FLUKA simulations for the optimization of the Beam Loss Monitors

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March 20, 2006

Abstract

The collimation system in the beam cleaning insertion IR7 of the future Large Hadron Collider (LHC) cleans the primary halo and the secondary radiation of a beam with unprecedented energy and intensity. Accidental beam losses can therefore entail severe consequences to the hardware of the machine. Thus, protection mechanisms, e.g. beam abort, must be instantaneously triggered by a set of Beam Loss Monitors (BLM's). The readings in the BLM's couple the losses from various irradiated objects, which renders the identification of any faulty unit rather complex. In the present study the detailed geometry of IR7[1] was upgraded with the insertion of the BLM's, and the Monte Carlo FLUKA transport code was used to estimate the individual contribution of every collimator to the showers detected in each BLM.

Contents

1 Introduction

1.1 Simulations of the IR7 insertion

The collimation system of the future Large Hadron Collider (LHC) at CERN is a challenging project, since the transverse energy intensities of the LHC beams are three orders of magnitude greater than those at other current facilities. Two insertions (IR3, IR7) of LHC are dedicated to beam cleaning with the design goal of absorbing part of the primary beam halo and of the secondary radiation. These insertions will house 54 movable, two-sided collimators and will be among the most radioactive areas of LHC. The collimators should withstand the deposited power, which for phase I can reach values of 25 kW in the upstream units.

The tertiary halo which escapes the collimation system in IR7 may heat some fragile elements up to unacceptable levels, if no additional absorber is used. In order to assess the energy deposition in sensitive components, extensive simulations were run with the Monte Carlo cascade code FLUKA[2, 3].

1.2 Setting simulations for the BLM

A horizontal and a vertical BLM are located downstream of each collimator, relatively close to the beam line. Due to their position, they can be used to measure the beam properties as well as the collimator alignment. Any change in the jaw aperture will affect the radiation distribution of interactions among the collimators and the radiation propagation along IR7. The optimization of the BLM location is therefore essential to maximize their sensitivity to the collimation efficiency. The present study is concerned with the estimation of the BLM response as a function of location and primary interactions in the collimators.

A starting set of FLUKA simulations first evaluated the dose level distribution (r,ϕ) in probe rings[1] centered around the beam pipe, 30 cm behind each collimator, as a response to the beam losses in each of the following collimators (section 2):

1. TCPC6h
2. TCPB6h
3. TCSGA6h
4. TCSGB5h
5. TCSGA5h
6. All losses.

The normalization factor (counts $\left[\frac{GeV}{cm^3\ prot.}\right] \rightarrow$ dose $\left[\frac{MGy}{y}\right]$) is obtained as:

$$F_n = Flux \left[\frac{prot.}{y}\right] \cdot \rho^{-1} \cdot 1.6 \cdot 10^{-13} \left[\frac{MGy\ cm^3}{GeV}\right] \qquad (1)$$

---

[1]20 cm long, $R = 65$, $r = 5$ cm

(a) **2-D vertical cut of a BLM set (stretched view)**
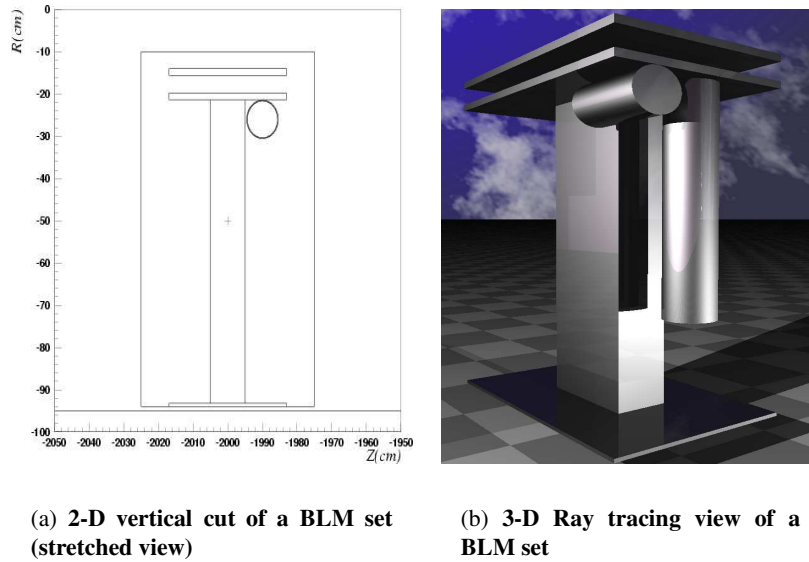
(b) **3-D Ray tracing view of a BLM set**

Figure 1: View of a BLM prototype as implemented in FLUKA. The cylinders are hollow with a wall thickness of 2 mm everywhere except in the endcaps (5 mm).

where:

$$Flux \left[\frac{p}{y} \right] = \begin{cases} 4.0 \cdot 10^{16} & \text{for ultimate luminosity} \\ 2.3 \cdot 10^{16} & \text{for nominal luminosity} \end{cases} \quad (2)$$

The dose in the candidate locations for the BLM was estimated with FLUKA via USRBIN cards like the following:

```
...
* 1. After TCP.D6L1.B1
USRBIN          11.0      ENERGY      -80.0        65.0         0.0      115.0TCPD6L1
USRBIN           5.0        0.0        95.0         6.0         8.0        1.0&
...
```

Sections 4 and 3 provide a closer look of the absolute (energy) and spectral signals in the the different BLM, respectively. To achieve these goals, a realistic BLM prototype was implemented and placed in the zones scanned in section 2. Details on the geometry are described below.

1.3 Geometrical description of the BLM

As for the other elements of the IR7 model, a prototype of the horizontal and vertical BLM was implemented and replicated along the tunnel via LATTICE. The

model includes the active air volume as well as the steel support and the metal container. Each BLM block contains a horizontal and a vertical BLM cylinder that are used as particle detectors throughout the simulations. The *horizontal detector* has its axis at 10 cm from the symmetry orbit between beam 1 and beam 2, the center of the detector being 26 cm below and 110.8 cm downstreams the (center of the) preceding collimator. The inner length is 21 cm and the active volume 1248.35 cm^3. As for the *vertical detector*, it also has 10 cm axial transverse shift with respect to the symmetry orbit and its center is 46.5 cm below, 130.8 cm downstreams the centroid of the preceding collimator. The length of the vertical collimator is 48 cm, which amounts to a volume of 2723.68 cm^3.

The geometrical arrangements of the BLM correspond to the ones shown in fig.1(b)

2   Best Location

As it has been justified, before the detailed simulations with realistic geometries and detection schemes, a coarse calculation of the level of radiation in the area behind each collimator was carried out in order to discard saturation or lack of signal issues in the BLM detectors. This was done for several beam sources. Subfigures 4(a) to 5(d)) in B.1, on pages 19, 20 show the response to a normal (full) horizontal beam loss scenario in the first 8 BLM's. From those results no major problem was identified and the study was pursued towards a computer calibration of the individual spectra detection (sec.3) and the loss source identification from the expected readings in the array of BLM's (sec.4).

3   Energy Spectra simulations in the BLM

3.1   Introduction

The implementation of the horizontal and vertical BLM in the FLUKA geometry allowed a more detailed analysis of the radiation seen by the detectors. Although the signal in a BLM mainly depends on the nuclear interactions occurring in the preceding collimator, the contribution from other upstream collimators can somewhat be important too, and represent a sort of background noise to the measurement. In order to associate the signal of a BLM to a single collimator, it is essential to quantify the background.

In the FLUKA geometry there are a vertical and a horizontal BLM downstream of the 3 TCP and of the first 6 TCS. For each BLM and each family of particles the tracklength was scored with USRTRACK cards and normalized to the real volume
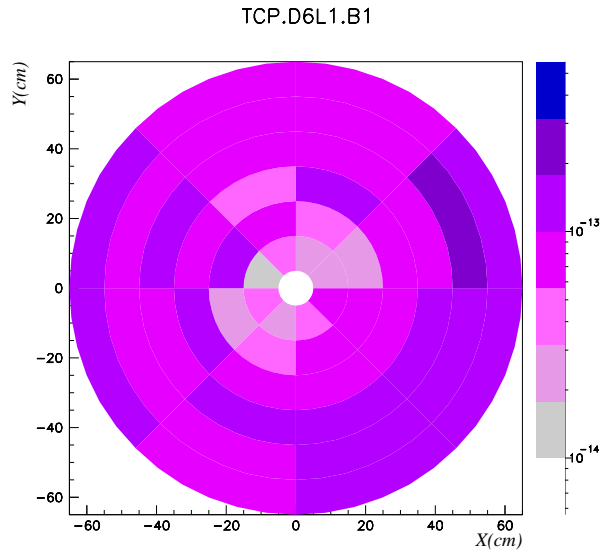
Figure 2: Dose (MGy/y) after TCPC6L7B1 for a horizontal full loss scenario. More plots can be found in fig.B.1, B.1 in the appendix B.1

of the detectors, in order to obtain the particle fluence as a function of energy. Results are in particles per cm^2 per GeV per primary proton.

The fluence inside the BLM was obtained for the following particles:

Protons from 10 MeV to 7 TeV   **Photons** from 100 keV to 7 TeV

Neutrons from 1 MeV to 7 TeV   **Electrons and pos.** from 100 keV to 7 TeV

Muons from 1 MeV to 7 TeV   **Pions** from 1 MeV to 7 TeV

The present study only considers the case of horizontal beam losses, which can be considered as representative of other scenarios (i.e., vertical losses or any combination of horizontal and vertical).

