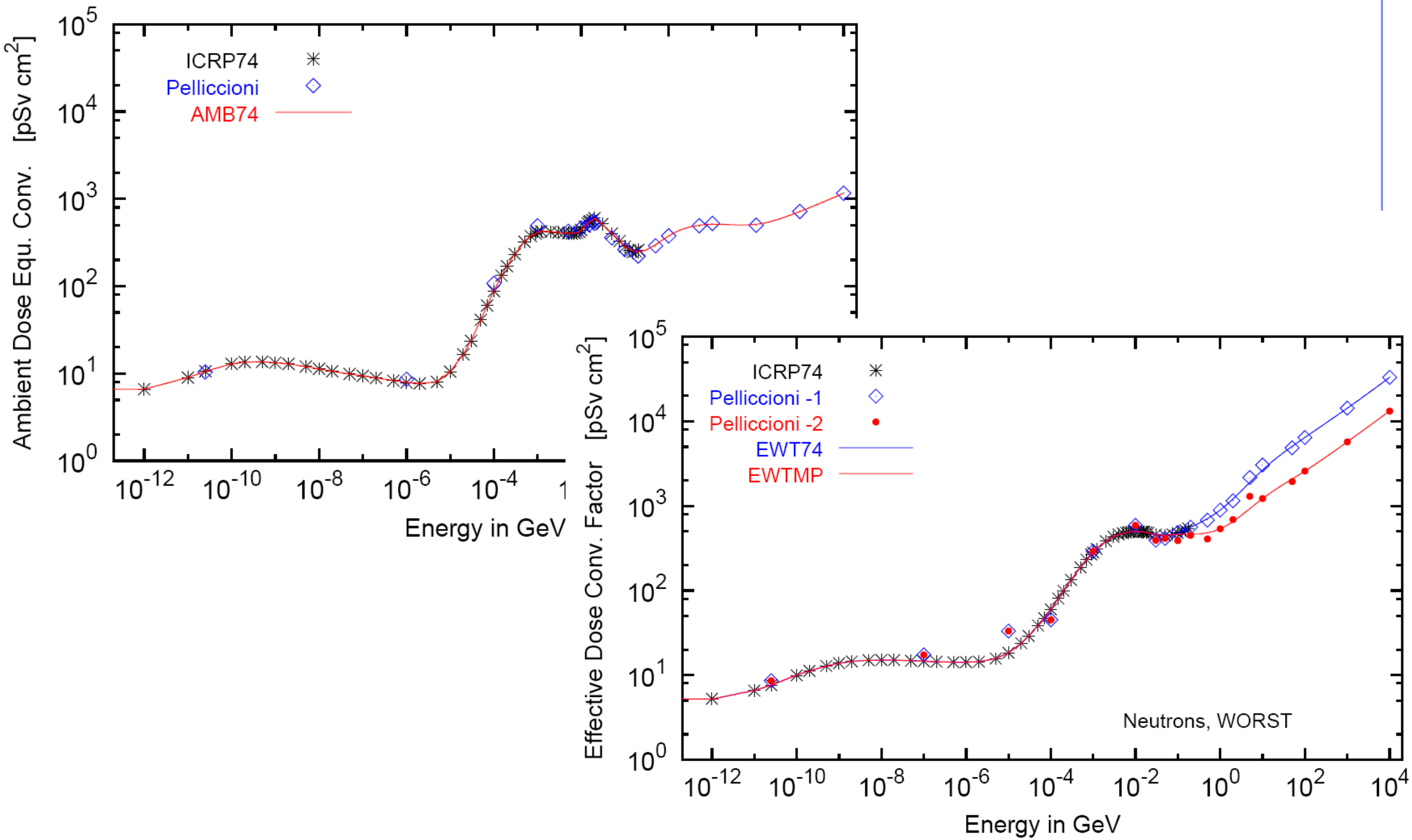
WHAT(1) Type:		**Type of estimator to associate with** drop down list of estimator types (USRBIN, USRBDX…)
WHAT(2) Part:	#	**particle or isotope to filter scoring** Particle or particle family list. If empty then flair will prompt for Z, A, and State for filtering on specific isotopes
WHAT(4,5) Det ..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

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

