Calculation of residual dose rate with FLUKA : Application to the beam dump caverns of the LHC (Point 6)

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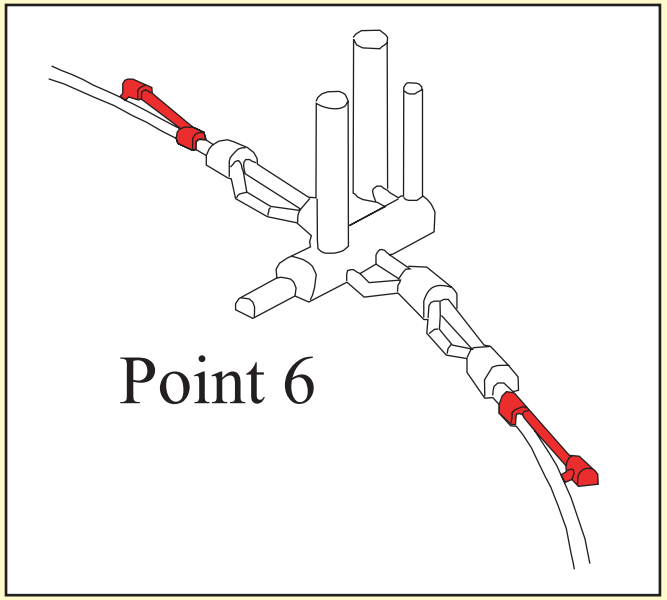
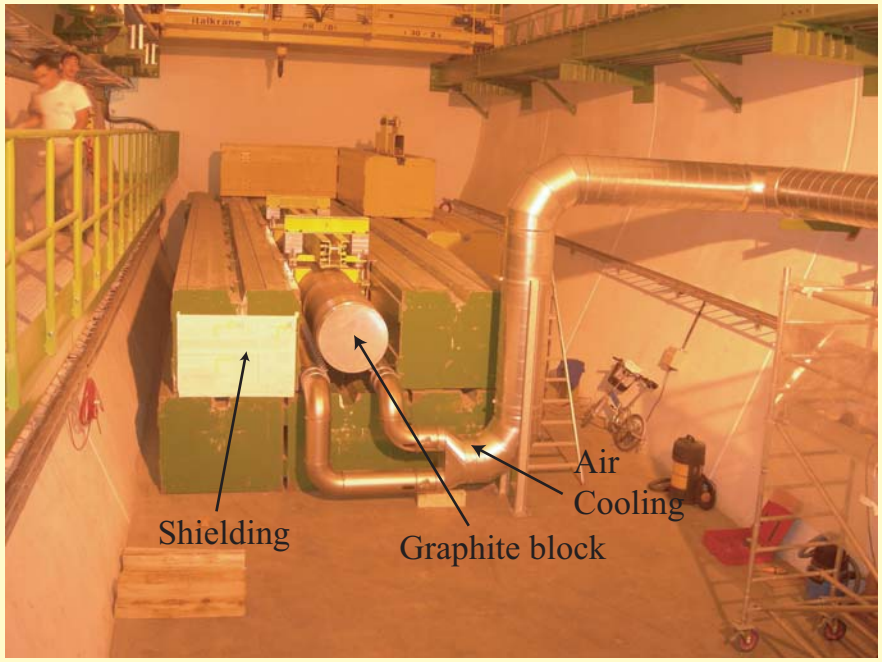
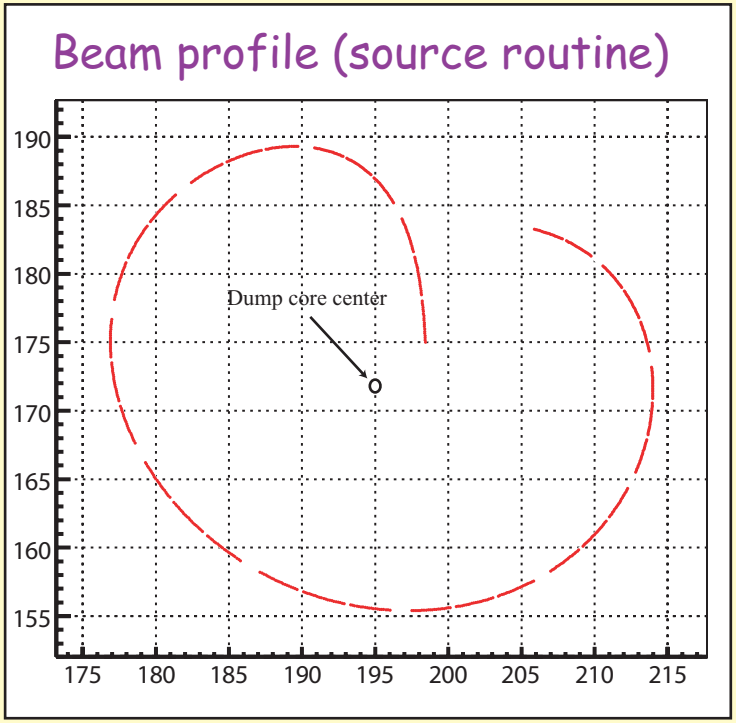
- LHC beam dump system

- The goal is to safely dump the beam in two dedicated absorbers at the end of the physics or in case of abnormal situation
- Two transfer tunnels (500 m) located at Point 6
- Several magnets to extract and dilute the beam
- 7.7 m long graphite cylinder with a 36 cm radius shielded with iron/concrete blocks
- Beam (2808 bunches) is swept over the core front face to limit the heat load







- FLUKA calculation for the beam dump cavern :

  * Air activation
  * Radioactive waste zoning
  * Energy deposition & Heat load
  * Remanent dose rate calculations

    • 1 Step calculation

    • 2 Steps calculation

      - some user routines mandatory (S. Roesler presentation)

      - parametric study (contribution of isotopes induced in different areas....)

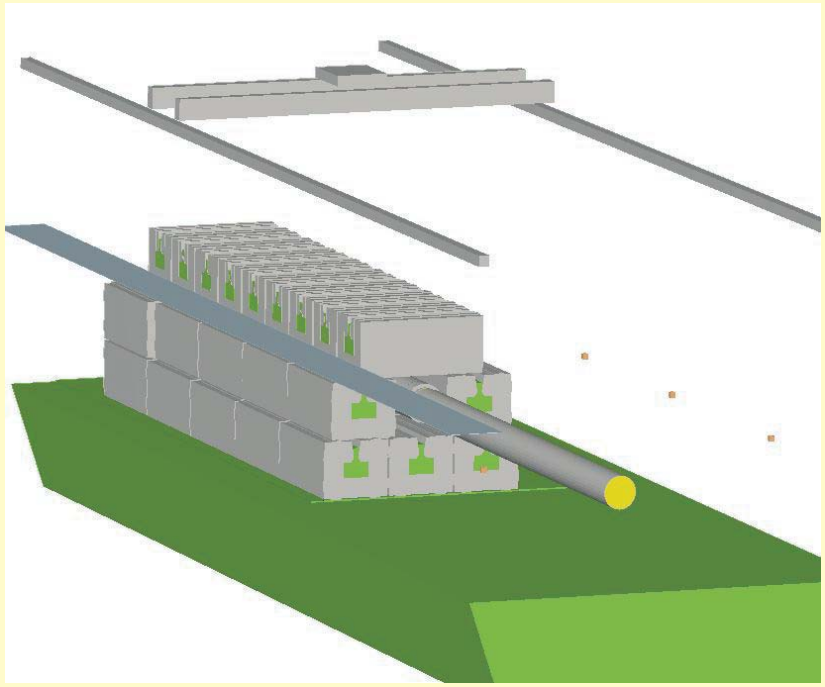
      - remanent dose rate when the shielding is open

- The FLUKA Geometry

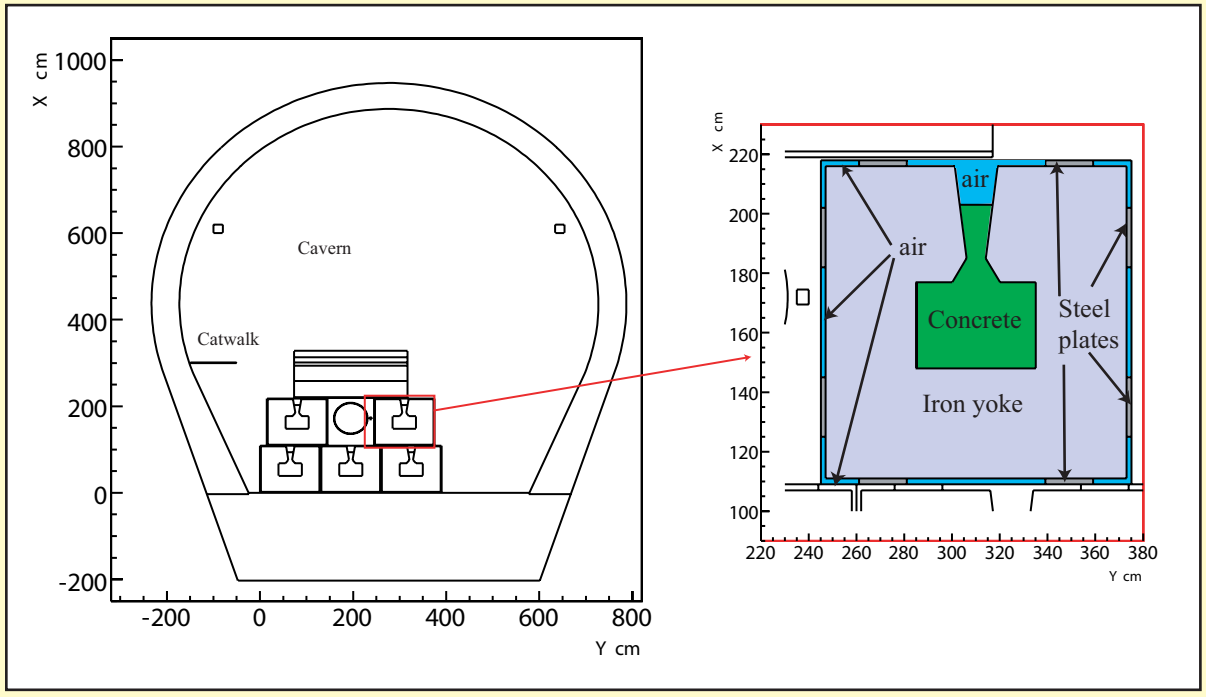
Detailed description of the dump core and its shielding