3.2   Results

The graphs 6(a) to 14(b) in pages 22 to 30 show that the spectra seen by the horizontal detector are very similar to those seen by the corresponding vertical detector, with the exception of high energy pions. The first graph (3.2) corresponds to the
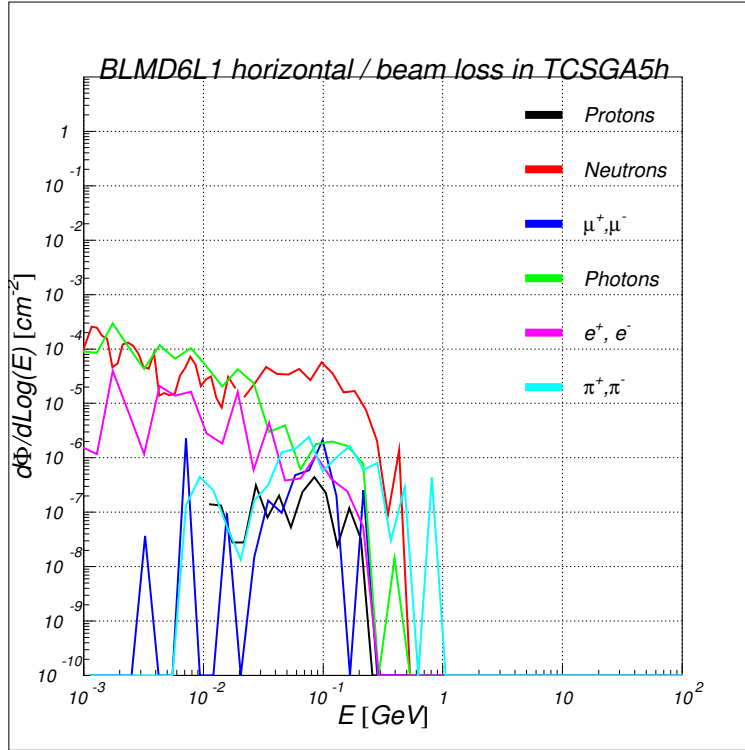
Figure 3: Fluence (per lost proton) in **BLMD6L1** for a horizontal (full) loss scenario. More plots can be found in the appendix B.2.

BLM upstream of the source of radiation (i.e., collimator TCPC6h) and it shows an important contribution from low energy neutrons. The statistical errors rise as a function of the distance from the source and are responsible for most of the fluctuations manifested in the last graphs.

4   Cross talk between BLM

The reading in a given BLM results mainly from the showers generated in the immediately preceding collimator but also from the cascades induced in earlier collimators and from the collimators placed *close after* the BLM which can contribute through backscattering events. Thus, in order to disentangle the individual contributions, it is necessary to know the *response matrix*, **M**, where the terms outside the diagonal are known as the cross-talk.

A given cell $[row(i), col(j)]$ of **M** represents the fraction of energy deposited

in $BLM(j)$ due to primary interactions in the collimator i with respect to the total energy deposition in $BLM(i)$ from all loss sources. Every row (i) in the matrix is obtained from a simulation with a loss source filtered [4] for the collimator (i) and after normalizing each cell to the sum of the corresponding column. The starting loss source can be, as for all simulations, horizontal (h), vertical (v), skew (s), or full (f)[2]. For each of these scenarios a different response matrix is expected[3]. Moreover, since every BLM block includes a horizontal and a vertical BLM detector, the number of matrices are multiplied by 2 to distinguish the two cases. From the readings in the BLM's ($\vec{r}$) it should be possible to obtain the losses in the collimators ($\vec{l}$)[4]

Initially the settings of the simulations for the computation of the energy deposition in the warm section [5] were used, but the big number of considered cases and the fact that the BLMs are off-beam-axis[5] recommended to adopt a variance reduction scheme for the simulations, which is printed in A.4. Dedicated programs (annex A.3) were written to parse the energy deposition values from each simulation case and build up the response tables.

4.1 Cross talk between BLM for a horizontal beam loss scenario

L1								R1	
C6	B6	A6	B5	A5	D4	B4	A4	A4	B5
0.991_{7}	0.693_{5}	$0.307_{4.7}$	$0.068_{9.9}$	$0.046_{8.3}$	0.013_{12}	0.007_{17}	0.009_{18}	0.019_{18}	0.065_{40}
0.009_{14}	0.307_{5}	$0.386_{5.6}$	$0.054_{8.2}$	0.053_{12}	0.014_{14}	0.008_{25}	0.008_{18}	0.015_{24}	0.106_{63}
0_{5}	$1.4\text{E-}5_{96}$	$0.308_{3.9}$	$0.223_{7.3}$	$0.159_{4.5}$	$0.053_{7.6}$	0.044_{16}	0.032_{16}	0.057_{26}	0.029_{43}
0_{5}	0_{3}	$0_{2.5}$	$0.653_{7.3}$	$0.6_{3.7}$	$0.344_{5.8}$	0.29_{11}	0.266_{11}	0.254_{11}	0.101_{38}
0_{5}	0_{3}	$0_{2.5}$	0.002_{76}	$0.141_{3.7}$	$0.576_{4.9}$	$0.65_{5.6}$	0.685_{14}	$0.655_{6.7}$	0.699_{53}

Table 1: Cross talk$_{ERROR[\%]}$ between vertical BLM's

In tables 2, 4, we observe the following:

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[2]Where f is a combination of h, v, s.

[3]That of the f scenario should be a linear combination of the other three.

[4]Losses ($\vec{l}$) and readings ($\vec{r}$) are related through the response matrix ($\mathbf{M}$):

$$\mathbf{M}^{\mathsf{T}}\vec{l} = \vec{r} \rightarrow \vec{l} = \begin{cases} (\mathbf{M}^{\mathsf{T}})^{-1}\vec{r} & if\ \exists\ \mathbf{M}^{-1} \\ (\mathbf{M}^{\mathsf{T}}\mathbf{M})^{-1}\mathbf{M}\vec{r} & if\ \exists\ (\mathbf{M}^{\mathsf{T}}\mathbf{M})^{-1} \end{cases} \tag{3}$$

[5]It is harder to collect statistics out of the highly irradiated area.

L1								R1	
C6	B6	A6	B5	A5	D4	B4	A4	A4	B5
$0.999_{5.7}$	0.685_{5}	$0.301_{6.1}$	$0.054_{8.4}$	0.047_{10}	0.013_{19}	0.008_{26}	0.017_{37}	0.009_{27}	0.207_{49}
0.001_{35}	0.315_{5}	$0.316_{4.6}$	0.055_{12}	$0.041_{7.3}$	0.011_{19}	0.012_{34}	0.007_{17}	0.011_{29}	0.053_{33}
0_{4}	0_{3}	$0.384_{8.8}$	$0.22_{6.5}$	$0.144_{4.5}$	0.053_{17}	0.109_{55}	0.024_{16}	0.073_{34}	0.146_{73}
0_{4}	0_{3}	$0_{3.5}$	$0.67_{3.9}$	$0.611_{3.6}$	$0.312_{6.8}$	$0.25_{9.9}$	0.224_{11}	0.282_{31}	0.191_{32}
0_{4}	0_{3}	$0_{3.5}$	$1.5\text{E-}4_{53}$	$0.157_{3.6}$	$0.611_{8.4}$	$0.621_{8.6}$	0.728_{14}	0.625_{12}	0.403_{22}

Table 2: Cross talk$_{ERROR[\%]}$ between horizontal BLM's

† The cross talk between horizontal detectors follows a similar pattern to that between the vertical ones.

† Backscattering is only relevant between BLMC6L1 ← BLMB6L1.

† Detectors placed downstream the source keep similar energy detection thresholds regardless of the particular position of the source.

† The radiation level after the first TCS (A6L1) is greater than that next to the primaries.

† B5L1 gets 2 to 3 times less radiation than the downstream element A5L1.

† A4R1 gets much more radiation that the neighboring detectors.

4.2   Cross talk between BLM for a vertical beam loss scenario

L1									R1
D6	C6	B6	A6	B5	A5	D4	B4	A4	A4
$0.998_{7.1}$	$0.563_{5.5}$	$0.332_{7.8}$	$0.242_{7.8}$	0.066_{13}	$0.046_{9.4}$	0.016_{16}	0.008_{26}	0.011_{23}	0.032_{21}
0.002_{21}	0.437_{8}	$0.474_{6.1}$	$0.211_{9.6}$	0.053_{29}	0.028_{12}	0.010_{21}	0.007_{32}	0.003_{32}	0.004_{31}
$2.6\text{E-}4_{84}$	$3.7\text{E-}4_{52}$	$0.194_{5.3}$	$0.269_{6.1}$	0.043_{11}	$0.036_{6.6}$	0.009_{13}	0.010_{35}	0.011_{44}	0.012_{25}
0_{5}	$0_{3.8}$	$0_{3.4}$	$0.278_{7.8}$	$0.177_{7.2}$	$0.14_{6.6}$	0.042_{15}	0.029_{20}	0.11_{66}	0.036_{19}
0_{5}	$0_{3.8}$	$0_{3.4}$	$0_{3.5}$	$0.661_{6.3}$	$0.596_{4.8}$	0.341_{10}	0.303_{11}	0.27_{14}	0.29_{16}
0_{5}	$0_{3.8}$	$0_{3.4}$	$0_{3.5}$	$7.7\text{E-}5_{58}$	0.154_{4}	$0.584_{6.6}$	$0.643_{7.8}$	0.594_{12}	0.626_{10}

Table 3: Cross talk$_{ERROR[\%]}$ between vertical BLM's

L1									R1
D6	C6	B6	A6	B5	A5	D4	B4	A4	A4
$0.962_{8.3}$	$0.578_{4.9}$	0.338_{5}	$0.247_{7.7}$	0.071_{12}	$0.054_{7.3}$	0.017_{21}	0.037_{71}	0.015_{23}	0.026_{28}
0.038_{13}	$0.419_{4.9}$	$0.499_{5.8}$	0.22_{6}	0.036_{11}	$0.028_{8.3}$	0.008_{25}	0.003_{29}	0.073_{94}	0.003_{20}
$5.5\text{E-}4_{39}$	0.003_{10}	$0.163_{5.8}$	$0.292_{7.7}$	0.066_{16}	$0.041_{7.3}$	0.013_{16}	0.004_{18}	0.007_{22}	0.020_{41}
$0_{5.8}$	$0_{2.9}$	0_{3}	$0.241_{6.8}$	$0.204_{7.6}$	$0.144_{4.5}$	0.053_{14}	0.039_{41}	0.052_{52}	0.034_{15}
$0_{5.8}$	$0_{2.9}$	0_{3}	$0_{3.2}$	$0.622_{8.4}$	$0.595_{3.6}$	$0.322_{5.9}$	$0.258_{8.5}$	0.252_{12}	$0.23_{8.3}$
$0_{5.8}$	$0_{2.9}$	0_{3}	$0_{3.2}$	$3.6\text{E-}4_{26}$	$0.139_{4.5}$	$0.588_{8.3}$	0.659_{7}	0.6_{13}	$0.681_{9.9}$

Table 4: Cross talk$_{ERROR[\%]}$ between vertical BLM's

A   BLM data extraction

A.1   Scoring cards

The energy spectra are generated with the USRTRACK command in the input file. In total there are 18 USRTRACK (from unit 50 to 67), corresponding to the 9 sets of 2 BLM detectors, after the TCP and behind the 6 first TCS. Thus, "50" is the horizontal BLM at D6L7B1, "51" the vertical BLM at the same location, "52" and "53" are at C6L7B1 and so on. Each USRTRACK has seven bins for the different types of particles. The USRTRACK are normalized to the volume of the horizontal and vertical detectors, which are 1248.35 and 2723.68 cm^3, respectively.

