FLUKA simulations for the optimization of the Beam Loss Monitors

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Abstract

The collimation system in the beam cleaning insertion IR7 of the Large Hadron Collider (LHC) is expected to clean 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 collimators, thus rendering the identification of any faulty unit rather complex. In the present study the detailed geometry of IR7[1] is upgraded with the insertion of the BLM's, and the Monte Carlo FLUKA transport code is used to estimate the individual contribution of every collimator to the showers detected in each BLM.

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1 Introduction

1.1 Beam Loss Monitors

A horizontal (ionization chamber) and a vertical (secondary emission monitor) 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 distribution of interactions among the collimators and the radiation propagation along IR7, which should be manifested in the BLM readings.

This study is divided into three main parts. The first one provides the spectra of different particles in every BLM detector for losses produced in each of the following sources[1]:

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

The second part provides the crosstalk arrays for the BLM_I (ionisation chamber) and BLM_S (SEM chamber) in terms of relative energy deposition in each detector.

The third part includes a slight geometry update and gives the phase-space coordinates (position and momenta) of a number of tracked particles at the moment of entrance into the BLM_I detector of the BLM block placed after the first secondary collimator, TCSGA6. The purpose of this calculations was to provide a source for subsequent more detailed simulations in the ionization chamber.

The here presented results, as well as all IR7 calculations which are based on pre-calculated loss patterns, rely on tracking simulations [2, 3, 4], whose output is used as direct input for FLUKA [5, 6] where the respective loss locations are then sampled and used as starting point of inelastic (non-elastic and single-diffractive) interactions.

In order to achieve the defined goals, a BLM block prototype with two detectors was implemented and replicated over the IR7 tunnel, starting 30 cm downstream of each collimator block. Each detector is defined as a hollow cylinder with a wall thickness of 2 mm everywhere except in the endcaps (5 mm) - see fig.1.

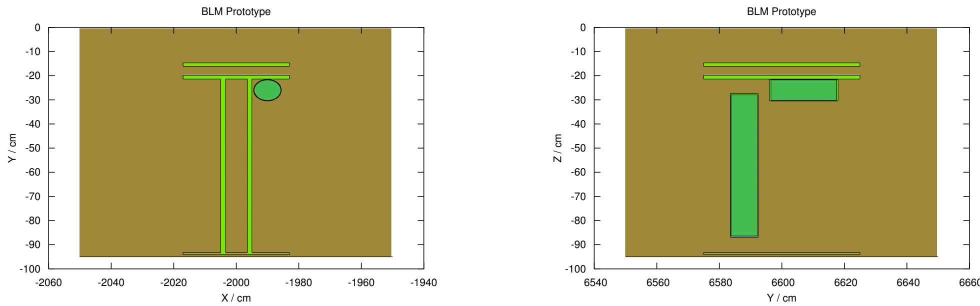


Figure 1: BLM prototype as implemented in FLUKA *for spectra and cross talk analysis*. The cylinders are hollow with a wall thickness of 2 mm everywhere except in the endcaps (5 mm).

1.2 Geometrical description of the BLM

As any 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 volume as well as the steel support and the metal container. Each BLM block contains a horizontal BLM (ionisation chamber) and a vertical SEM (secondary emission monitor) that are used as particle detectors throughout the simulations. The *horizontal detector* is aligned along the beam axis (z) and has its transversal (xy) centre at x: -10 cm (-1990 in the graph), i.e., at 10cm distance from the geometrical centre beween the two beam pipes (beam1 and beam2) and with its vertical position being 26 cm below, as well as longitudinally 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 has the same lateral position (x: -10cm) however the vertical centre of the detector being at 46.5 cm below the beam axis and longitudinally (z) 130.8 cm downstreams the centroid of the preceding collimator. The length of the vertical collimator is 48 cm, thus with an active volume of 2723.68 cm^3. The geometrical layout of the BLM correspond to the ones shown in figure 1.

[1]These sources are obtained by filtering the *horizontal* beam loss scenario to the losses in each of these objects.

2 Energy spectra simulations in the BLM

2.1 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 losses occurring in the preceding collimator, the contribution from other upstream collimators can be important. In order to associate the signal of a BLM to a single collimator, it is essential to quantify this contribution in form of a response matrix.

The FLUKA geometry contains for each collimator vertical and a horizontal BLM. For each BLM and each family of particles the particle fluence was calculated as a function of energy, by scoring tracklength (USRTRACK card) and then normalize it to the volume of the respective detector, with results given in Lethargy units ($\left[\frac{d\Phi}{dLog(E)}\right]$).