Simplified layout for other equipments inside the cavern (crane, catwalk...)

SimpleGeo view (3D)



PLOTGEOM View (2D)



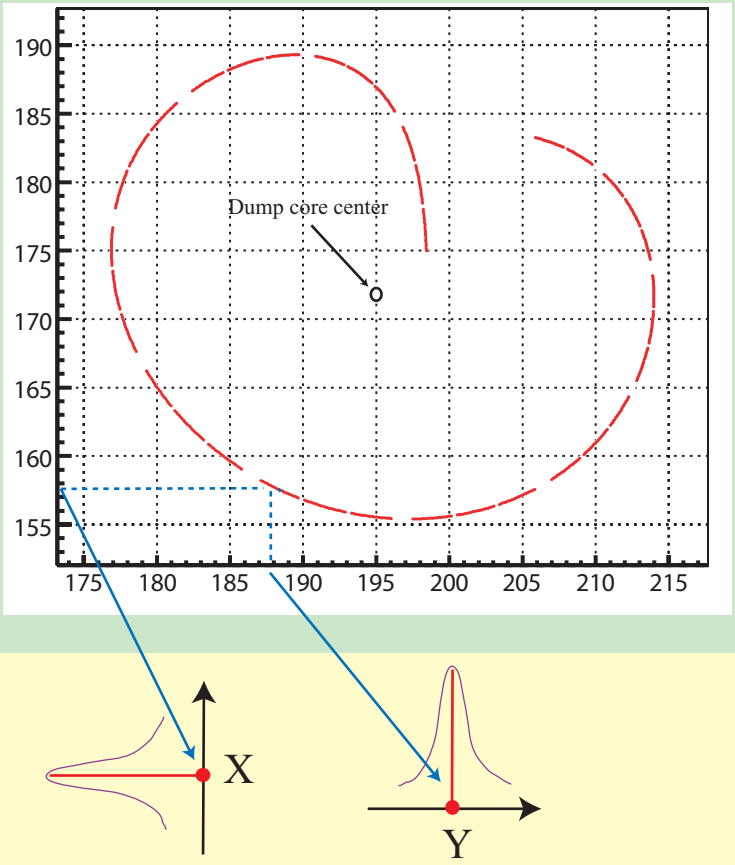
- For any calculation : using a source routine

- Bunches position (and direction) taken from an external file

Y	X	Y'	X'
17.871	30.331	0.018968	0.048646
16.279	30.741	0.017264	0.049305
14.922	31.15	0.015809	0.04996
13.564	31.556	0.014354	0.050612
12.324	31.962	0.013025	0.051263
11.084	32.366	0.011695	0.05191
10.077	32.769	0.010615	0.052557
⋮	⋮	⋮	⋮

position (relatively to the dump core axis)

angle with the dump core axis in mrad



- The primary protons starting position is sampled from the 2808 bunches position
- Vertical and horizontal beam size (Gaussian) for each bunch taken into account

```
*$ CREATE SOURCE.FOR
*COPY SOURCE
*
*=== source ============================================================*
*
      SUBROUTINE SOURCE ( NOMORE )

      INCLUDE '(DBLPRC)'
      INCLUDE '(DIMPAR)'
      INCLUDE '(IOUNIT)'
*
*----------------------------------------------------------------------*
*                                                                      *
*     Copyright (C) 1990-2006      by    Alfredo Ferrari & Paola Sala  *
*     All Rights Reserved.                                             *
*                                                                      *
*                                                                      *
*     New source for FLUKA9x-FLUKA200x:                                *
*                                                                      *
*     Created on 07 january 1990   by    Alfredo Ferrari & Paola Sala  *
*                                                   Infn - Milan       *
*                                                                      *
*     Last change on 03-mar-06     by    Alfredo Ferrari               *
*                                                                      *
*  This is just an example of a possible user written source routine.  *
*  note that the beam card still has some meaning - in the scoring the *
*  maximum momentum used in deciding the binning is taken from the     *
*  beam momentum.  Other beam card parameters are obsolete.            *
*                                                                      *
*----------------------------------------------------------------------*
*
      INCLUDE '(BEAMCM)'
      INCLUDE '(FHEAVY)'
      INCLUDE '(FLKSTK)'
      INCLUDE '(IOIOCM)'
      INCLUDE '(LTCLCM)'
      INCLUDE '(PAPROP)'
      INCLUDE '(SOURCM)'
      INCLUDE '(SUMCOU)'
*
      LOGICAL LFIRST
*

      SAVE LFIRST
      DATA LFIRST / .TRUE. /

      CHARACTER*14 CFNAME
      CHARACTER*13 SFNAME
      PARAMETER (LUNBUN=61)
      PARAMETER (LUNSOU=62)
      PARAMETER (CFNAME = 'TDE_window.txt')
      PARAMETER (SFNAME = 'SG_source.txt')
      PARAMETER (MAXBUN = 2809)
      DIMENSION XWIN(MAXBUN),YWIN(MAXBUN),X2WIN(MAXBUN),Y2WIN(MAXBUN),
     &          XPOS(MAXBUN),YPOS(MAXBUN),XDIR(MAXBUN),YDIR(MAXBUN)
      NOMORE = 0

*  +--------------------------------------------------------------------*
*  |  First call initializations:
      IF ( LFIRST ) THEN
*  |  *** The following 3 cards are mandatory ***
```

File and variable names

Start initialisation

```
         TKESUM = ZERZER
         LFIRST = .FALSE.
         LUSSRC = .TRUE.
*  |  *** User initialization ***
         WRITE(LUNOUT,*)
     &       ' SOURCE: beam parameter read from file ',CFNAME
         OPEN(LUNBUN,FILE='../'//CFNAME,STATUS='UNKNOWN')
         OPEN(LUNSOU,FILE='../'//SFNAME,STATUS='UNKNOWN')
         NBUNCH = 0
    1    CONTINUE
            NBUNCH = NBUNCH+1
            IF (NBUNCH.GT.MAXBUN) STOP ' SOURCE: NBUNCH > MAXBUN !'
            READ(LUNBUN,*,END=2)
     &         YWIN(NBUNCH),XWIN(NBUNCH),Y2WIN(NBUNCH),X2WIN(NBUNCH)
             XPOS(NBUNCH) = 172.0D+00 + XWIN(NBUNCH)/1.0E+01
             YPOS(NBUNCH) = 195.0D+00 + YWIN(NBUNCH)/1.0E+01
             XDIR(NBUNCH) = SIN(X2WIN(NBUNCH)*1.0D-03)
             YDIR(NBUNCH) = SIN(Y2WIN(NBUNCH)*1.0D-03)
         GOTO 1
    2    CONTINUE
         NBUNCH =  NBUNCH - 1
      END IF
*
*  Sample the bunch index
         IDXBUN = NBUNCH*FLRNDM(WHASOU(1))+1
*  |
*  +-------------------------------------------------------------------*
*  Push one source particle to the stack. Note that you could as well
*  push many but this way we reserve a maximum amount of space in the
*  stack for the secondaries to be generated
* Npflka is the stack counter: of course any time source is called it
* must be =0
      NPFLKA = NPFLKA + 1
* Wt is the weight of the particle
      WTFLK  (NPFLKA) = ONEONE
      WEIPRI = WEIPRI + WTFLK (NPFLKA)
* Particle type (1=proton.....). Ijbeam is the type set by the BEAM
* card
*  +-------------------------------------------------------------------*
*  |  Heavy ion:
      IF ( IJBEAM .EQ. -2 ) THEN
         IJHION = IPROZ  * 1000 + IPROA
         IJHION = IJHION * 100 + KXHEAV
         IONID  = IJHION
         CALL DCDION ( IONID )
         CALL SETION ( IONID )
         ILOFLK (NPFLKA) = IJHION
*  |
*  +-------------------------------------------------------------------*
*  |  Normal hadron:
      ELSE
         IONID  = IJBEAM
         ILOFLK (NPFLKA) = IJBEAM
      END IF
*  |
*  +-------------------------------------------------------------------*
* From this point .....
* Particle generation (1 for primaries)
      LOFLK  (NPFLKA) = 1
* User dependent flag:
      LOUSE  (NPFLKA) = 0
```

Reading the position and directions of the bunches (2808 maxi.) and allocating the arrays values

adapting to FLUKA geometry coordinate system.....