As an example, this is the first USRTRACK:

```
*  Detector horizontal, D6L7B1
*    Volume= 4.35^2 * 3.14 * 21 = 1248.35
*23456789 123456789 123456789 123456789 123456789 123456789 123456789 1
USRTRACK         -1.0         1.      -50.0      501.     1248.35       60.0BLMD6L1
USRTRACK                      0.01                                           &
*
USRTRACK         -1.0         8.      -50.0      501.     1248.35       72.BLMD6L1
USRTRACK     0.0196      1.E-14                                              &
*
USRTRACK         -1.0         8.      -50.0      501.     1248.35       60.0BLMD6L1
USRTRACK                    0.0196                                           &
* Muons
USRTRACK         -1.0       212.      -50.0      501.     1248.35       60.0BLMD6L1
USRTRACK                     1.E-3                                           &
* Photons
USRTRACK         -1.0         7.      -50.0      501.     1248.35       60.0BLMD6L1
USRTRACK                     1.E-4                                           &
* electrons/positrons
USRTRACK         -1.0       213.      -50.0      501.     1248.35       60.0BLMD6L1
USRTRACK                     1.E-4                                           &
* pions
USRTRACK         -1.0       209.      -50.0      501.        1.0       60.0BLMD6L1
USRTRACK                     1.E-3
```

A.2   User defined subroutines: fluscw.f

Any USRTRACK card is defined for a specific FLUKA region. If the region is replicated in several lattices, the contribution from each lattice will be summed. This is equivalent to having a single region extended over different elements and obtaining a spectra which is the average of all BLM. In order to differentiate the single contributions, a user written routine (fluscw.f) was triggered via the USER-WEIG card. The routine distinguishes every BLM from the lattice name that is indicated in the USRTRACK sdum.

```
      IF (ISCRNG.eq.3) THEN
* ISCRNG = 3 --> Track  length    estimator                   *
      CALL GEOL2N(MLATTC,LATNAM,Ierr)
* MLATTC is the number of the lattice in which the particle is
* LATNAM is the name of the lattice, associated to MLATTC
* GEOL2N is a function which converts the Lattice number into Name (L2N)
      IF (TITUTC(JSCRNG).eq.LATNAM) THEN
* TITUTC(JSCRNG) is the sdum of the USRTRACK
         LSCZER=.FALSE.
* if LSCZER is .TRUE., the normalization factor will be zero
* if we are here, it is because the particle is in the BLM we want to
* score and its contribution should be counted (LSCZER = .FALSE.)
      ELSE
         LSCZER=.TRUE.
      END IF
    END IF
```

A.3   Analysis of the data

When running the code, results for the USRTRACK are stored in the binary files ⋆.*fort_num*⋆, where *num* ranges from 50 to 67. The program *ustsuw* then generates formatted summary files ⋆_*num* and ⋆_*num_sum.lis* from which energy vs. track length tables can be produced by the script *usrbdx.r*.

This chain of transformations is integrated into the script *anBLM.sh*, which also prepares the customized labels and titles for the individual plots, and triggers PAW to perform these plots with the settings stored in the *ustdum.kumac*. Therefore, typing anBLM.sh is enough to get the tables and plots once the results of FLUKA have been delivered.

A.3.1   The anBLM.sh script:

```
#!/bin/bash
i=50
while [ $i -le 67 ]
do
 ls ./*/*fort.$i > input
 echo " ">>input
 echo "usrtrack_$i">> input
```

```
ustsuw<input
j=1
while [ $j -le 7 ]
do
  usrbdx.r $j usrtrack_${i}_sum.lis usrtrackh_$i.$j
  j='expr $j + 1'
done
sed -i.bck "s/@/$i/" ustdum.kumac
if [ $i -eq 50 ]
then
  sed -i.del "s/BLMNAME/BLMD6L1 horizontal detector/" ustdum.kumac
elif [ $i -eq 51 ]
then
  sed -i.del "s/BLMNAME/BLMD6L1 vertical detector/" ustdum.kumac
elif [ $i -eq 52 ]
then
  sed -i.del "s/BLMNAME/BLMC6L1 horizontal detector/" ustdum.kumac
elif [ $i -eq 53 ]
then
  sed -i.del "s/BLMNAME/BLMC6L1 vertical detector/" ustdum.kumac
elif [ $i -eq 54 ]
then
  sed -i.del "s/BLMNAME/BLMB6L1 horizontal detector/" ustdum.kumac
elif [ $i -eq 55 ]
then
  sed -i.del "s/BLMNAME/BLMB6L1 vertical detector/" ustdum.kumac
elif [ $i -eq 56 ]
then
  sed -i.del "s/BLMNAME/BLMA6L1 horizontal detector/" ustdum.kumac
elif [ $i -eq 57 ]
then
  sed -i.del "s/BLMNAME/BLMA6L1 vertical detector/" ustdum.kumac
elif [ $i -eq 58 ]
then
  sed -i.del "s/BLMNAME/BLMB5L1 horizontal detector/" ustdum.kumac
elif [ $i -eq 59 ]
then
  sed -i.del "s/BLMNAME/BLMB5L1 vertical detector/" ustdum.kumac
elif [ $i -eq 60 ]
then
  sed -i.del "s/BLMNAME/BLMA5L1 horizontal detector/" ustdum.kumac
elif [ $i -eq 61 ]
then
  sed -i.del "s/BLMNAME/BLMA5L1 vertical detector/" ustdum.kumac
elif [ $i -eq 62 ]
then
  sed -i.del "s/BLMNAME/BLMD4L1 horizontal detector/" ustdum.kumac
elif [ $i -eq 63 ]
then
  sed -i.del "s/BLMNAME/BLMD4L1 vertical detector/" ustdum.kumac
elif [ $i -eq 64 ]
then
  sed -i.del "s/BLMNAME/BLMB4L1 horizontal detector/" ustdum.kumac
elif [ $i -eq 65 ]
then
  sed -i.del "s/BLMNAME/BLMB4L1 vertical detector/" ustdum.kumac
```

```
 elif [ $i -eq 66 ]
 then
   sed -i.del "s/BLMNAME/BLMA4L1 horizontal detector/" ustdum.kumac
 elif [ $i -eq 67 ]
 then
   sed -i.del "s/BLMNAME/BLMA4L1 vertical detector/" ustdum.kumac
 fi
 rm *.del
 paw<ustdum.kumac
 cp ustdum.kumac.bck ustdum.kumac
 i='expr $i + 1'
done$
```

A.3.2   The ustdum.kumac:

```
1
For/File 66 ustplo_@.ps
Meta 66 -113
set gsiz 0.40
set asiz 0.35
set vsiz 0.35
set *fon 53
title 'Full beam loss detection in BLMNAME'
set gsiz 0.38
* Reading data
v/read E21,E11,x1,dx1 usrtrackh_@.1
v/read E22,E12,x2,dx2 usrtrackh_@.2
v/read E23,E13,x3,dx3 usrtrackh_@.3
v/read E24,E14,x4,dx4 usrtrackh_@.4
v/read E25,E15,x5,dx5 usrtrackh_@.5
v/read E26,E16,x6,dx6 usrtrackh_@.6
v/read E27,E17,x7,dx7 usrtrackh_@.7
*
* Plotting
opt logx
opt logy
opt grid
null 0.001 100 0.0000000001 10.0
set lwid 4
set plci 1
graph $vdim(E21) $sigma(sqrt(E21*E11)) $sigma(x1*sqrt(E21*E11)) 'l'
set plci 2
graph $vdim(E22) $sigma(sqrt(E22*E12)) $sigma(x2*sqrt(E22*E12)) 'l'
set plci 2
graph $vdim(E23) $sigma(sqrt(E23*E13)) $sigma(x3*sqrt(E23*E13)) 'l'
set plci 4
graph $vdim(E24) $sigma(sqrt(E24*E14)) $sigma(x4*sqrt(E24*E14)) 'l'
set plci 3
graph $vdim(E25) $sigma(sqrt(E25*E15)) $sigma(x5*sqrt(E25*E15)) 'l'
set plci 6
graph $vdim(E26) $sigma(sqrt(E26*E16)) $sigma(x6*sqrt(E26*E16)) 'l'
set plci 7
graph $vdim(E27) $sigma(sqrt(E27*E17)) $sigma(x7*sqrt(E27*E17)) 'l'
*
* LEGENDS
set pmci 1
```

```
set faci 1
g/h/key 10 1 ! 'Protons'
set pmci 2
set faci 2
g/h/key 10 0.1 ! 'Neutrons'
set pmci 4
set faci 4
g/h/key 10 0.01 ! '[m]ˆ+!,[m]ˆ-!'
set pmci 3
set faci 3
g/h/key 10 0.001 ! 'Photons'
set pmci 6
set faci 6
g/h/key 10 0.0001 ! 'eˆ+!, eˆ-!'
set pmci 7
set faci 7
g/h/key 10 0.00001 ! '[p]ˆ+!,[p]ˆ-!'
*
atitle 'E "M#GeV"N#' 'd#[F]/dLog(E) "M#cmˆ-2!"N#' ! 222
Close 66
exit$
```