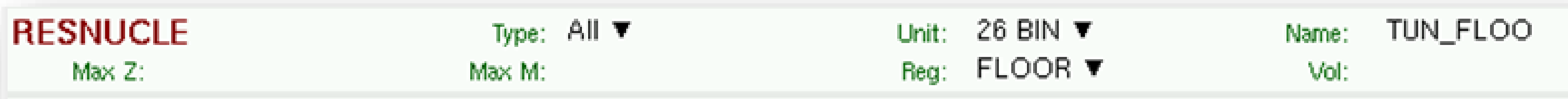
Conversion Coefficients (Examples)



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
```



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

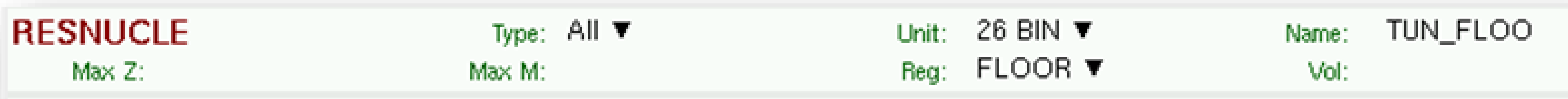
WHAT(4) **Maximum M = N - Z - NMZ_min**

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) Reg:	scoring region number/name (Default = 1.0 ; -1.0 or @ALLREGS all regions)
WHAT(6) Vol:	volume of the region in cm^3 (Default = 1.0)