End of initialisation

Sampling the bunch index

```
* User dependent spare variables:
      DO 100 ISPR = 1, MKBMX1
         SPAREK (ISPR,NPFLKA) = ZERZER
 100  CONTINUE
* User dependent spare flags:
      DO 200 ISPR = 1, MKBMX2
         ISPARK (ISPR,NPFLKA) = 0
 200  CONTINUE
* Save the track number of the stack particle:
      ISPARK (MKBMX2,NPFLKA) = NPFLKA
      NPARMA = NPARMA + 1
      NUMPAR (NPFLKA) = NPARMA
      NEVENT (NPFLKA) = 0
      DFNEAR (NPFLKA) = +ZERZER
* ... to this point: don't change anything
* Particle age (s)
      AGESTK (NPFLKA) = +ZERZER
      AKNSHR (NPFLKA) = -TWOTWO
* Group number for "low" energy neutrons, set to 0 anyway
      IGROUP (NPFLKA) = 0
* Kinetic energy of the particle (GeV)
      TKEFLK (NPFLKA) = SQRT ( PBEAM**2 + AM (IONID)**2 ) - AM (IONID)
* Particle momentum
      PMOFLK (NPFLKA) = PBEAM
*     PMOFLK (NPFLKA) = SQRT ( TKEFLK (NPFLKA) * ( TKEFLK (NPFLKA)
*    &                       + TWOTWO * AM (ILOFLK(NPFLKA)) ) )
* Cosines (tx,ty,tz)
      TXFLK  (NPFLKA) = XDIR(IDXBUN)
      TYFLK  (NPFLKA) = YDIR(IDXBUN)
      TZFLK  (NPFLKA) = SQRT ( ONEONE - XDIR(IDXBUN)**2
     &                                - YDIR(IDXBUN)**2 )
* Polarization cosines:
      TXPOL  (NPFLKA) = -TWOTWO
      TYPOL  (NPFLKA) = +ZERZER
      TZPOL  (NPFLKA) = +ZERZER
* Particle coordinates
      CALL FLNRR2(RGAUS1,RGAUS2)
      RGAUS1 = RGAUS1*WHASOU(1)
      RGAUS2 = RGAUS2*WHASOU(2)
      XFLK   (NPFLKA) = XPOS(IDXBUN)+RGAUS1
      YFLK   (NPFLKA) = YPOS(IDXBUN)+RGAUS2
      ZFLK   (NPFLKA) = -1027.0D+00
      WRITE(LUNOUT,*)
     &      ' XXX YYY ZZZ',XFLK(NPFLKA),YFLK(NPFLKA),ZFLK(NPFLKA)
      WRITE(LUNOUT,*)
     &      ' U V W',TXFLK(NPFLKA),TYFLK(NPFLKA),TZFLK(NPFLKA)
      WRITE(LUNOUT,*)
     &      'IND GAUSSX GAUSSY',IDXBUN,RGAUS1,RGAUS2
      WRITE(LUNSOU,*)
     &     IJBEAM,WTFLK(NPFLKA)
     &         ,XFLK(NPFLKA),YFLK(NPFLKA)
     &         ,ZFLK(NPFLKA),TXFLK(NPFLKA),TYFLK(NPFLKA),TZFLK(NPFLKA)

*  Calculate the total kinetic energy of the primaries: don't change
      IF ( ILOFLK (NPFLKA) .EQ. -2 .OR. ILOFLK (NPFLKA) .GT. 100000 )
     &   THEN
         TKESUM = TKESUM + TKEFLK (NPFLKA) * WTFLK (NPFLKA)
      ELSE IF ( ILOFLK (NPFLKA) .NE. 0 ) THEN
         TKESUM = TKESUM + ( TKEFLK (NPFLKA) + AMDISC (ILOFLK(NPFLKA)) )
     &          * WTFLK (NPFLKA)
      ELSE
```

value of σ for X and Y are passed through WHAT(1) and WHAT(2) of the source card

Sampling horizontal and gaussian spread, defining particle starting position

```
         TKESUM = TKESUM + TKEFLK (NPFLKA) * WTFLK (NPFLKA)
      END IF
*  Flag this is prompt radiation
      LRADDC (NPFLKA) = .FALSE.
      RADDLY (NPFLKA) = ZERZER
*  Here we ask for the region number of the hitting point.
*     NREG (NPFLKA) = ...
*  The following line makes the starting region search much more
*  robust if particles are starting very close to a boundary:
      CALL GEOCRS ( TXFLK (NPFLKA), TYFLK (NPFLKA), TZFLK (NPFLKA) )
      CALL GEOREG ( XFLK  (NPFLKA), YFLK  (NPFLKA), ZFLK  (NPFLKA),
     &              NRGFLK(NPFLKA), IDISC )
*  Do not change these cards:
      CALL GEOHSM ( NHSPNT (NPFLKA), 1, -11, MLATTC )
      NLATTC (NPFLKA) = MLATTC
      CMPATH (NPFLKA) = ZERZER
      CALL SOEVSV
      RETURN
*=== End of subroutine Source =========================================*
      END
```

- Calculation of the dose rate in a single calculation (standard)

- The dose rate is calculated using a track length estimator and fluence to dose energy dependent conversion factors (for the two methods) FLUSCW routine

Stefan Roesler and Graham R. Stevenson, "deq99.f - A FLUKA user-routine converting fluence into effective dose and ambient dose equivalent", Technical Note CERN-SC-2006-070-RP-TN, EDMS No. 809389 (2006)

Definition of the irradiation profile, cooling times connected to detectors

```
* Cutt off relevant for decay particles
EMFCUT        -5E-05     1E-05       0.0       1.0  @LASTREG       1.0
*
*
*
* ****************************************************************************
*
RADDECAY         1.0                  5.0          0000099999
* One year of irradiation in this case
IRRPROFI    1.5552E7 3.85802E9
* For dose rate calculation
*...+....1....+....2....+....3....+....4....+....5....+....6....+....7..
DCYTIMES      3600.0    2.88E4    8.64E4   6.048E5   2.592E6  1.0368E7
*
*              1hour    1month
* Associating decay times to detectors
*
DCYSCORE         1.0                              1.0       1.0          USRBIN
DCYSCORE         2.0                              2.0       2.0          USRBIN
DCYSCORE         3.0                              3.0       3.0          USRBIN
DCYSCORE         4.0                              4.0       4.0          USRBIN
DCYSCORE         5.0                              5.0       5.0          USRBIN
DCYSCORE         6.0                              6.0       6.0          USRBIN
* Big cartesian mesh which includes the cavern walls....
USRBIN          10.0  ALL-PART     -55.0    1050.0     950.0    1600.0EWT74C1h
USRBIN        -250.0    -350.0   -1500.0      65.0      65.0     155.0&
*
* Big cartesian mesh which includes the cavern walls....
USRBIN          10.0  ALL-PART     -55.0    1050.0     950.0    1600.0EWT74C8h
USRBIN        -250.0    -350.0   -1500.0      65.0      65.0     155.0&
```

Threshold for electron/positron and gammas

kills the prompt contribution to the electromagnetic cascade

180 days of irradiation with 6×10^{16} protons

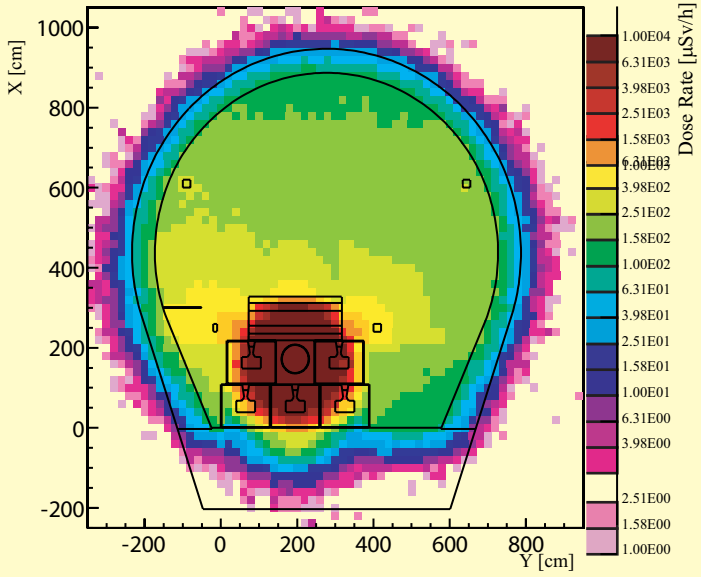
6 different cooling times from 1 hour to 4 months

associating the cooling times to the different detector (USRBIN)