A.3.3 The anCROSS.sh script:

```bash
#!/bin/bash
#------- init table -----------------------------
echo '\begin{table}[htb]\centering'
echo '\begin{tabular}{||llllllll|ll||}'
echo '%Row: 1'
echo '\cline{1-10}'
echo '\vbox to3.08ex{\vspace{1pt}\vfil\hbox to4.8ex{\hfil L7B1 \hfil}} &'
echo '\vbox to3.08ex{\vspace{1pt}\vfil\hbox to4.8ex{\hfil \hfil}} &'
echo '\vbox to3.08ex{\vspace{1pt}\vfil\hbox to4.8ex{\hfil \hfil}} &'
echo '\vbox to3.08ex{\vspace{1pt}\vfil\hbox to4.8ex{\hfil \hfil}} &'
echo '\vbox to3.08ex{\vspace{1pt}\vfil\hbox to4.8ex{\hfil \hfil}} &'
echo '\vbox to3.08ex{\vspace{1pt}\vfil\hbox to4.8ex{\hfil \hfil}} &'
echo '\vbox to3.08ex{\vspace{1pt}\vfil\hbox to4.8ex{\hfil \hfil}} &'
echo '\vbox to3.08ex{\vspace{1pt}\vfil\hbox to4.8ex{\hfil \hfil}} &'
echo '\vbox to3.08ex{\vspace{1pt}\vfil\hbox to4.8ex{\hfil R7B1 \hfil}} &'
echo '\vbox to3.08ex{\vspace{1pt}\vfil\hbox to4.9ex{\hfil \hfil}} \\'
echo '\cline{1-10}'
echo '%Row: 2'
echo '\vbox to3.08ex{\vspace{1pt}\vfil\hbox to4.8ex{\hfil C6 \hfil}} &'
echo '\vbox to3.08ex{\vspace{1pt}\vfil\hbox to4.8ex{\hfil B6 \hfil}} &'
echo '\vbox to3.08ex{\vspace{1pt}\vfil\hbox to4.8ex{\hfil A6 \hfil}} &'
echo '\vbox to3.08ex{\vspace{1pt}\vfil\hbox to4.8ex{\hfil B5 \hfil}} &'
echo '\vbox to3.08ex{\vspace{1pt}\vfil\hbox to4.8ex{\hfil A5 \hfil}} &'
echo '\vbox to3.08ex{\vspace{1pt}\vfil\hbox to4.8ex{\hfil D4 \hfil}} &'
echo '\vbox to3.08ex{\vspace{1pt}\vfil\hbox to4.8ex{\hfil B4 \hfil}} &'
echo '\vbox to3.08ex{\vspace{1pt}\vfil\hbox to4.8ex{\hfil A4 \hfil}} &'
echo '\vbox to3.08ex{\vspace{1pt}\vfil\hbox to4.8ex{\hfil A4 \hfil}} &'
echo '\vbox to3.08ex{\vspace{1pt}\vfil\hbox to4.9ex{\hfil B5 \hfil}} \\'
echo '\cline{1-10}'
echo '%Row: 3'
#-------------------------------------------------
dir[2]=TCPC6h
```

```
dir[3]=TCPB6h
dir[4]=TCSGA6h
dir[5]=TCSGB5h
dir[6]=TCSGA5h
#
jmin=2
jmax=6
jl='expr $jmax - $jmin'
imin=2
imax=12
il='expr $imax - $imin'
#
j=$jmin
while [ $j -le $jmax ]
do
  cd $IR7/BLM/hori/${dir[$j]}/SPECTRA
#  echo '---------' ${dir[$j]}
  BLMname[1]=BLMD6L1
  BLMname[2]=BLMC6L1  # dir1
  BLMname[3]=BLMB6L1  # dir2
  BLMname[4]=BLMA6L1  # dir3
  BLMname[5]=BLMB5L1  # dir4
  BLMname[6]=BLMA5L1  # dir5
  BLMname[7]=BLMD4L1
  BLMname[8]=BLMB4L1
  BLMname[9]=BLMA4L1
  BLMname[10]=BLMA4R1
  BLMname[11]=BLMB5R1
  BLMname[12]=BLMD5R1
  BLMname[13]=BLME5R1
  BLMname[14]=BLM6R1
  i=$imin
  while [ $i -le $imax ]
  do
    name=${BLMname[$i]}
# vertical
    vert[$i]='grep -A15 ${name} LatticeWatt | grep BLMvert
 | sed "s/:[0-9]*/@/" | cut -d@ -f2 | sed "s/+-/@/" | cut -d@ -f1 | sed 's/e/E/''
    a='grep -A15 ${name} LatticeWatt | grep BLMvert'
    if [ $? -eq 0 ]
    then
      evert[$i]='grep -A15 ${name} LatticeWatt | grep BLMvert
| sed "s/:[0-9]*/@/" | cut -d@ -f2 | sed "s/+-/@/" | cut -d@ -f2
| cut -d% -f1 | sed 's/e/E/''
    else
      vert[$i]=0
      evert[$i]=0
    fi
# horizontal
    hori[$i]='grep -A15 ${name} LatticeWatt | grep BLMhori
| sed "s/:[0-9]*/@/" | cut -d@ -f2 | sed "s/+-/@/" | cut -d@ -f1 | sed 's/e/E/''
    a='grep -A15 ${name} LatticeWatt | grep BLMhori'
    if [ $? -eq 0 ]
    then
      ehori[$i]='grep -A15 ${name} LatticeWatt | grep BLMhori
| sed "s/:[0-9]*/@/" | cut -d@ -f2 | sed "s/+-/@/" | cut -d@ -f2
```

```
| cut -d% -f1 | sed 's/e/E/''
    else
      hori[$i]=0
      ehori[$i]=0
    fi
#
    i='expr $i + 1'
  done
  Mvert[$j]=${vert[*]}
  Mhori[$j]=${hori[*]}
  eMvert[$j]=${evert[*]}
  eMhori[$j]=${ehori[*]}
  j='expr $j + 1'
done
# Init the vector sum h,v, er{} are relative errors (%), ea{}2 are (absolute errors)^2
j=$jmin
  i=1
  while [ $i -le $il ]
  do
    h[$i]='echo ${Mhori[$j]} | cut -d' ' -f$i'
    v[$i]='echo ${Mvert[$j]} | cut -d' ' -f$i'
    erh[$i]='echo ${eMhori[$j]} | cut -d' ' -f$i'
    eah2[$i]='python -c "print ({$erh[$i]}**2)*(${h[$i]}**2)*0.0001"'
    erv[$i]='echo ${eMvert[$j]} | cut -d' ' -f$i'
    eav2[$i]='python -c "print (${erv[$i]}**2)*(${v[$i]}**2)*0.0001"'
    i='expr $i + 1'
  done
# Now add up all the other j h and v vectors (and absolute square errors)
j='expr $j + 1'
while [ $j -le $jmax ]
do
  i=1
  while [ $i -le $il ]
  do
  # hori
    temp='echo ${Mhori[$j]} | cut -d' ' -f$i'
    h[$i]='python -c "print $temp + ${h[$i]}"'
    temp2='echo ${eMhori[$j]} | cut -d' ' -f$i'
    temp3='python -c "print $temp2 * $temp2 * $temp * $temp * 0.0001"'
    eah2[$i]='python -c "print $temp3 + ${eah2[$i]}"'
  # vert
    temp='echo ${Mvert[$j]} | cut -d' ' -f$i'
    v[$i]='python -c "print $temp + ${v[$i]}"'
    temp2='echo ${eMvert[$j]} | cut -d' ' -f$i'
    temp3='python -c "print $temp2 * $temp2 * $temp * $temp * 0.0001"'
    eav2[$i]='python -c "print $temp3 + ${eav2[$i]}"'
  #
    i='expr $i + 1'
  done
  j='expr $j + 1'
done
# Now compute the j vectors cv[i]=Mvert[i]/v[i] and ch[i]=Mhori[i]/h[i]
 (and the errors)
j=$jmin
while [ $j -le $jmax ]
do
```

```
  i=1
  while [ $i -le $il ]
  do
  # hori
    temp='echo ${Mhori[$j]} | cut -d' ' -f$i'
    temp2=${h[$i]}
    temp3='echo ${eMhori[$j]} | cut -d' ' -f$i'
    erh[$i]='rexx - "say 100*sqrt(${eah2[$i]})/$temp2"'
    ch[$i]='rexx - "numeric digits 3; say $temp/$temp2"'
    erch[$i]='rexx - "numeric digits 2; say sqrt((${erh[$i]}*${erh[$i]})
+($temp3*$temp3))"'
  # vert
    temp='echo ${Mvert[$j]} | cut -d' ' -f$i'
    temp2=${v[$i]}
    temp3='echo ${eMvert[$j]} | cut -d' ' -f$i'
    erv[$i]='rexx - "say 100*sqrt(${eav2[$i]})/$temp2"'
    cv[$i]='rexx - "numeric digits 3; say $temp/$temp2"'
    ercv[$i]='rexx - "numeric digits 2; say sqrt((${erv[$i]}*${erv[$i]})
+($temp3*$temp3))"'
  #
    if [ $i -lt $il ]
    then
      echo '\vbox to2.00ex{\vspace{1pt}\vfil\hbox to4.8ex
{\small{'${cv[$i]}'}\tiny{\textit{' ${ercv[$i]}'}}}} &'
#     echo '\vbox to2.00ex{\vspace{1pt}\vfil\hbox to4.8ex
{\small{'${ch[$i]}'}\tiny{\textit{' ${erch[$i]}'}}}} &'
    elif [ $i -eq $il ]
    then
      echo '\vbox to2.00ex{\vspace{1pt}\vfil\hbox to4.9ex
{\small{'${cv[$i]}'}\tiny{\textit{' ${ercv[$i]}'}}}} \\'
#     echo '\vbox to2.00ex{\vspace{1pt}\vfil\hbox to4.9ex
{\small{'${ch[$i]}'}\tiny{\textit{' ${erch[$i]}'}}}} \\'
      k='expr $j + 2'
      echo '%Row: ' $k
    fi
    i='expr $i + 1'
  done
# echo $j, ratio: ${ch[*]}
# echo $j, err: ${erch[*]}
  j='expr $j + 1'
done
echo '\cline{1-10}'
echo '\end{tabular}'
echo '\caption{\small{Cross talk between BLMs}}'
echo '\label{table:crosstalk}'
echo '\end{table}'
```