The fluence inside the BLM was obtained for the following particles: Protons, Neutrons, Muons, Photons, Electrons, Positrons and Pions.

2.2 Results

The graphs 2(a) to 10(b) in pages 17 to 25 show that the spectra seen by the horizontal detector are very similar to those seen by the corresponding vertical detector. The first graph (2(a)) corresponds to the BLM upstream of the source of radiation (i.e., collimator TCPC6) and it thus shows neutrons as being the dominant contribution. Please note that statistical errors become high at larger distances from the considered loss location (collimator) and can be seen in the important fluctuations.

2.3 Uncertainties

When simulating the cascade induced by 7 TeV beam protons lost in the collimator jaws, these are carried by i. loss assumptions, ii. grazing impacts (the jaw surface roughness is not taken into account), iii. FLUKA models and cross section extrapolation at 7 TeV, iv. geometry/material implementation and large distances between collimators and concerned BLM locations (implying an important dependence on a tiny fraction of solid angle in the angular distribution of the reaction products).... An overall safety factor of 1.5-2 should therefore be taken into account.

NOTE THAT THE FOLLOWING RESULTS HAVE TO BE INTERPRETED QUALITATIVELY, IN ADDITION TO STATISTICAL ERRORS, IMPORTANT SYSTEMATIC UNCERTAINTIES MIGHT AFFECT THE CALCULATIONS AND

HAVE TO BE CAREFULLY CONSIDERED BEFORE ANY RESPECTIVE APPLICATION.

3 Cross talk between BLM

3.1 Introduction

The reading in a given BLM results 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*, $\mathbf{M}$, where the terms outside the diagonal are known as the cross-talk.

A given cell $[row(i), col(j)]$ of $\mathbf{M}$ 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 $BLM(j)$ for all loss cases. Every row (i) in the matrix is obtained from a simulation with a loss source filtered 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 case (including a full simulation for the various loss scenarios and respectie distribution) a different response matrix can be calculated. Moreover, since every BLM block includes a horizontal and a vertical BLM detector, the number of matrices doubles to distinguish the two cases. The goal, during later LHC operation, is that from the readings in the BLM's ($\vec{r}$) it should be possible to obtain the respective losses in the collimators ($\vec{l}$)[3].

The given geometrical layout, even though complete, still contains certain short-comings in terms of surrounding installations which could possibly have an influence on the detailed results (e.g., collimator supports). This together with the fact that after installation of the monitors in the LHC it will be needed to verify the original assumptions for positioning, leads to the important requirement to review the here presented results at a later stage when the above information becomes available.

In terms of technicalities, the settings of the simulations are similar to those of the computation of the energy deposition in the warm section [1] except for part of

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

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

$$\mathbf{M}^{\mathsf{T}}\vec{l} = \vec{r} \rightarrow \vec{l} = \{ \ (\mathbf{M}^{\mathsf{T}})^{-1}\,\vec{r} \quad if \,\exists\, \mathbf{M}^{-1} \tag{1}$$

the variance reduction scheme, as stated in A.4. Dedicated analysis programs (annex A.3) are available to parse the energy deposition values from each simulation case and build up the response tables.

3.2 Cross talk among BLM for a horizontal beam loss scenario

L1								R1		
C6	B6	A6	B5	A5	D4	B4	A4	A4	B5	**Source**
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}	TCP**C6**
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}	TCP**B6**
0_{5}	1.4E-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}	TCSG**A6**
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}	TCSG**B5**
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}	TCSG**A5**

Table 1: Cross talk$_{ERROR[\%]}$ between vertical BLM's (signal is derived from deposited energy as simulated with FLUKA) assuming a horizontal loss scenario in terms of respective loss locations. All columns are normalized to one in order to account for a normalized 'total' signal in all BLM detectors. This illustration is chosen according to the request from the BLM team to be later used for a possible unfolding of the observed BLM signals and respective translation into losses on each collimator, however assuming a given loss distribution. To actually determine the cross talk in relative terms and normalized for each collimator loss position one would have to normalize each row seperately, however using the original not normalized energy deposition data.

In tables 1, 2, as well as the spectras collected in the appendix, we observe the following:

- † The cross talk between horizontal detectors follows a pattern similar to that between the vertical ones.
- † Backscattering has no relevance.
- † Detectors placed downstream the source keep similar energy detection thresholds regardless of the particular position of the source.
- † B5L1 gets 2 to 3 times less radiation than the downstream element A5L1.
- † A4R1 gets much more radiation than the neighboring detectors.