SDUM Name:	character string identifying the detector (max. 10 characters)

Notes:

1. In the case of heavy ion projectiles the default NMZ, based on the region material, is not necessarily sufficient to score all the residual nuclei, which could include possible ion fragments
2. Residual nuclei from low-energy neutron interactions are only scored if that information is available in the low-energy neutron data set (see Manual)
3. 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

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

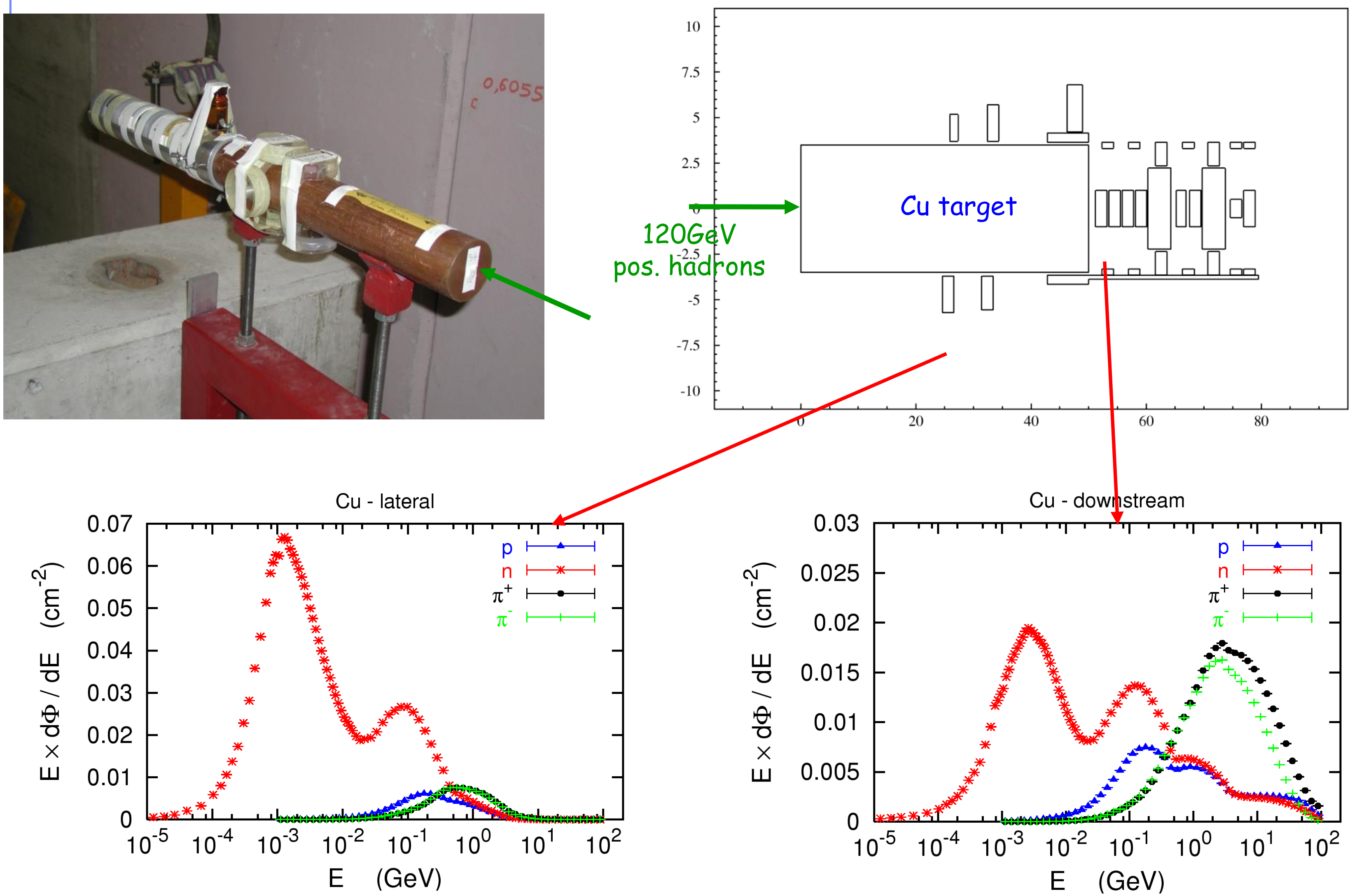
switch to activate the evaporation of heavy fragments (up to A=24) and the simulation of coalescence

Back-up Material

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

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

$0.8 < R < 1.2$

$0.8 < R \pm \text{Error} < 1.2$

Exp/MDA < 1

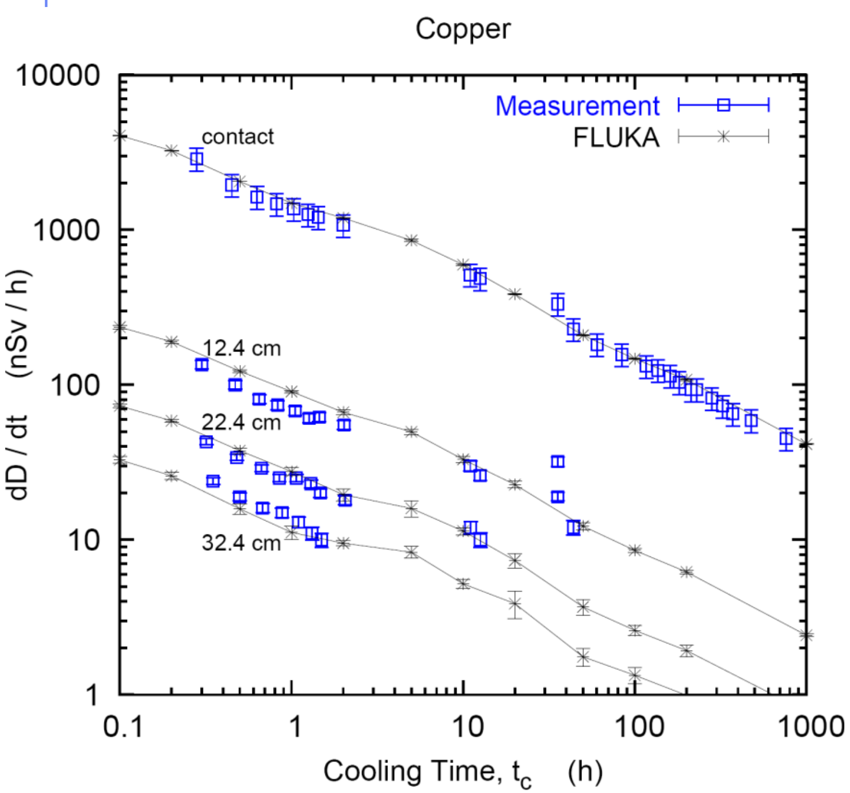