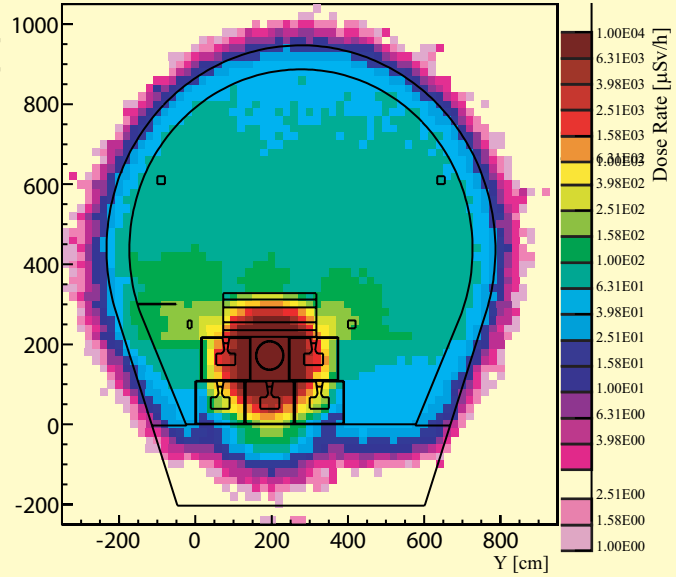
Scoring particles (all) track length in a cartesian 3D mesh, routine FLUSCW to convert to effective dose (using worst possible irradiation factors....) don't forget USERWEIG !!!!!

- RESULTS deq99.f + irradiation profile → results in pSv/s (3600/1000000)

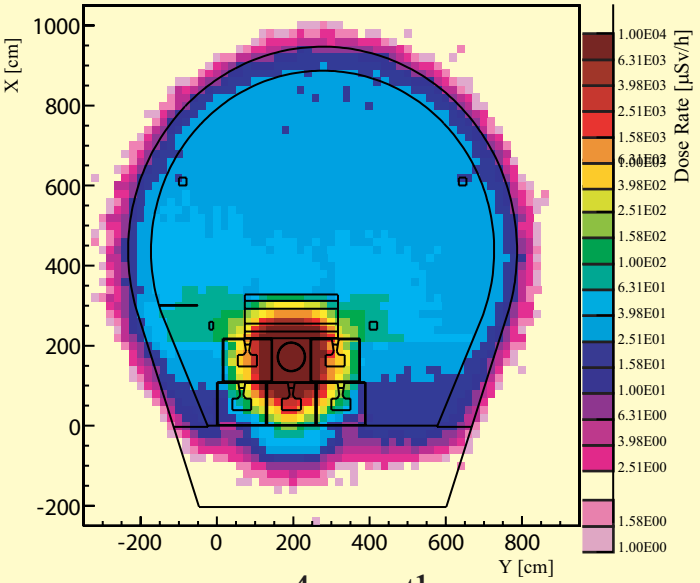
1 hour



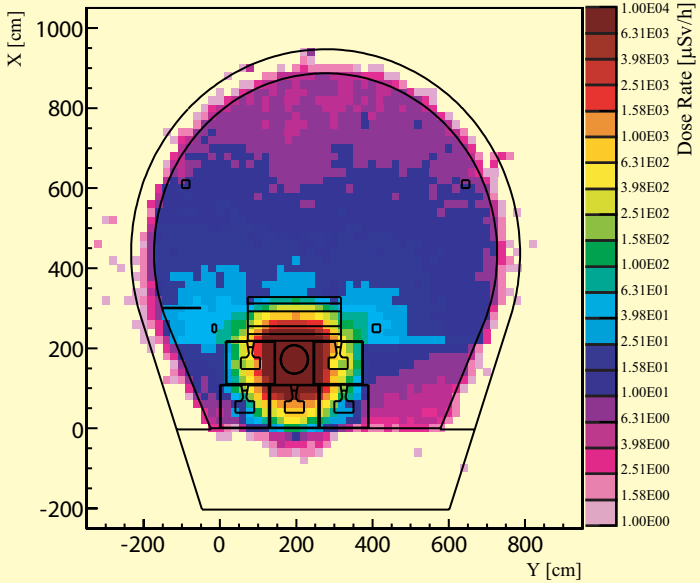
8 hours



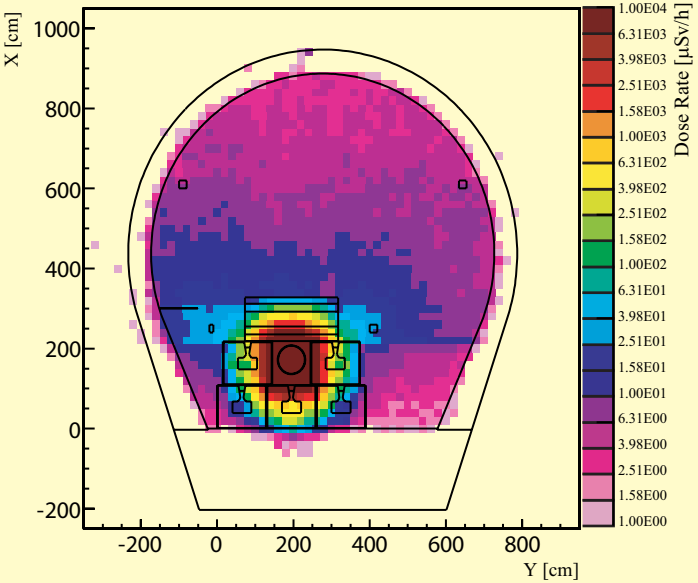
1 day



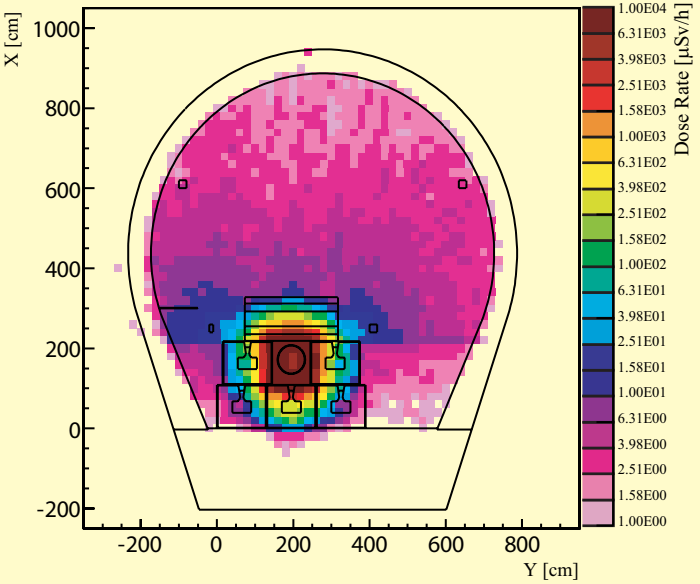
7 days



1 month



4 months

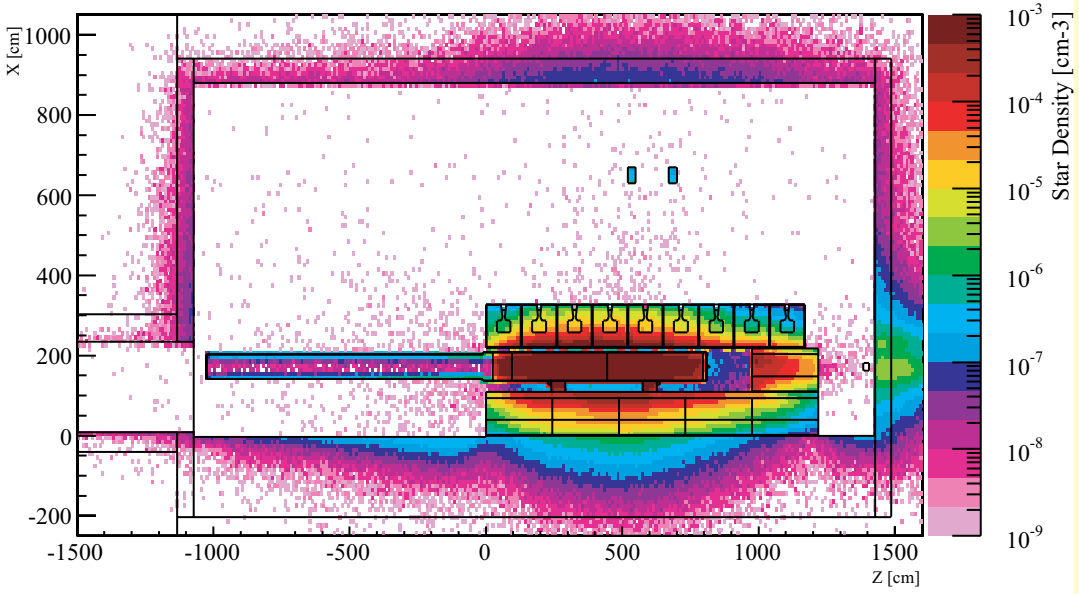


SAME CALCULATION USING THE TWO STEPS APPROACH

Perform two calculations, the first one is dedicated to the calculation of isotopes production for a given irradiation pattern and different cooling times. The transport of decay radiations for one cooling time is performed in the second step of the calculation.