Note also the following remarks:

L1								R1		
C6	B6	A6	B5	A5	D4	B4	A4	A4	B5	**Source**
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 $_{49}$	TCP**C6**
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 $_{33}$	TCP**B6**
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 $_{73}$	TCSG**A6**
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 $_{32}$	TCSG**B5**
0 $_{4}$	0 $_{3}$	0 $_{3.5}$	1.5E-4 $_{53}$	0.157 $_{3.6}$	0.611 $_{8.4}$	0.621 $_{8.6}$	0.728 $_{14}$	0.625 $_{12}$	0.403 $_{22}$	TCSG**A5**

Table 2: As described in table 1 but here for the horizontal detectors (SEMs).

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

† Near IP7 a non-negligible cross talk can be expected between beam 1 and beam 2 (not shown here).

3.3 Cross talk between BLM for a vertical beam loss scenario

The procedure was identical to that for the horizontal beam loss scenario, but with the vertical loss pattern. The results for the SEM and for the ionization chamber cross talks are presented in tables 3 and 4.

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 $_{21}$	TCP**D6**
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 $_{31}$	TCP**C6**
2.6E-4 $_{84}$	3.7E-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 $_{25}$	TCP**B6**
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 $_{19}$	TCSG**A6**
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 $_{16}$	TCSG**B5**
0 $_{5}$	0 $_{3.8}$	0 $_{3.4}$	0 $_{3.5}$	7.7E-5 $_{58}$	0.154 $_{4}$	0.584 $_{6.6}$	0.643 $_{7.8}$	0.594 $_{12}$	0.626 $_{10}$	TCSG**A5**

Table 3: Cross talk$_{ERROR[\%]}$ between the vertical BLM detectors and for a vertical loss scenario. Details see caption for table 1

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}	TCP**D6**
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}	TCP**C6**
$5.5E\text{-}4_{39}$	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}	TCP**B6**
$0_{5.8}$	$0_{2.9}$	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}	TCSG**A6**
$0_{5.8}$	$0_{2.9}$	0_{3}	$0_{3.2}$	$0.622_{8.4}$	$0.595_{3.6}$	$0.322_{5.9}$	$0.258_{8.5}$	0.252_{12}	$0.23_{8.3}$	TCSG**B5**
$0_{5.8}$	$0_{2.9}$	0_{3}	$0_{3.2}$	$3.6E\text{-}4_{26}$	$0.139_{4.5}$	$0.588_{8.3}$	0.659_{7}	0.6_{13}	$0.681_{9.9}$	TCSG**A5**

Table 4: Cross talk$_{ERROR[\%]}$ between the horizontal detectors (SEM) and for a vertical loss scenario. Details see caption for table 1

4 Phase space of individual detections

4.1 Introduction

The **third** step in the BLM FLUKA computations provides the phase-space (position and momenta) of the tracked particles in the moment of entrance into the BLM detectors of the block placed after the first secondary collimator, TCSGA6.

4.2 Geometry

First of all, the geometry of the BLM block was updated with the latest available information. This implied moving and re-dimensioning the two detectors. The axis of the vertical detector was moved 32 cm upstream (12 cm upstream with respect to the center of the BLM block) and the length was extended 10.5 below the beam plane. As for the vertical detector, the axis was moved 7 cm downstream and the radius was shrunken by 1 mm.

```
RPP BLMBODY    -2025.0  -1975.0  -94.0  -14.65  6570.0  6630.0
*
RPP PLATEXY1   -2017.0  -1983.0  -16.2  -14.7   6575.0  6625.0
RPP PLATEXY2   -2017.0  -1983.0  -21.4  -19.8   6575.0  6625.0
RPP PLATEXY3   -2017.0  -1983.0  -95.0  -93.2   6575.0  6625.0
*
RPP PILLAROU   -2005.0  -1995.0  -96.0  -21.0   6590.0  6610.0
RPP PILLARIN   -2003.4  -1996.4  -96.0  -21.0   6591.6  6608.4
```

For the first two parts, this was the arrangement of the two cylinders:

```
*
RCC BLMvOU     -1990.0   -27.4  6588.0   0.0   -59.5   0.0   4.45
```

```
RCC  BLMvIN    -1990.0   -27.9  6588.0   0.0   -58.5    0.0   4.25
*
RCC  BLMhOU    -1990.0   -26.0  6596.0   0.0     0.0   22.0   4.45
RCC  BLMhIN    -1990.0   -26.0  6596.5   0.0     0.0   21.0   4.25
```