$R + \text{Error} < 0.8$ or
$R - \text{Error} > 1.2$

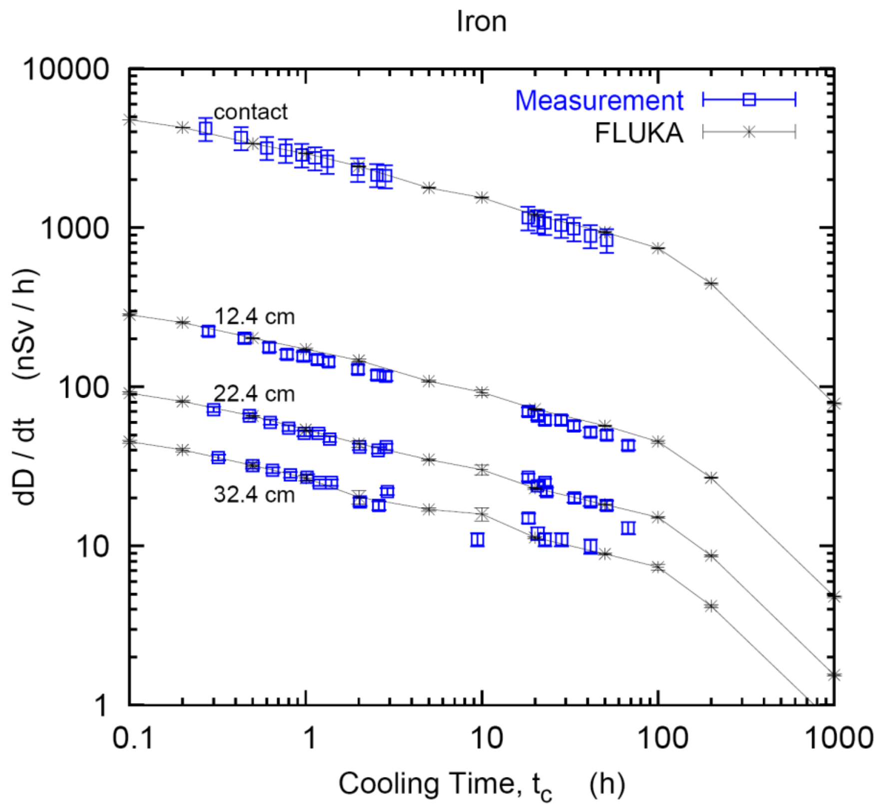
Reference:
M. Brugger, S. Roesler *et al.*, Nuclear Instruments and Methods A 562 (2006) 814-818

Benchmark experiment – *Results 1*

Dose rate as function of cooling time

for different distances between sample and detector

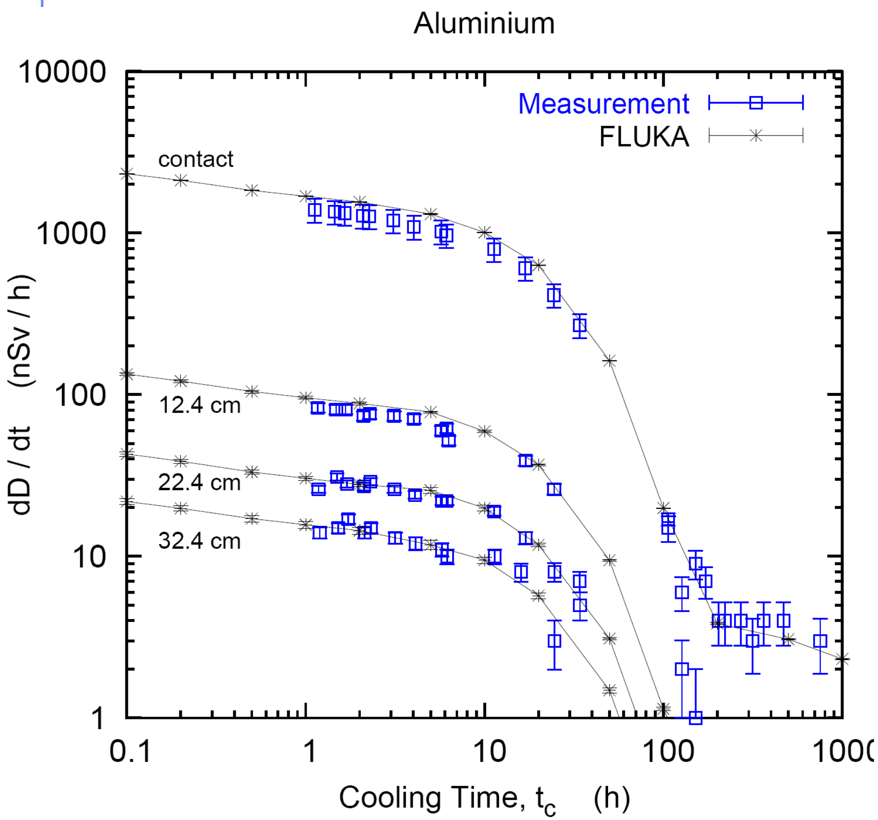


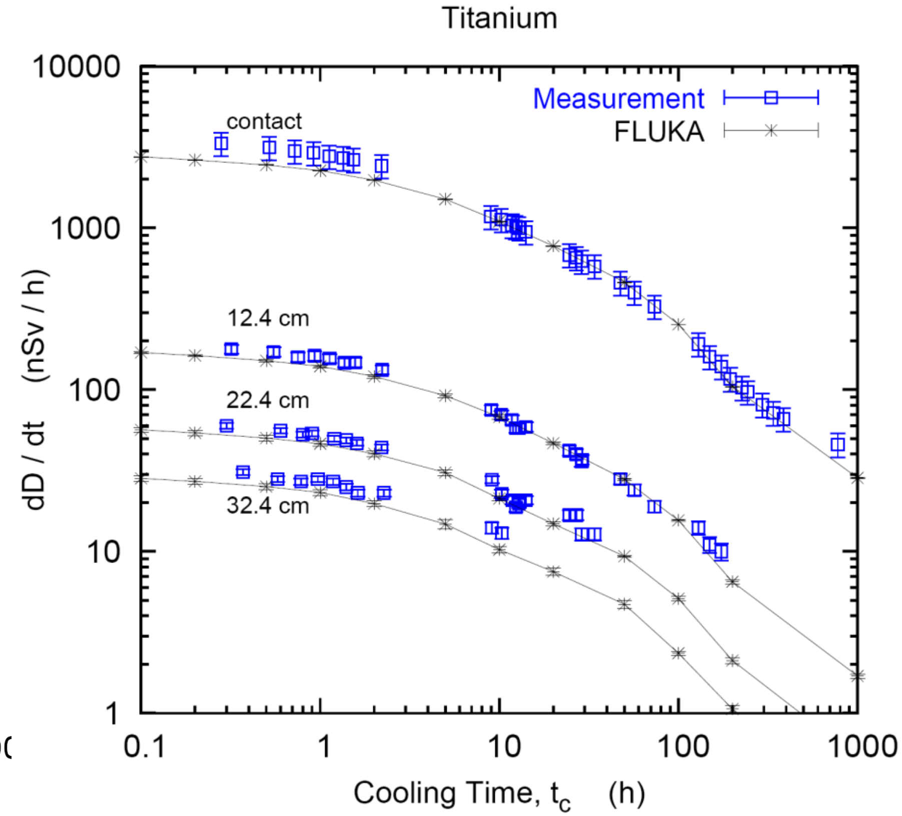


<u>Reference:</u> M. Brugger, S. Roesler *et al.*, Radiat. Prot. Dosim. 116 (2005) 12-15