A.4 Variance Reduction Scheme

In order to reduce the CPU consumption, low energy particles where not trans-
ported in areas from which they could not possibly reach the BLM detectors.
Therefore, the following EMF-CUT instructions were inserted into the input file:

```
* 1MeV energy threshold far from the BLM's
```

```
EMFCUT           0.001     0.001      0.00    BLACK    MSVACUU
* exceptions (areas close/around) the BLM's:
EMFCUT          0.0001    0.0004      0.00    TUNAAIR
EMFCUT          0.0001    0.0004      0.00    TUNBAIR
EMFCUT          0.0001    0.0004      0.00    TUNCAIR   TUNCAIR2
EMFCUT          0.0001    0.0004      0.00    TUNDAIR
EMFCUT          0.0001    0.0004      0.00    TUNEAIR
EMFCUT          0.0001    0.0004      0.00   PARK_AIR
EMFCUT          0.0001    0.0004      0.00   Plat1BLM    airBLM
EMFCUT          0.0001    0.0004      0.00   TCPflaui   TCPexit
EMFCUT          0.0001    0.0004      0.00    TCPbox
EMFCUT          0.0001    0.0004      0.00    TCPVO2     TCPVO1
EMFCUT          0.0001    0.0004      0.00   TCSflaui   TCSexit
EMFCUT          0.0001    0.0004      0.00    TCSbox
EMFCUT          0.0001    0.0004      0.00    TCSVO2     TCSV01
```

B   Extra plots

B.1   Scanning the BLM response

The dose plots in the candidate areas for the BLM's in the full horizontal loss scenario are listed below:

1. TCP.C6.L7.B1, fig. 4(a)
2. TCP.B6.L7.B1, fig. 4(b)
3. TCSG.A6.L7.B1, fig. 4(c)
4. TCSG.B5.L7.B1, fig. 4(d)
5. TCSG.A5.L7.B1, fig. 5(a)
6. TCSG.D4.L7.B1, fig. 5(b)
7. TCSG.B4.L7.B1, fig. 5(c)
8. TCSG.A4.L7.B1, fig. 5(d)

B.2   Graphs of the spectra in the BLM's

1. horizontal BLM after TCP.D6.L7.B1, fig. 6(a)
2. horizontal BLM after TCP.C6.L7.B1, fig. 7(a)
3. horizontal BLM after TCP.B6.L7.B1, fig. 8(a)
4. horizontal BLM after TCSG.A6.L7.B1, fig. 9(a)
5. horizontal BLM after TCSG.B5.L7.B1, fig. 10(a)
6. horizontal BLM after TCSG.A5.L7.B1, fig. 11(a)
7. horizontal BLM after TCSG.D4.L7.B1, fig. 12(a)
8. horizontal BLM after TCSG.B4.L7.B1, fig. 13(a)
9. horizontal BLM after TCSG.A4.L7.B1, fig. 14(a)

(a) Dose (MGy/y) in BLM 1

(b) Dose (MGy/y) in BLM 2

(c) Dose (MGy/y) in BLM 3

(d) Dose (MGy/y) in BLM 4
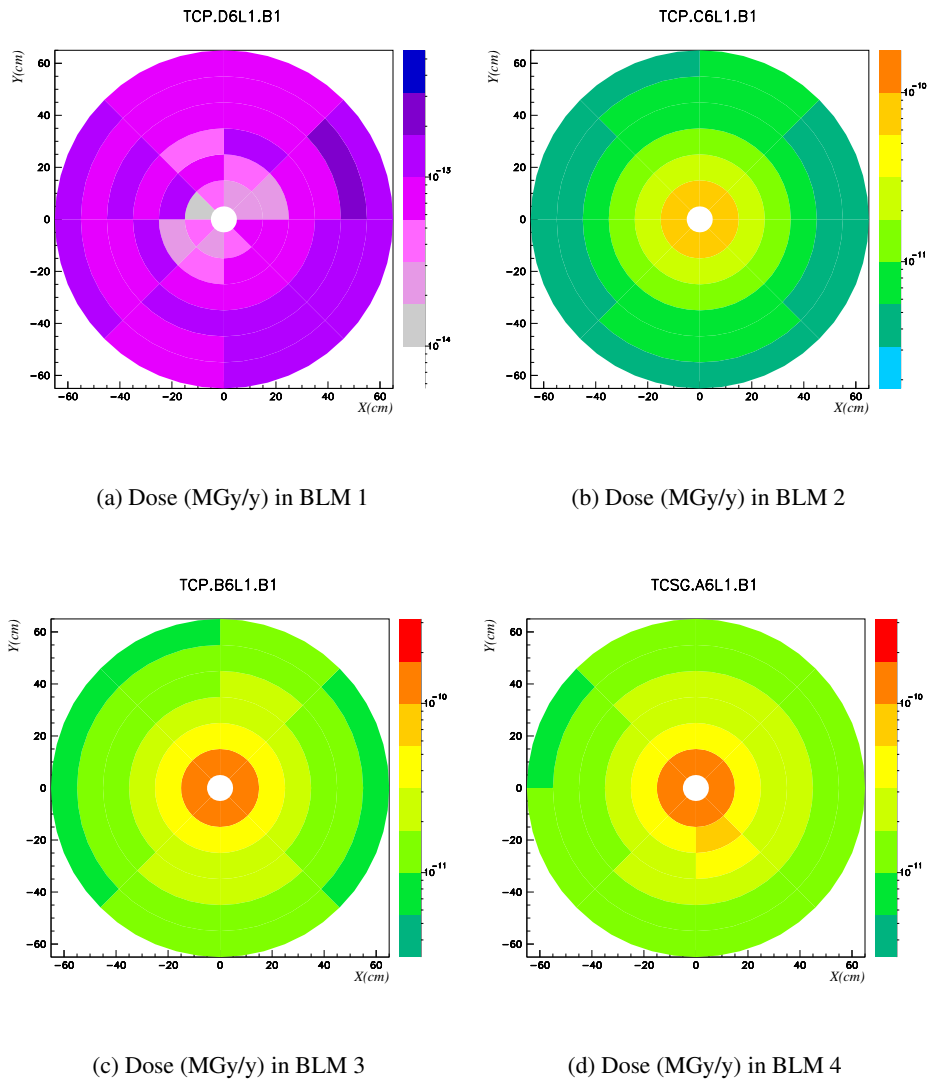
Figure 4: Dose (MGy/y) maps in the first 4 BLM for the horizontal (full) beam loss scenario

(a) Dose (MGy/y) in BLM 5

(b) Dose (MGy/y) in BLM 6

(c) Dose (MGy/y) in BLM 6

(d) Dose (MGy/y) in BLM 8
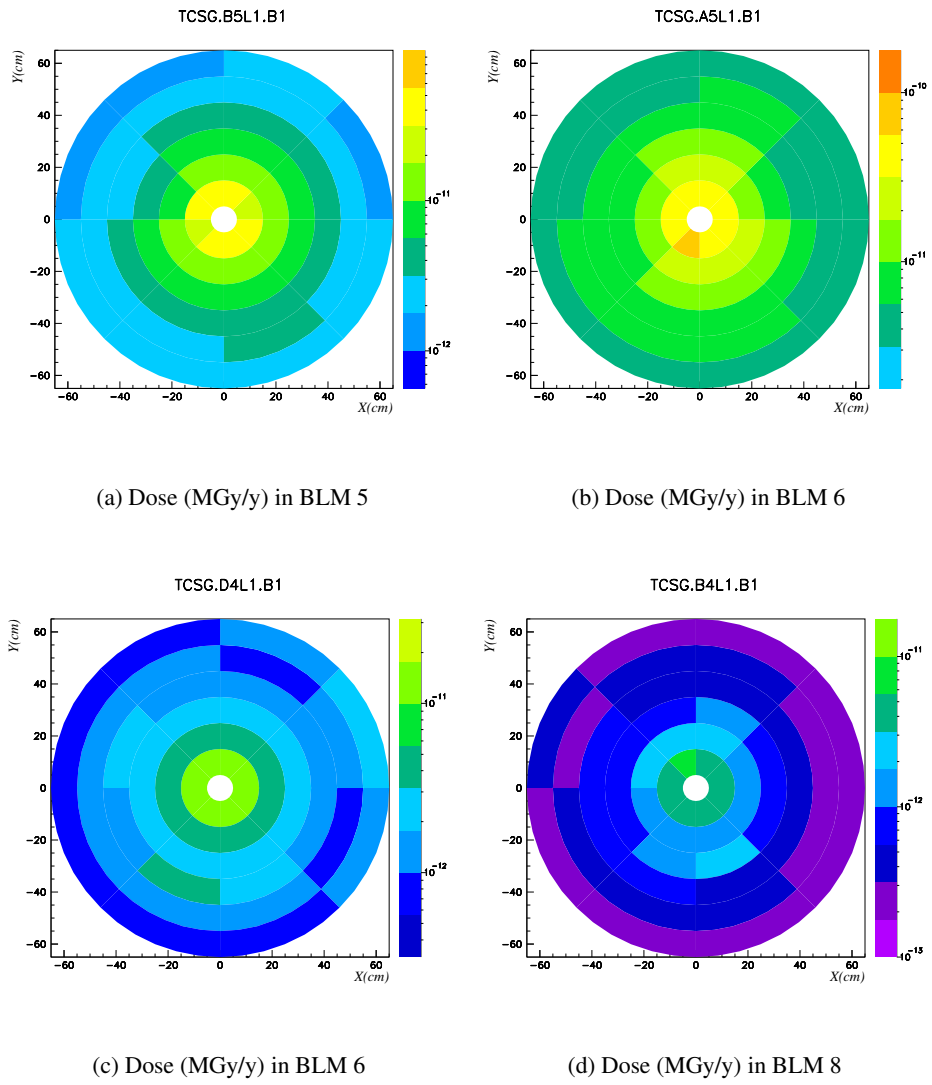
Figure 5: Dose (MGy/y) maps in the second 4 BLM's for the full horizontal beam loss scenario

10. vertical BLM after TCP.D6.L7.B1, fig. 6(b)

11. vertical BLM after TCP.C6.L7.B1, fig. 7(b)

12. vertical BLM after TCP.B6.L7.B1, fig. 8(b)

13. vertical BLM after TCSG.A6.L7.B1, fig. 9(b)

14. vertical BLM after TCSG.B5.L7.B1, fig. 10(b)

15. vertical BLM after TCSG.A5.L7.B1, fig. 11(b)

16. vertical BLM after TCSG.D4.L7.B1, fig. 12(b)

17. vertical BLM after TCSG.B4.L7.B1, fig. 13(b)

18. vertical BLM after TCSG.A4.L7.B1, fig. 14(b)

References

[1] M. Magistris, A. Ferrari, M. Santana, K. Tsoulou, and V.Vlachoudis. Studies for magnet and electronics protection in the LHC betatron-cleaning insertion. *Nucl. Inst. and Meth. A*, Submitted, 2006.