Contribution of radioactive decay score in three different calculations to limit the size of isodump.dat file (first step)

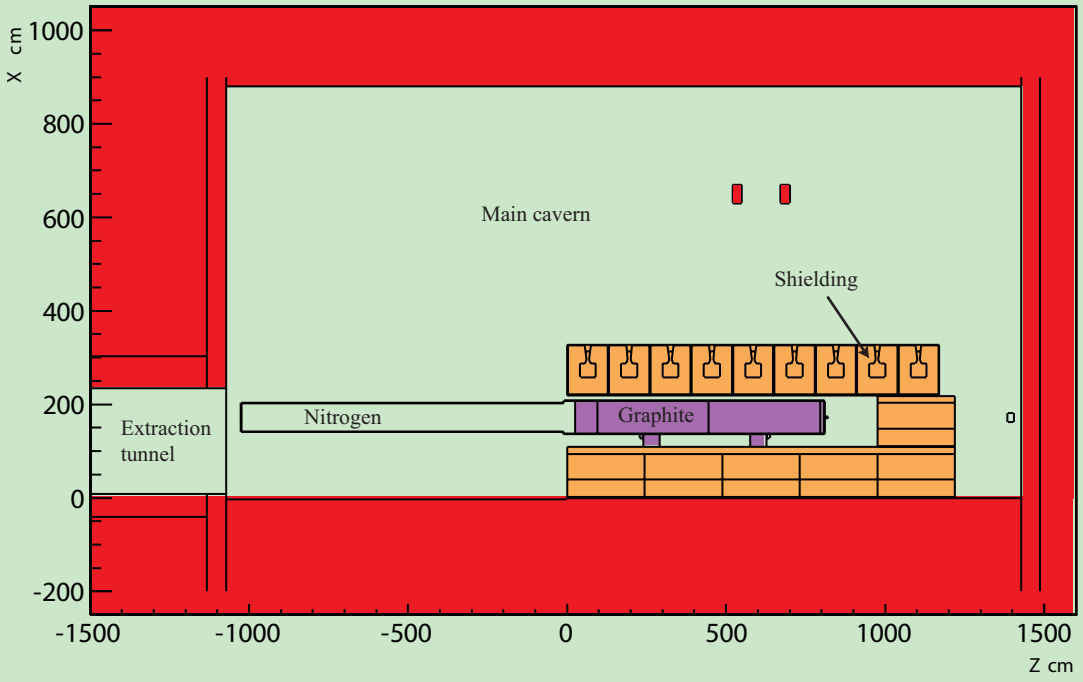
Star density map



1 - Cavern fixed structure (walls, floor...)

2 - Shielding blocks

3 - dump core (might be exchanged....)



Dumping the isodump.dat file (first step)

```
*****************************************************************
*
EMF                                                          EMF-OFF
*
*          switching off em cascade since particles emitted after
*          the radioactive decay are not transported in the first step
* ***************************************************************************
*             Card to store residual nuclei location
*
* ***************************************************************************
* Adding a RESNUCLE card to call the user routine
* (in the first part of the graphite core)
RESNUCLE         3.0     -89.0                  CorePG1 2.6939E05PG1-a
* activate call to Usrrnc                  mandatory
USERWEIG                                                      1.0
*
USRICALL         1.0       8.0                                TCOOLH
USRICALL         1.0       7.0      30.0     120.0            TCOOLD
USRICALL         1.0                                         TCOOLY
*                    cooling times mixing of hour, days, years ok
USRICALL           4                                         DUMPING
*                      electron emitters are
USRICALL         125     133.0       not taken into account DUMPREG
USRICALL         1.0                                        OUTPUT
** biased isotope dumping          dumping only isotopes induced
USRICALL         200       0.2     in the dump core, default biasing BIASING
USRICALL         125     133.0     applied to all regions concerned BIASREG
*
* ***************************************************************************
*
*
* Big cartesian mesh which includes the cavern walls....
USRBIN           0.0  ALL-PART     -70.0    1050.0     950.0    1600.0Stars
USRBIN        -250.0    -350.0   -1500.0     130.0     130.0     310.0&
* ***************************************************************************
BEAM         -7000.0                                            PROTON
SOURCE         0.136     0.159
RANDOMIZE        1.0
START          400.0                                  0.0
USROCALL
STOP
```

Running the first step of the calculation

- Irradiation cycle described in the irrcyc.inp file

```
3.8580247E09
d180.0
s0
1
s1
```

180 days of irradiation for 6E16 protons

not used but mandatory....

- FLUKA linked to the additional user routines and the source routine to sample from the diluted beam (different in the second step)
- rfluka script with the necessary data files

Preparing the second step

At the end of the standard output file, parameters mandatory for the second step of the calcualtion

```
      Parameters for USRICALL:
         - all regions
               8.270E+02 8.143E+02 7.817E+02 6.776E+02 5.852E+02 5.036E+02
               4.952E+02
         - regions no.  125
               4.640E+00 4.640E+00 4.635E+00 2.312E+00 2.312E+00 2.312E+00
               2.312E+00
         - regions no.  126
               1.018E+02 9.978E+01 9.558E+01 5.700E+01 5.602E+01 4.151E+01
               4.139E+01
         - regions no.  127
               6.974E+01 6.974E+01 6.970E+01 3.417E+01 3.417E+01 3.417E+01
               3.417E+01
         - regions no.  128
               5.081E+02 4.997E+02 4.782E+02 4.556E+02 3.851E+02 3.337E+02
               3.270E+02
         - regions no.  129
               1.317E+00 1.312E+00 6.400E-01 6.250E-01 5.600E-01 5.475E-01
                     -01
                                        .
                                        .
                                        .
```

7 values corresponding to the 7 cooling times

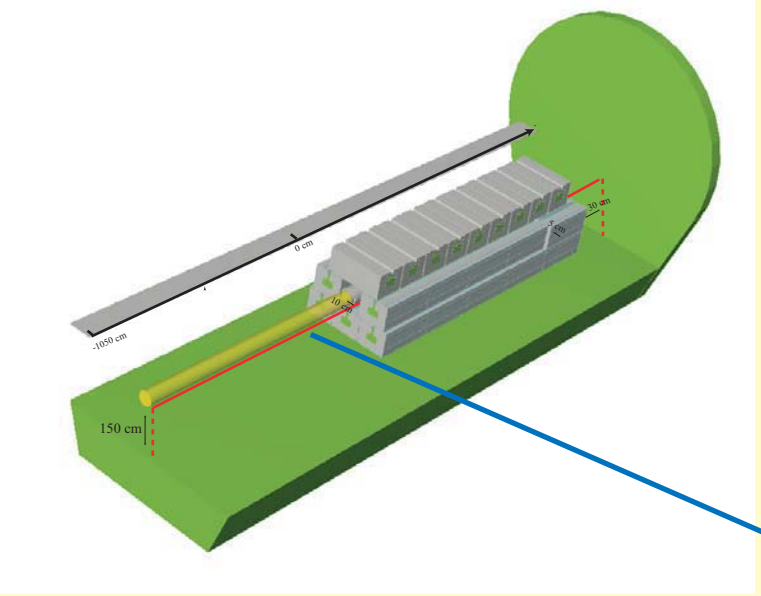
if all decay products from all regions are considered
Otherwise contribution of individual regions must be added

all regions for which isotopes were dumped in the first step are considered....