Benchmark experiment – *Results 2*

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

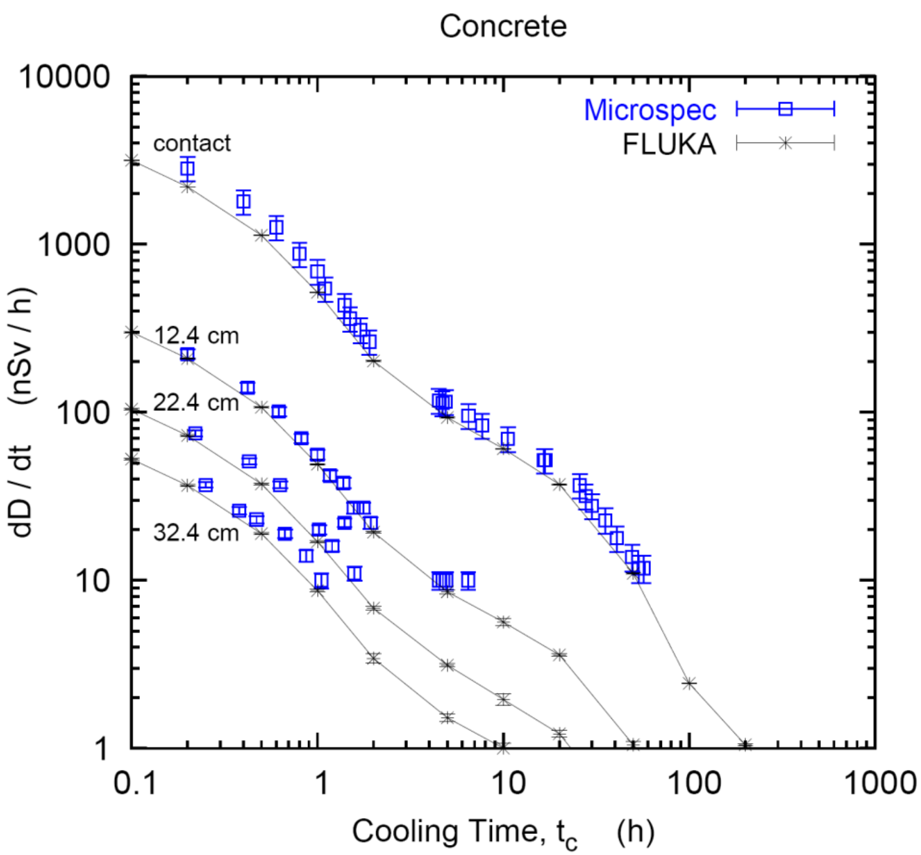




Reference: M. Brugger, S. Roesler *et al.*, Radiat. Prot. Dosim. 116 (2005) 12-15

Benchmark experiment – *Results 3*

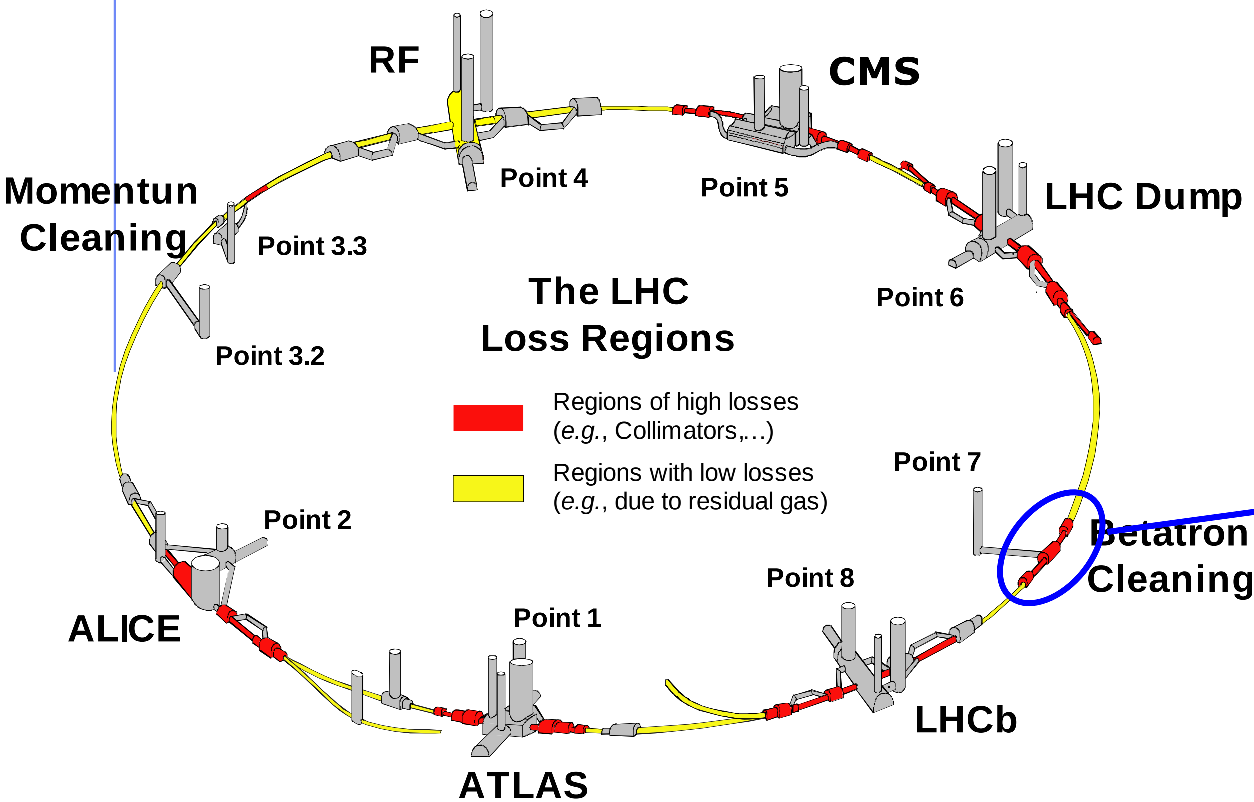
Dose rate as function of cooling time
for different distances between sample and detector

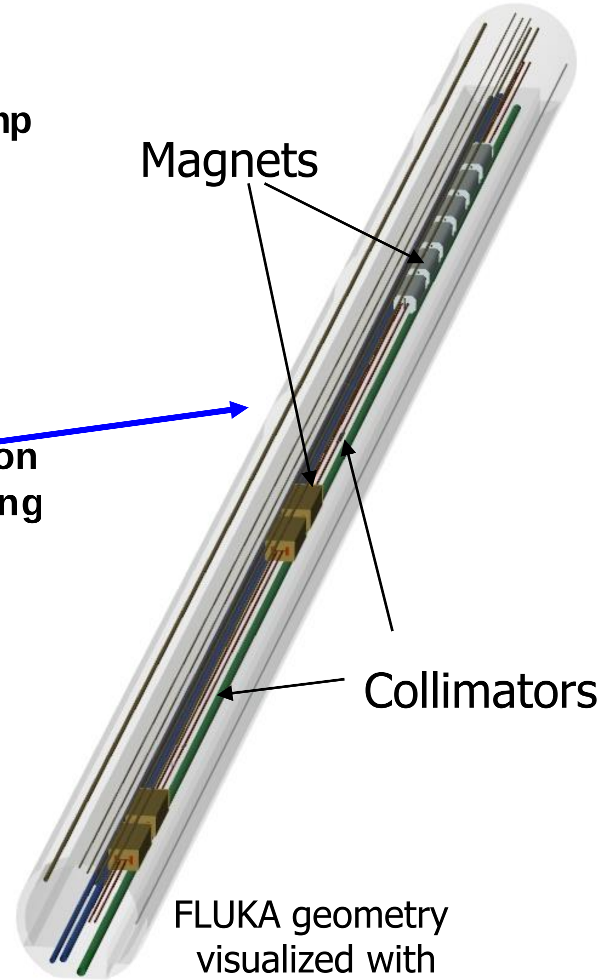