[2] A. Fassò, A. Ferrari, and P.R. Sala. Electron-photon transport in FLUKA: status. In F. Barao, M. Nakagawa, L. Tavora, and P. Vaz, editors, *Proceedings of the MonteCarlo 2000 Conference, Lisbon, October 23–26 2000*, pages 159–164. Springer-Verlag Berlin, October 2001.

[3] A. Fassò, A. Ferrari, J. Ranft, and P.R. Sala. FLUKA: Status and prospective for hadronic applications. In A. Kling, F. Barao, M. Nakagawa, L. Tavora, and P. Vaz, editors, *Proceedings of the MonteCarlo 2000 Conference, Lisbon, October 23–26 2000*, pages 955–960. Springer-Verlag Berlin, October 2001.

[4] M. Magistris, M. Santana-Leitner, V. Vlachoudis, and A. Ferrari. Implementation of the IR7 section at LHC for the FLUKA transport code. Technical report, CERN-AB-ATB, 2006.

[5] M. Santana-Leitner, M. Magistris, V. Vlachoudis, and A. Ferrari. Protection of warm elements at IR7. passive absorbers and collimators. Technical report, CERN-AB-ATB, 2006.
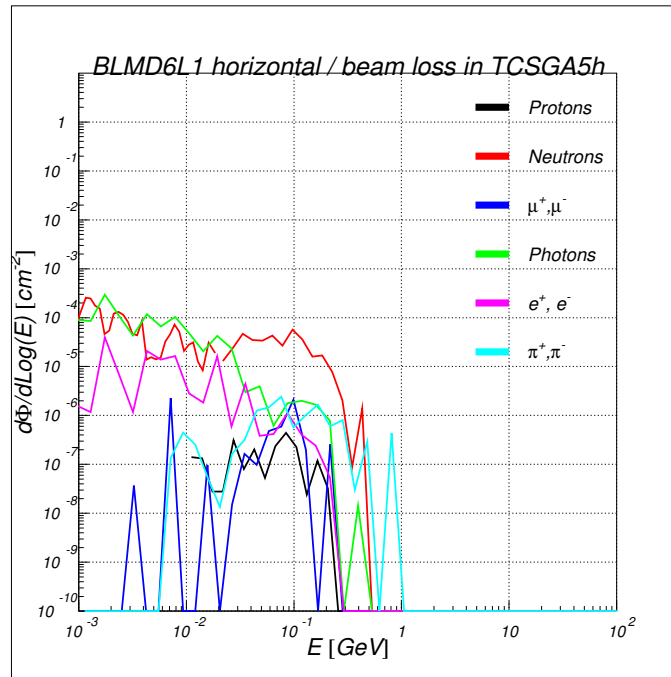
(a) **Horizontal detector**
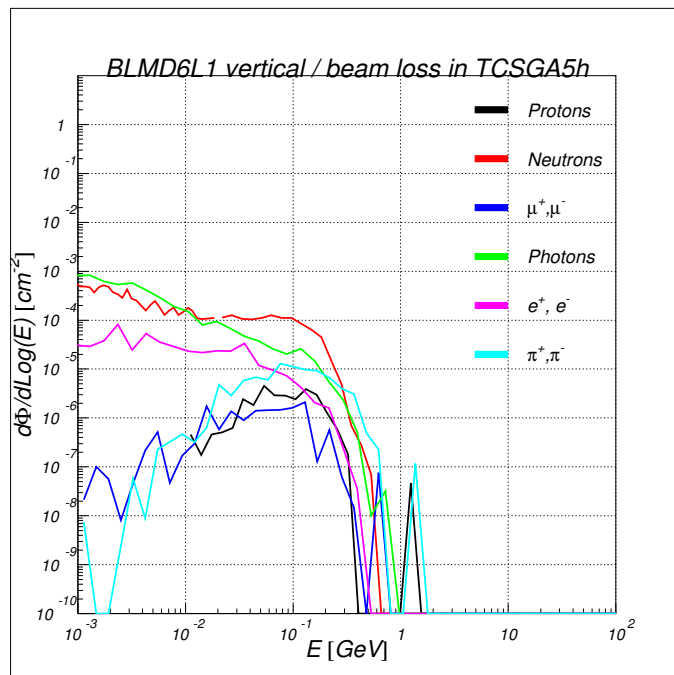
(b) **Vertical detector**

Figure 6: Fluence (per lost proton) in **BLMD6L1**
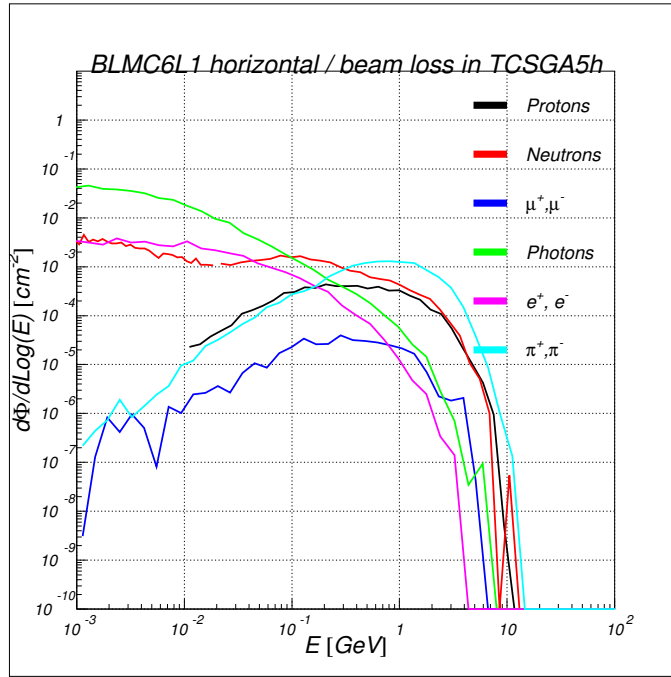
(a) **Horizontal detector**
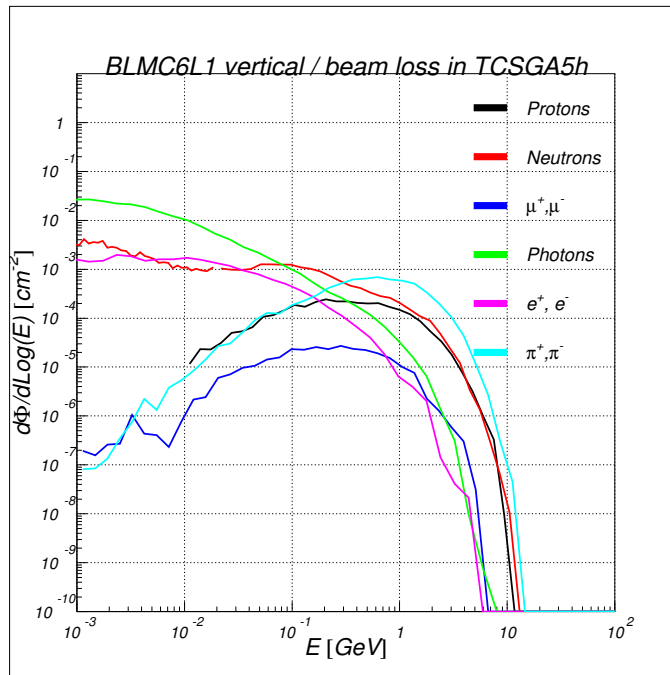
(b) **Vertical detector**
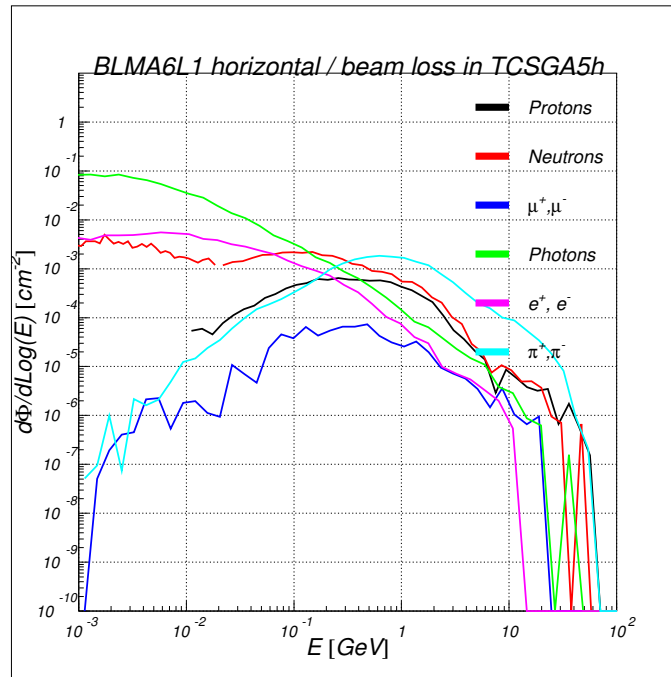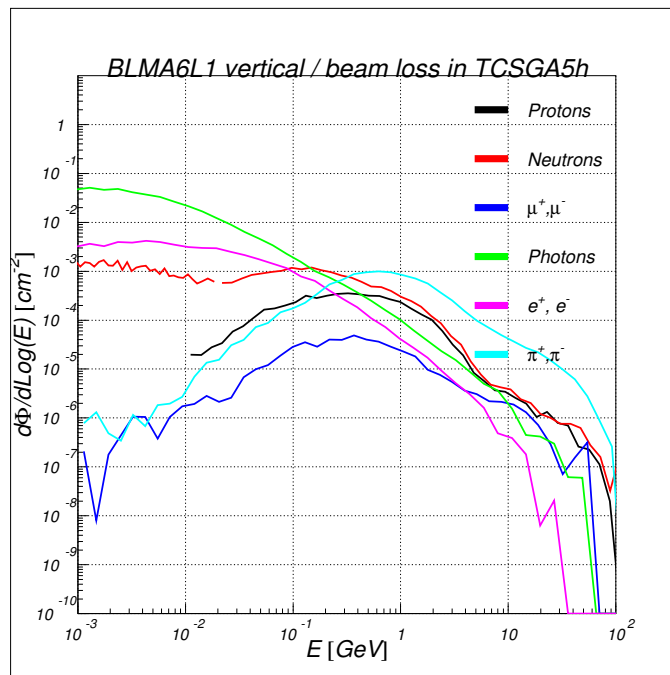
Figure 7: Fluence (per lost proton) in **BLMC6L1**
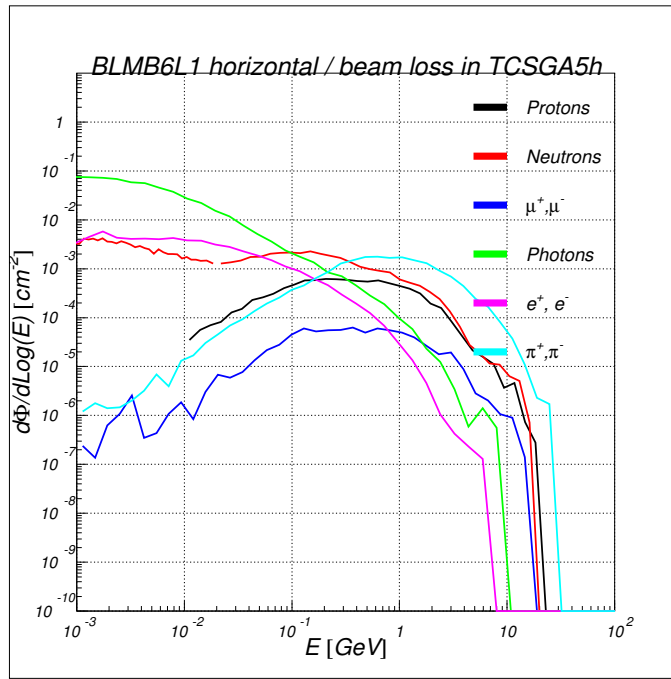
(a) **Horizontal detector**
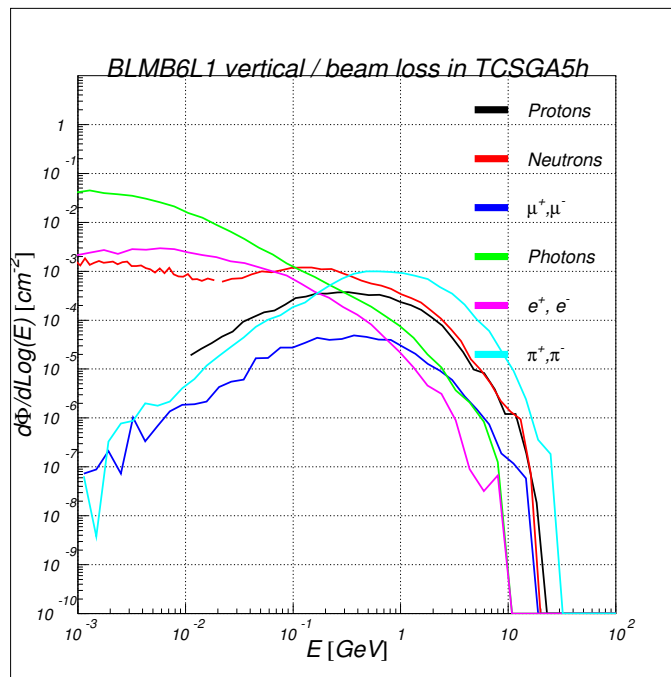
(b) **Vertical detector**