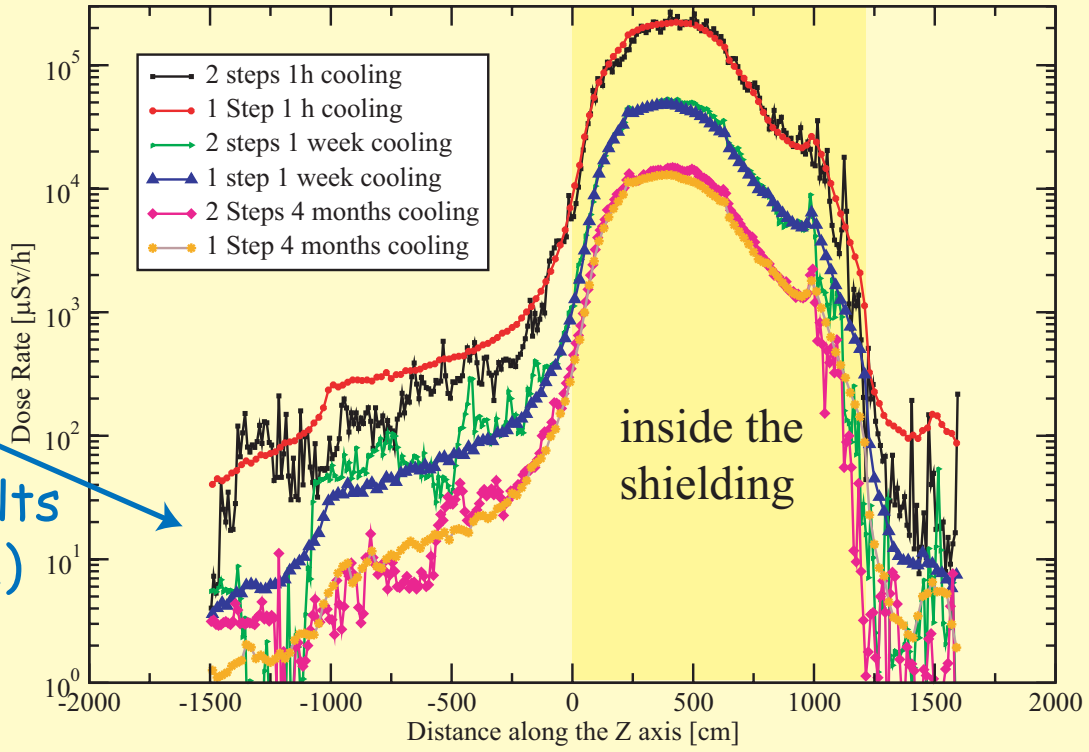
```
*
USRICALL         125     133.0                                        SAMPREG
USRICALL         1.0                                                  OUTPUT
*
*...+....1....+....2....+....3....+....4....+....5....+....6....+....7..
USRICALL   8.270E+02 8.143E+02 7.817E+02 6.776E+02 5.852E+02 5.036E+02WCOOL
USRICALL   4.952E+02                                                  WCOOL
* ***************************************************************************
*
*
* ***************************************************************************
*                                  Dose Rate map for scoring
* ***************************************************************************
*
*
* Big cartesian mesh which includes the cavern walls....
USRBIN          10.0  ALL-PART     -55.0    1050.0     950.0    1600.0EWT74C1h
USRBIN        -250.0    -350.0   -1500.0     130.0     130.0     310.0&
*
BEAM         -7000.0                                                  PROTON
*
*
*
SOURCE             4         4
*
RANDOMIZE        1.0
START      1000000.0                                    0.0
USROCALL
STOP
```

fourth cooling time
electron emitters omitted

Comparison of the two methods



Dose rate profile along the beam pipe

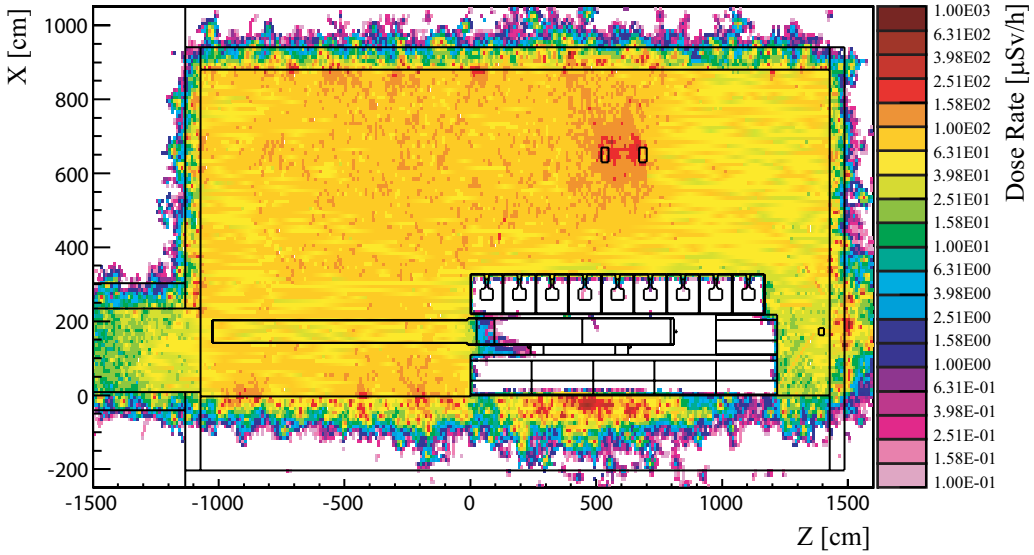


- The two methods lead to identical results (standard method ran on CERN cluster...)
- Single calculation for one step method
- 5 calculation (1 + 4 cooling times) for the two steps methods

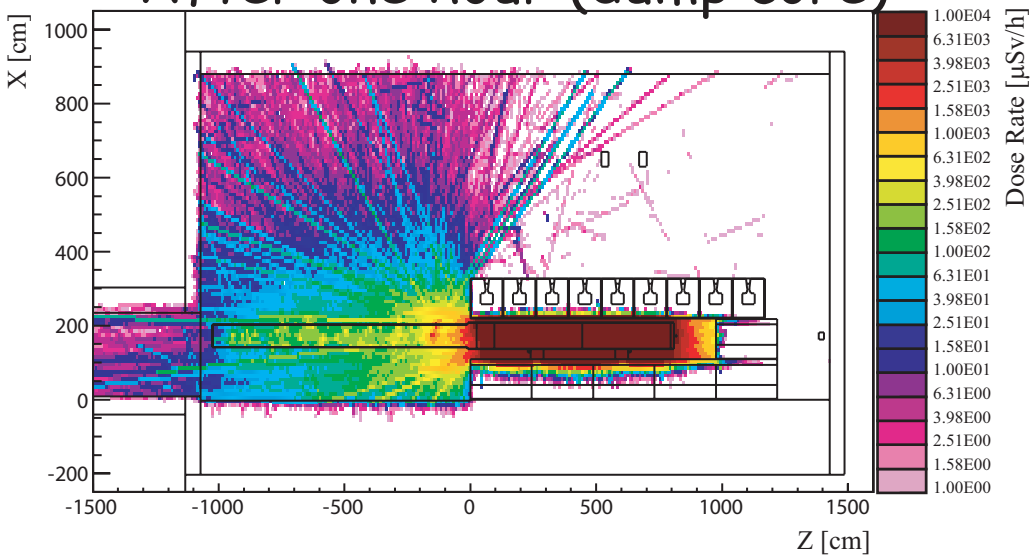
The standard method is easier and faster but with the two steps method it is possible to perform parametric studies (contribution of radioactive isotopes induced in different areas), modify the geometry (what happens when part of the shielding is removed.....) as shown in the coming example.....

In the second step looking only at the contribution of decay radiation from some areas (concrete, dump core and shielding...)

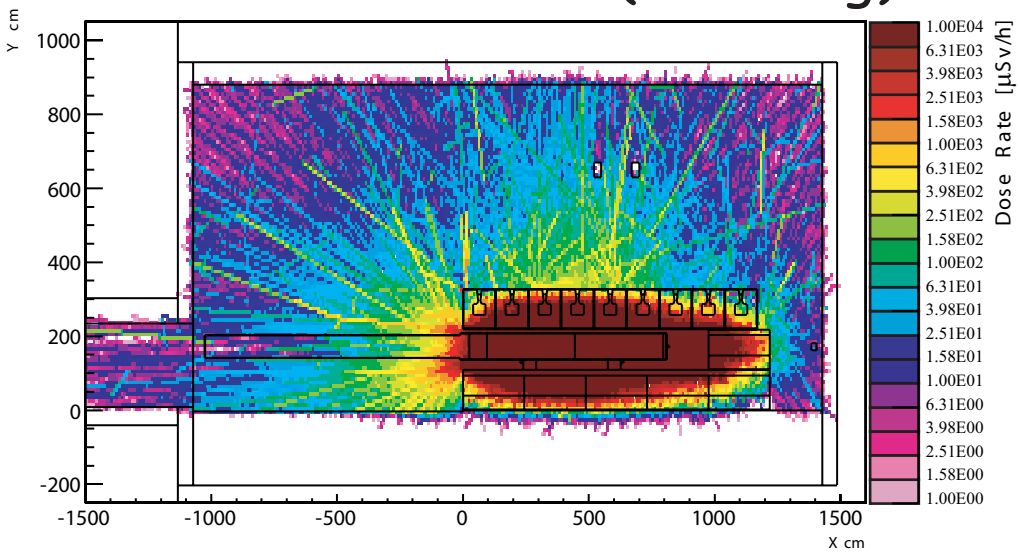
After one hour (cavern structure)



After one hour (dump core)

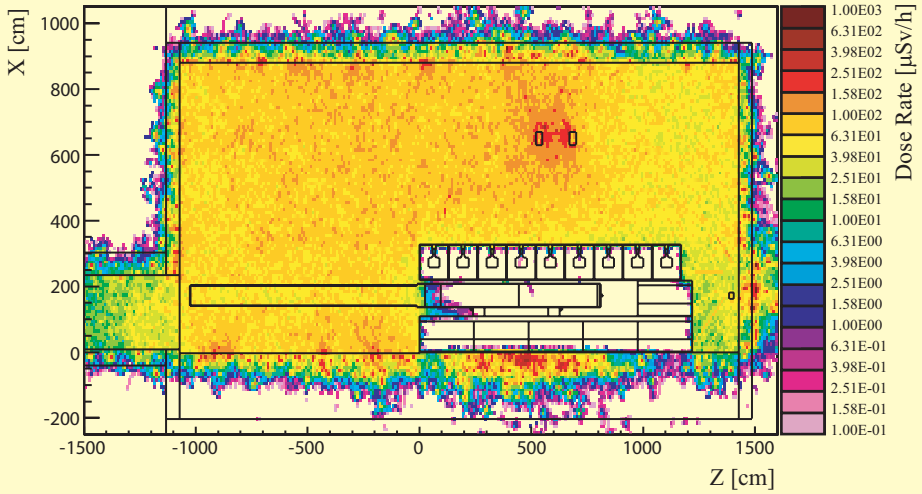


After one hour (shielding)