<u>Reference:</u> M. Brugger, S. Roesler *et al.*, Radiat. Prot. Dosim. 116 (2005) 12-15

Applications

Applications – *LHC collimation region*





FLUKA geometry
visualized with
SimpleGeo

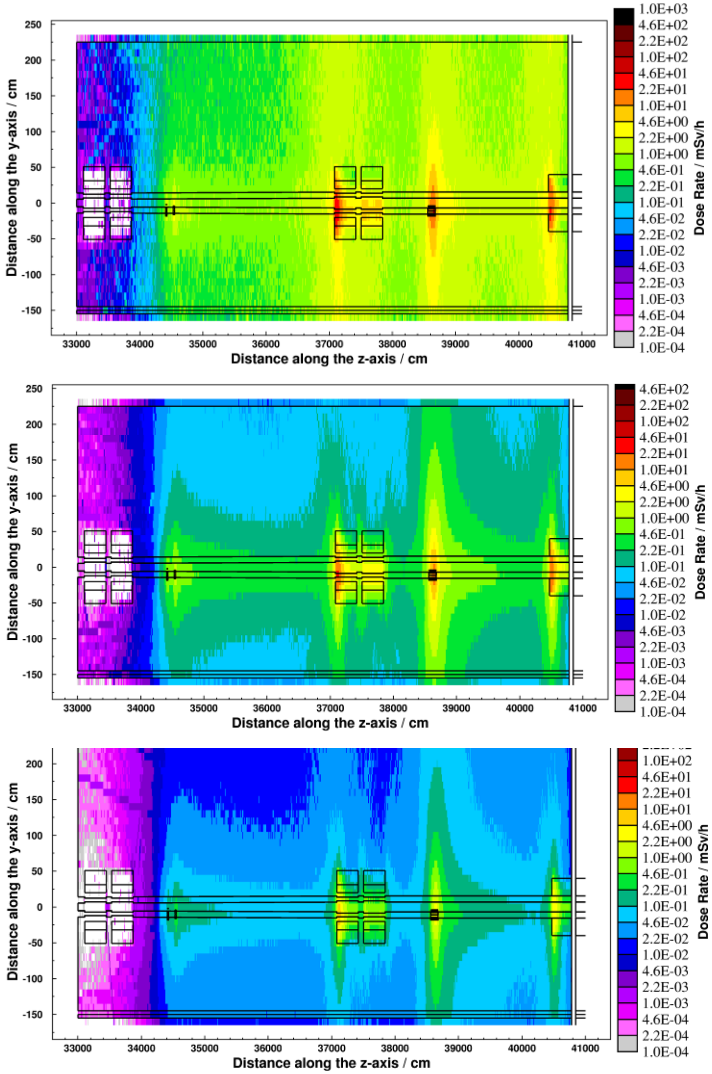
Applications – *LHC collimation region*

Cooling time

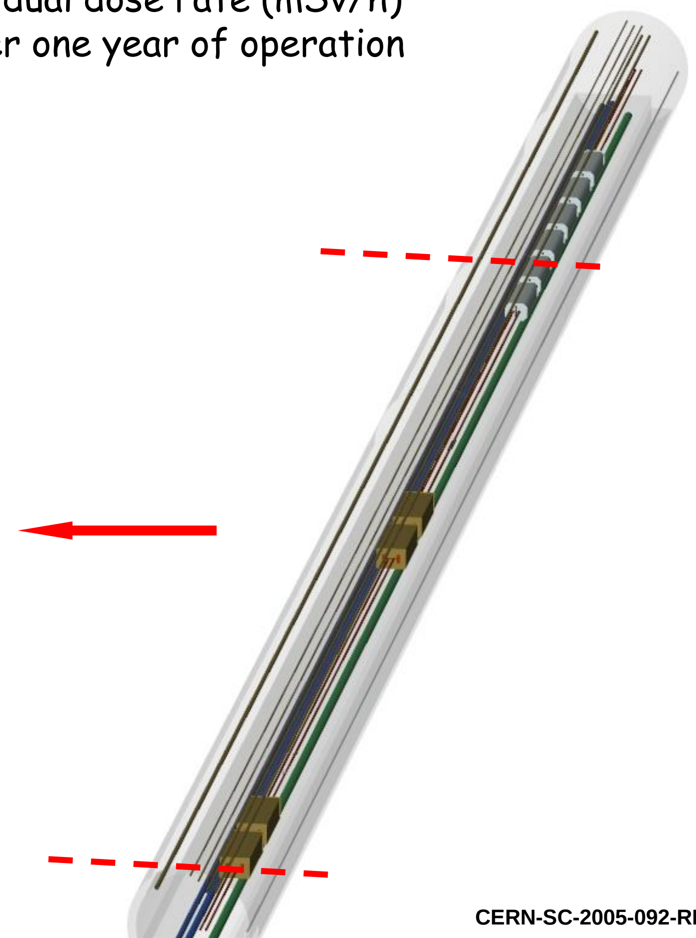
8 hours

1 week

4 months



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



CERN-SC-2005-092-RP-TN

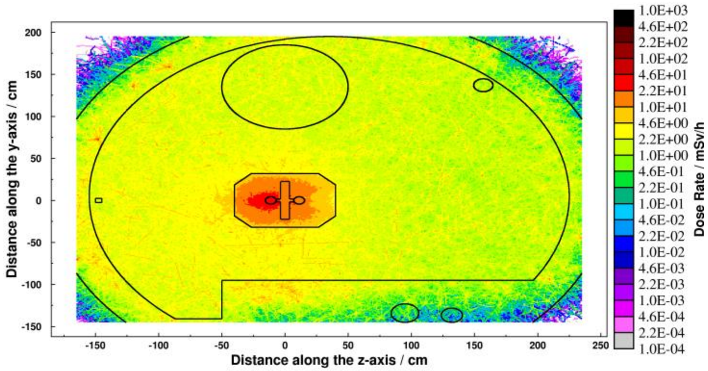