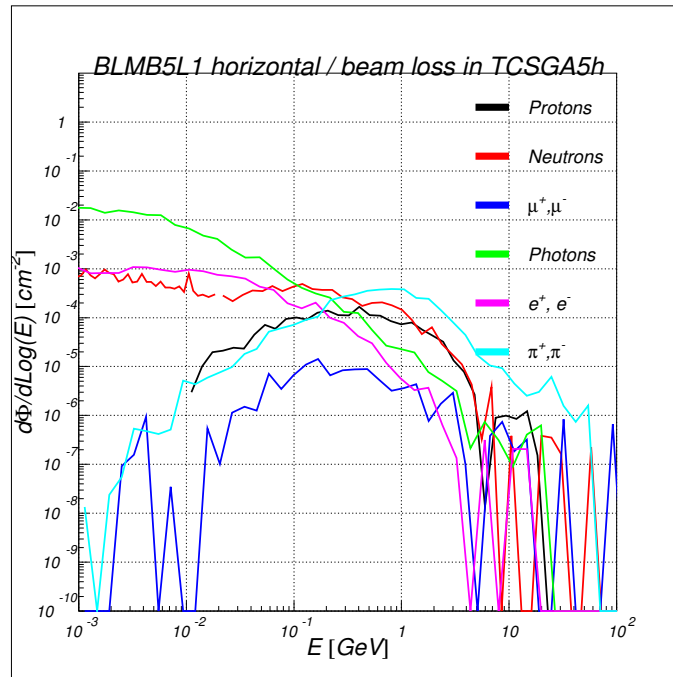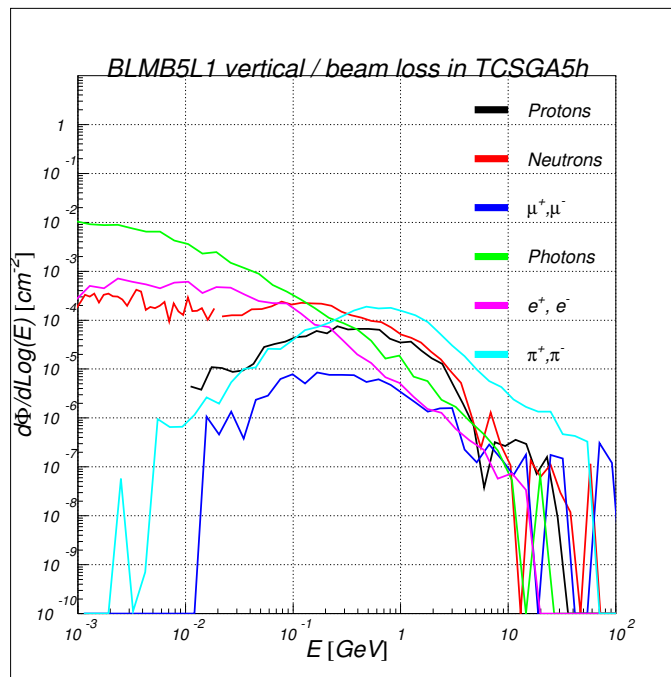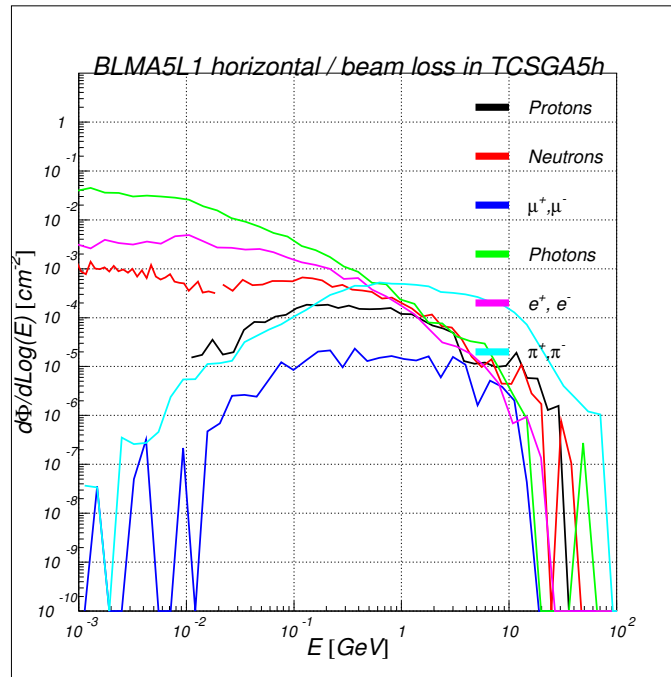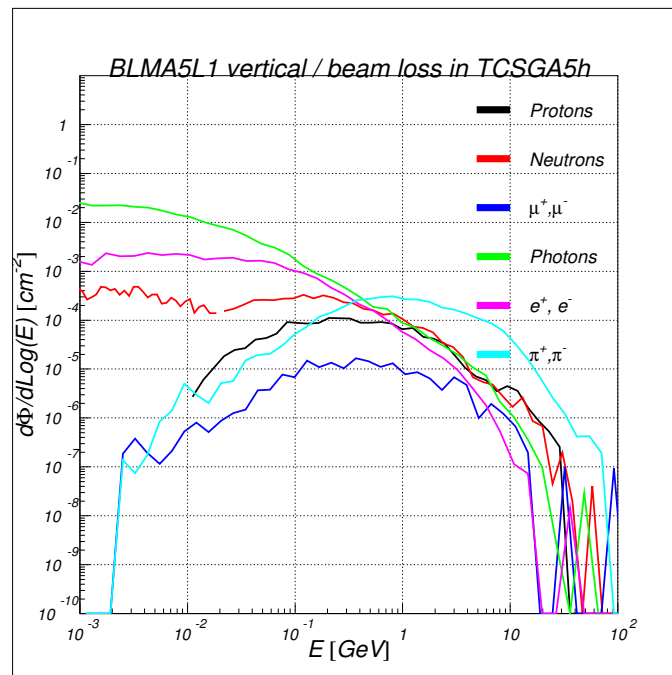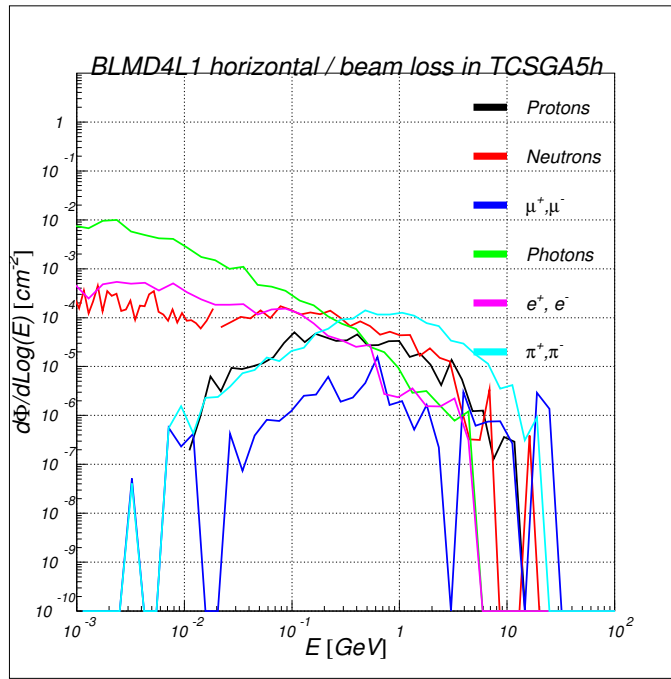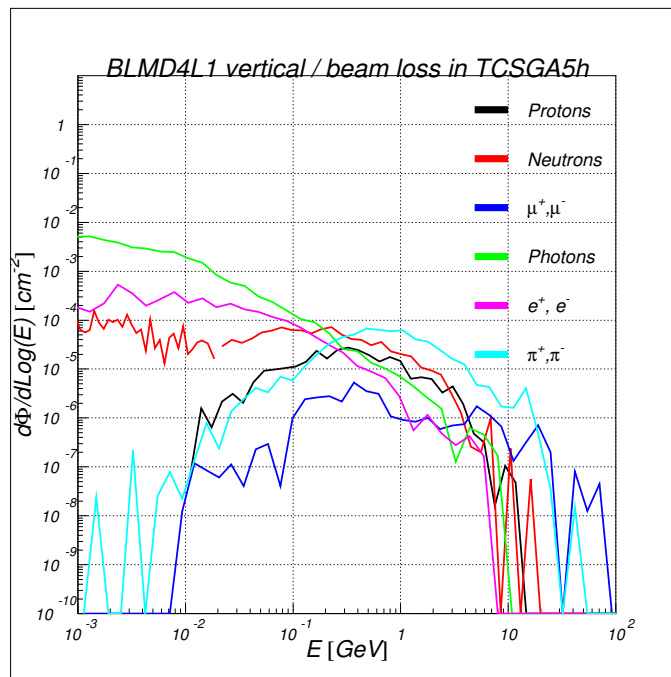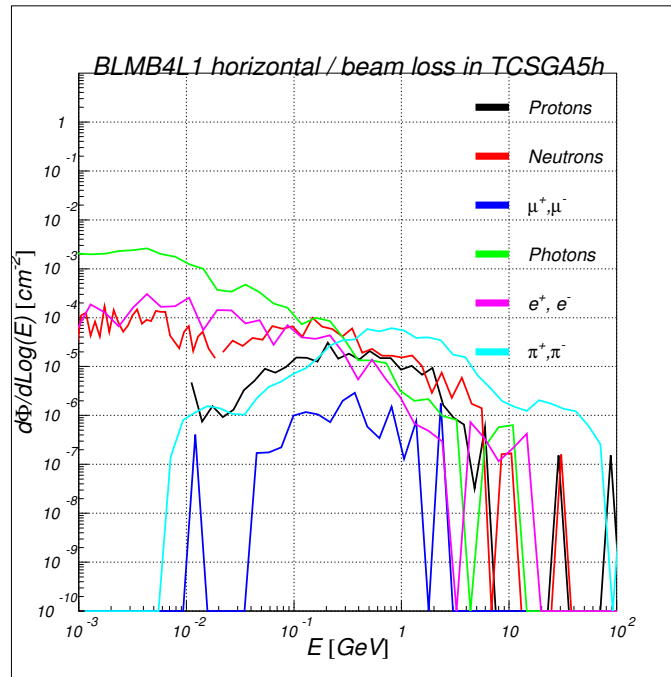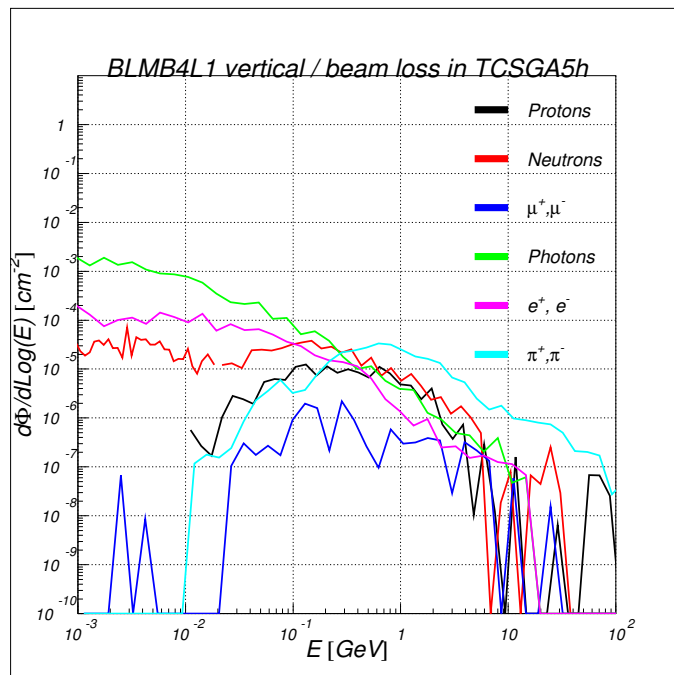Figure 8: Fluence (per lost proton) in **BLMB6L1**