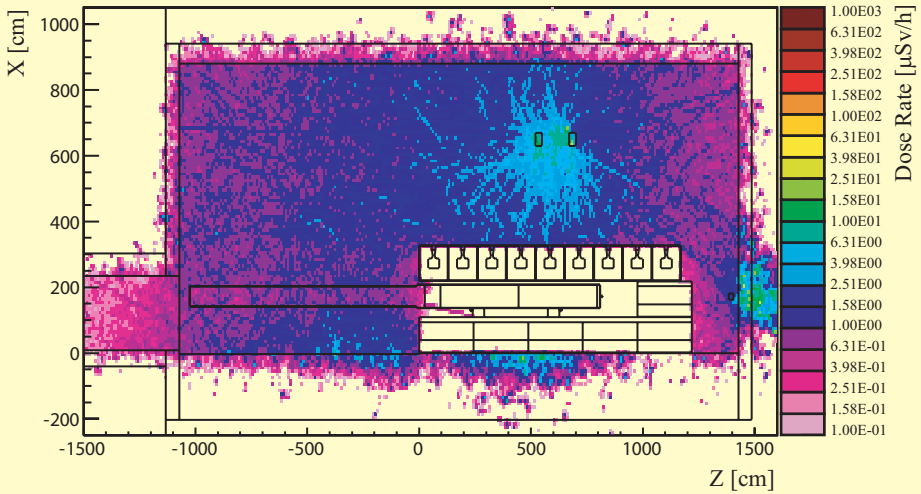


Very powerful to perform details study ....

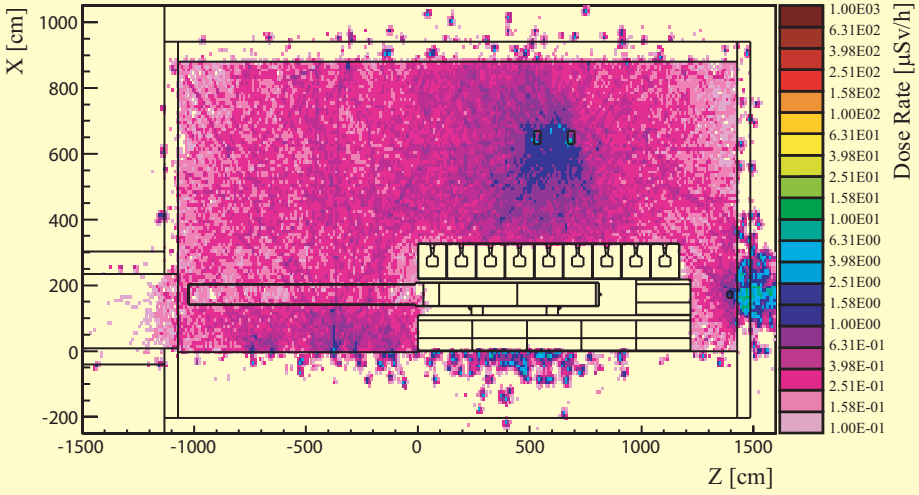
one hour cooling



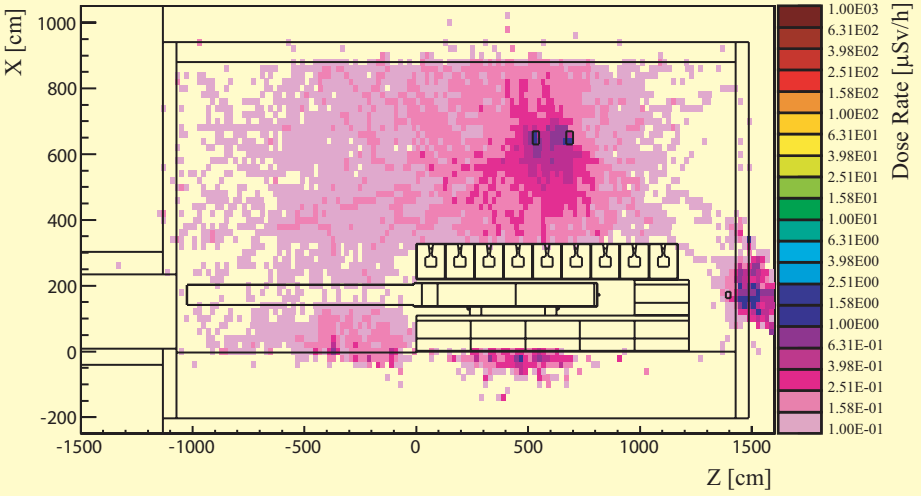
one week



one month



four months

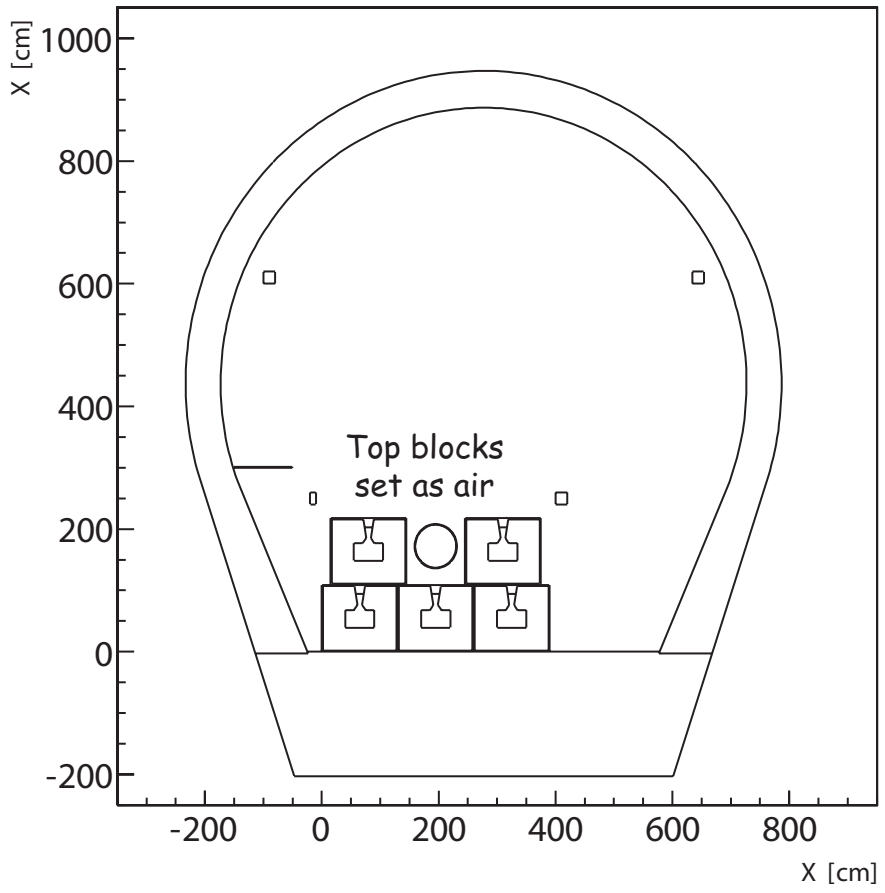


For example the contribution of radioactive isotopes induced in the concrete is very low after a few weeks

How to modify a part of the geometry in the second step ?

When the shielding is open, no contribution of the top shielding blocks...

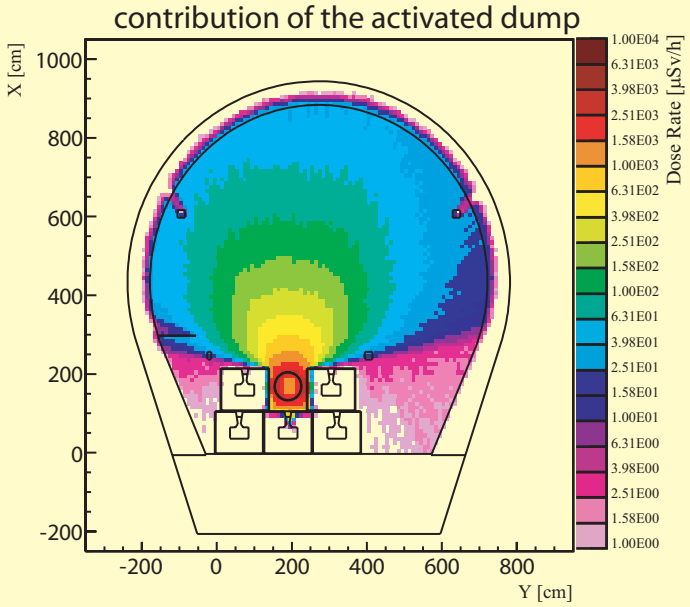
necessary if the dump has to be replaced

