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

<table>
<thead>
<tr>
<th>Y</th>
<th>X</th>
<th>Y'</th>
<th>X'</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.871</td>
<td>30.331</td>
<td>0.018968</td>
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<td>16.279</td>
<td>30.741</td>
<td>0.017264</td>
<td>0.049305</td>
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<td>12.324</td>
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<td>0.051263</td>
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<td>10.077</td>
<td>32.769</td>
<td>0.010615</td>
<td>0.052557</td>
</tr>
</tbody>
</table>

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
SUBROUTINE SOURCE ( NOMORE )

INCLUDE '(DBLPRC)' 
INCLUDE '(DIMPAR)' 
INCLUDE '(IUNIT)' 

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 ***
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
IDXUN = 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
* 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 ( ONE - XDIR(IDXBUN)**2 - YDIR(IDXBUN)**2 )
* Polarization cosines:
  TXPOL (NPFLKA) = -TWOTWO
  TYPOL (NPFLKA) = +ZERZER
  TZPOL (NPFLKA) = +ZERZER
* Particle coordinates
  CALL FLNRR2(RGAUS2,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)) )
  ELSE
    * WTFLK (NPFLKA)

value of \( \sigma \) 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.
RADLY (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


**Definition of the irradiation profile, cooling times connected to detectors**

```plaintext
* Cut 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 $6 \times 10^{16}$ protons
- 6 different cooling times from 1 hour to 4 months

**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

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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)

1 - Cavern fixed structure (walls, floor...)
2 - Shielding blocks
3 - dump core (might be exchanged....)
Dumping the isodump.dat file (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

USERWEIG

* USRICALL 1.0 8.0 
USRICALL 1.0 7.0 30.0 120.0
USRICALL 1.0 

* mandatory

USRICALL 4 

USRICALL 125 133.0
USRICALL 1.0 

** biased isotope dumping

USRICALL 200 0.2
USRICALL 125 133.0 

* biasing applied to all regions concerned

* Big cartesian mesh which includes the cavern walls....

USRBIN 0.0 ALL-PART -70.0 1050.0 950.0 1600.0 Stars
USRBIN -250.0 -350.0 -1500.0 130.0 130.0 310.0 &

* cooling times mixing of hour, days, years ok

electron emitters are not taken into account

dumping only isotopes induced in the dump core, default biasing

switching off em cascade since particles emitted after the radioactive decay are not transported in the first step

mandatory
Running the first step of the calculation

- Irradiation cycle described in the irrcyc.inp file

\begin{verbatim}
3.8580247E09
d180.0
s0
1
s1
\end{verbatim}

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 calculation:

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
- 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
- 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 5.475E-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+02 WCOOL
* 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 1600.0 EWT74C1h
* 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

- 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....

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...

- 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

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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 requires 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.