(a) **Horizontal detector**

(b) **Vertical detector**

Figure 9: Fluence (per lost proton) in **BLMA6L1**

(a) **Horizontal detector**

(b) **Vertical detector**

Figure 10: Fluence (per lost proton) in **BLMB5L1**

(a) **Horizontal detector**

(b) **Vertical detector**

Figure 11: Fluence (per lost proton) in **BLMA5L1**

(a) **Horizontal detector**

(b) **Vertical detector**

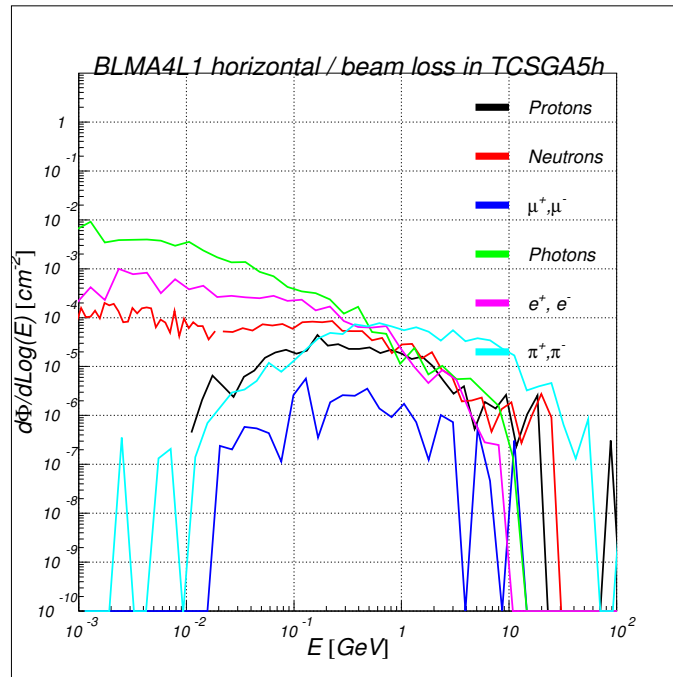Figure 12: Fluence (per lost proton) in **BLMD4L1**

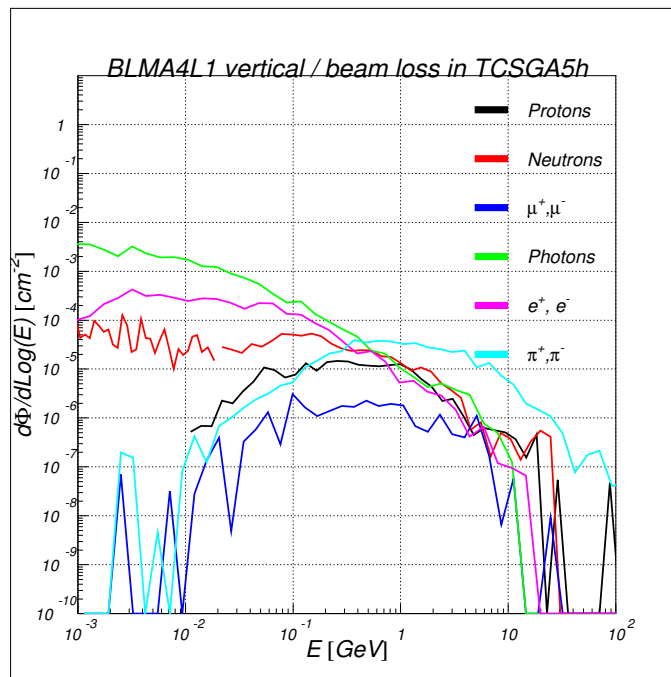(a) **Horizontal detector**

(b) **Vertical detector**

Figure 13: Fluence (per lost proton) in **BLMB4L1**

(a) **Horizontal detector**

(b) **Vertical detector**

Figure 14: Fluence (per lost proton) in **BLMA4L1**