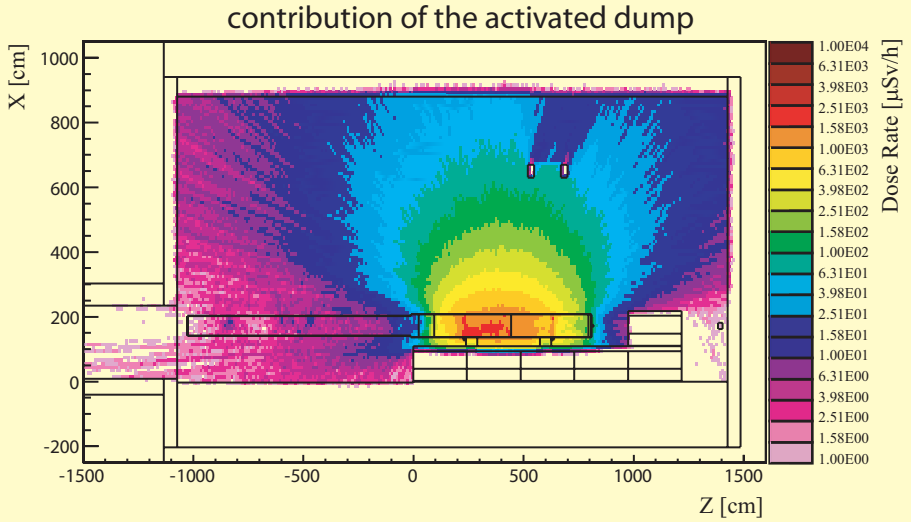


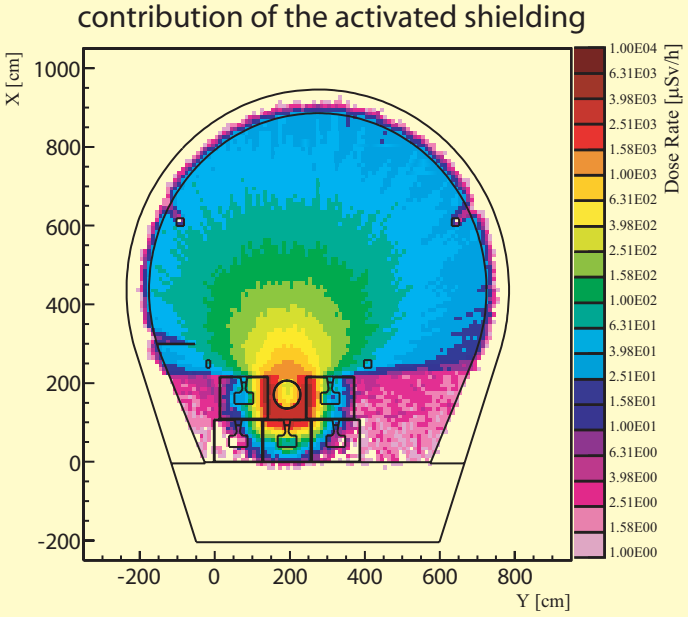
- Modify the geometry of the second step of the calculation, in practice the removed blocks are defined as "air" to avoid possible errors due to region indexing

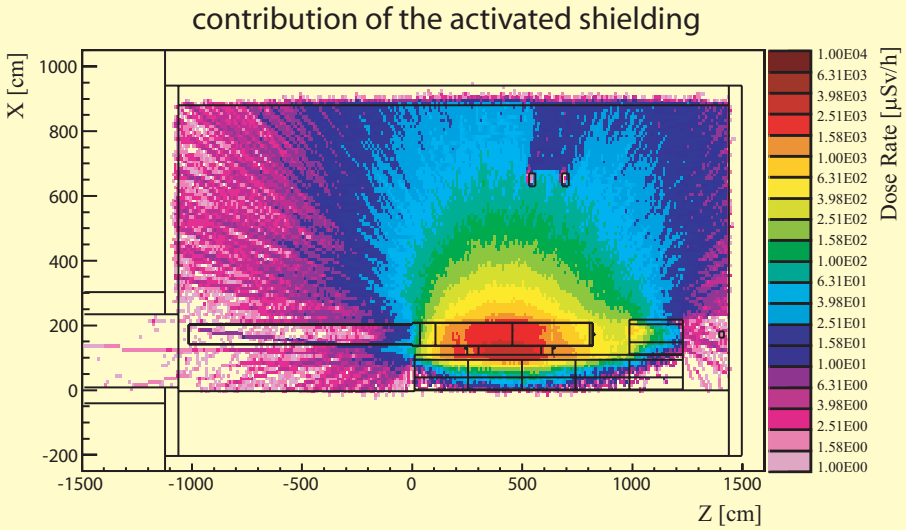
- Calculate the weight of the regions from which particles emitted following radioactive have to be sampled

Example of modified geometry in the second step

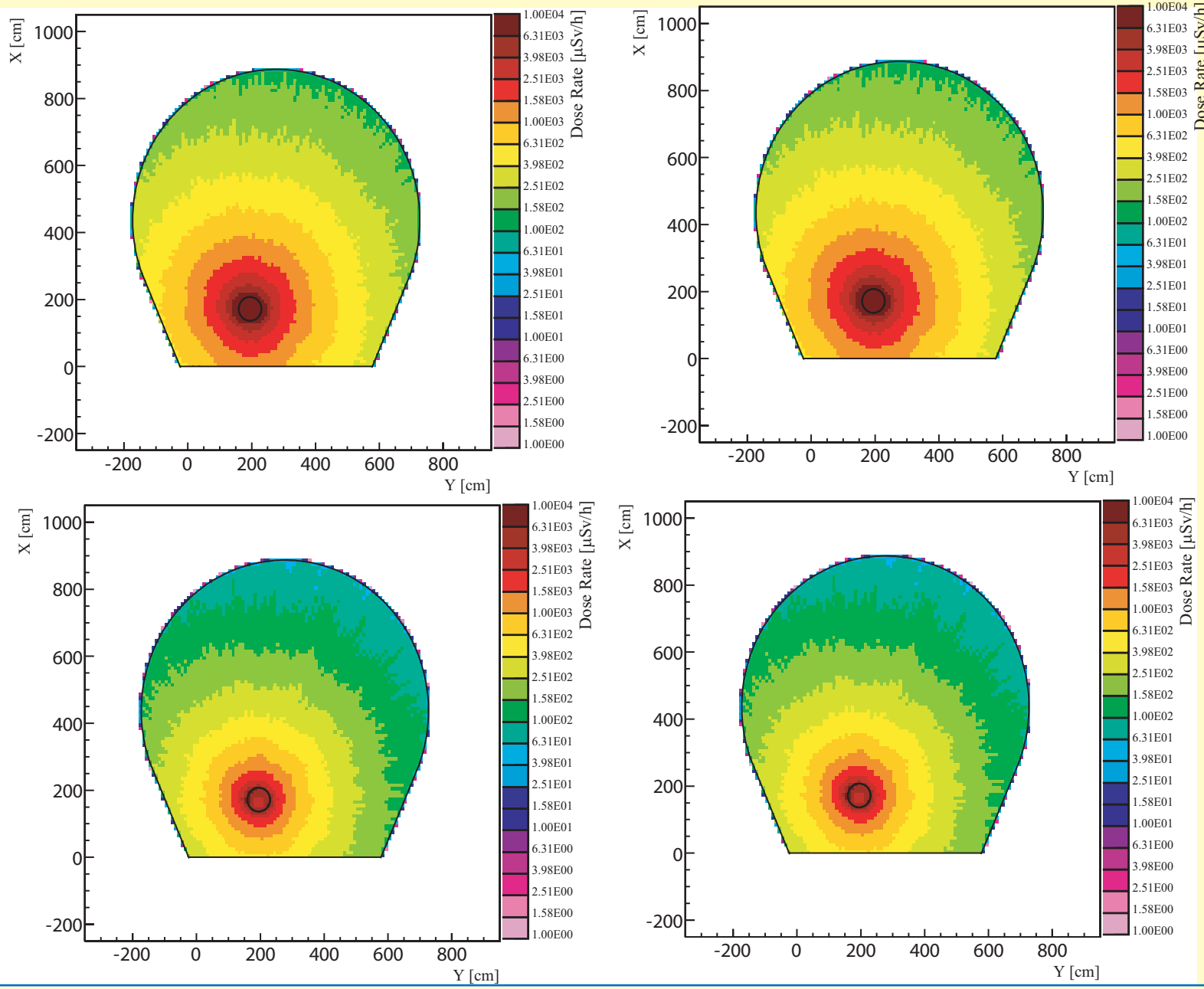








Dose rate from the dump core itself with no shielding around



Design of temporary shielding for transport

Set the "removed" regions as being filled with air

Adding new region at the end of the input to avoid changing region index

Conclusion

- Two methods to transport radiations emitted after radioactive decay for a given irradiation pattern and different cooling times were investigated....

- The first method which is a standard feature of FLUKA allows to obtain results for different cooling times in one single calculation

- The second one based on the implementation of several user routines recquires several calculation, one for the determination of radioactive isotopes and one for each cooling times to transport particles from the radioactive decay

- Results are identical, the first method is faster the second one is more flexible and allows to modify the geometry transporting radiations from the radioactive decay