REMANENT DOSE RATE MAPS OF THE LHC BETATRON CLEANING INSERTION (IR7)

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

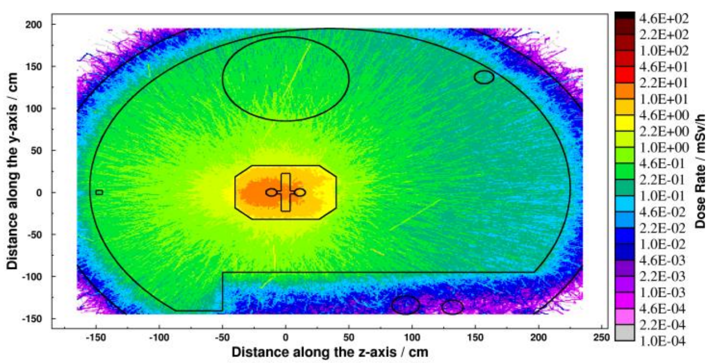
Applications – *LHC collimation region*

Cooling time

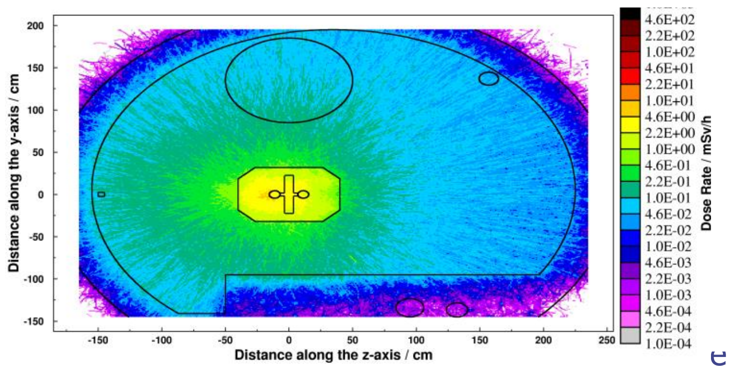
8 hours



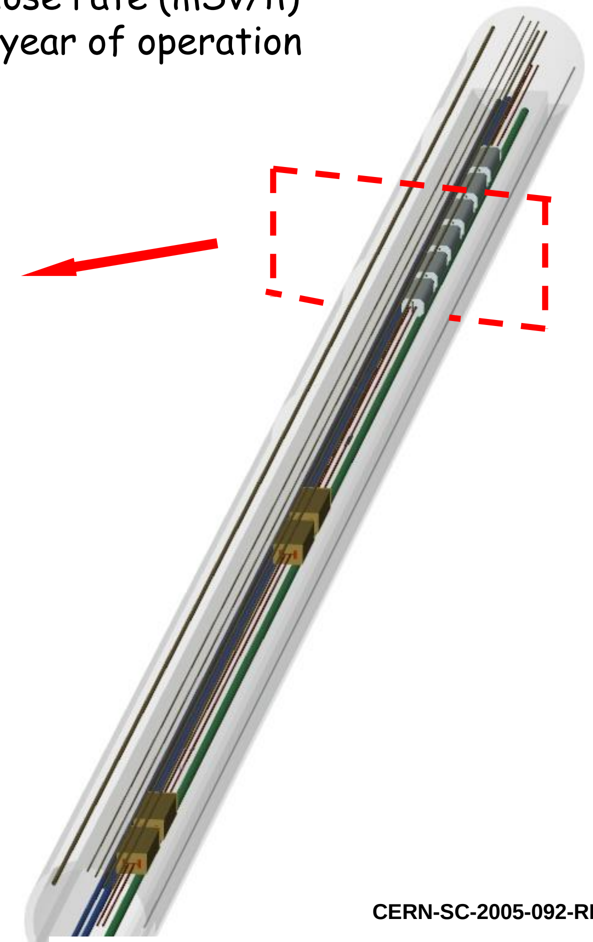
1 week



4 months



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



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