For the third part this is the new arrangement:

```
*
RCC  BLMvOU    -1990.0   -27.4  6588.0   0.0   -59.5    0.0   4.45
RCC  BLMvIN    -1990.0   -27.9  6588.0   0.0   -58.5    0.0   4.25
*
RCC  BLMhOU    -1990.0   -26.0  6596.0   0.0     0.0   22.0   4.45
RCC  BLMhIN    -1990.0   -26.0  6596.5   0.0     0.0   21.0   4.25
```

4.3 Methodology

To allow the simulation including the detector response in the BLM detectors in a second step and as a function of distinguished losses in the collimators required to modify the input file (*ir7.fluka*, the *usrini.f* and *source.f* routines[4] and the *fluscw.f* function (to print out the full information of the evolving cascade intercepting the BLM detector volume.).

To technically perform the latter, the input file has to include a definition for the BLM simulation case that activates two *usrbdx* cards, which will trigger actions through the instructions provided in the subroutine *fluscw.f*

```
*#define BLM
...
...
#if BLM
* Vertical detector
USRBDX        -1.0              -50.0   BLMvert   3701.58      60.0BLMA6L1
USRBDX                  0.01                                         &
* Horizontal detector
USRBDX        -1.0              -50.0   BLMhori   1368.65      60.0BLMA6L1
USRBDX                  0.01                                         &
#endif
```

The subroutine *usrini.f* creates the file SEL_HIST when it is called for the first time. In addition, for each new event through *source.f*, the initial conditions are written into SEL_HIST:

The function *fluscw.f* was edited in the following way. Upon first call the ASCII file BLM_HIST is created and the code searches for the regions *airBLM* (all the air within the BLM prototype delimiting box), *BLMcylV* (the aluminum cylindrical wall of the ionization chamber) and *BLMcylH* (the aluminum external wall of the SEM detector) through the function *GEON2R*. Then, when a particle crosses a surface, the code retrieves the lattice number of the current object. If that number

[4] In order to save the initial phase space of the primary lost in the collimator

is 84, then it means that the tracked particle is in the BLM block after TCSGA6L1. In that case the function checks whether the particle is entering either detector (that is to say, whether the particle was in the air outside, *airBLM* and now is in any of the aluminum walls, *BLMcylV*, *BLMcylH*). If that is the case, *fluscw.f* reads the last line in SEL_HIST and prints out in BLM_HIST the relevant data of the primary and secondary particle, as described in 4.4.

4.4 Results

Each line in the file BLM_HIST contains the data of an incoming secondary as well as of the corresponding primary lost proton. The first 10 columns collect the information of the secondary particle:

- The first column tells about the entered detector (1=Ion chamber, 2=SEM).
- The second column is the numeric equivalence of the particle type as defined in FLUKA[6], page 45, e.g.:

α → -6	e^- → 3	$\bar{n}$ → 9	K^- → 16
^3He → -5	e^+ → 4	μ^+ → 10	λ → 17
^3H → -4	ν_e → 5	μ^- → 11	π^0 → 23
^2H → -3	$\bar{\nu_e}$ → 6	π^+ → 13	K^0 → 24
p → 1	γ → 7	π^- → 14	$\bar{K^0}$ → 25
$\bar{p}$ → 2	n → 8	K^+ → 15	... $\ldots$

- The third column tells about the statistical weight of the secondary particle.
- Columns 4-6 are the absolute X, Y, Z coordinates when entering the detector volume, and must be within the external surface of those.
- Column 7 is the kinetic energy (GeV) in the laboratory frame.
- Columns 8-10 correspond to the direction cosines.

The last eight columns collect the information about the corresponding primary lost proton.

- Column 11 shows the lattice number where the primary proton interacted, i.e:

- 73 TCP.D6L7.B1
- 75 TCP.C6L7.B1
- 77 TCP.B6L7.B1
- 83 TCSG.A6L7.B1
- 97 TCSG.B5L7.B1
- 99 TCSG.A5L7.B1
- 104 TCSG.D4L7.B1
- 113 TCSG.B4L7.B1
- 115 TCSG.A4L7.B1
- 117 TCSG.A4R7.B1
- 130 TCSG.B5R7.B1
- 134 TCSG.D5R7.B1
- 136 TCSG.E5R7.B1
- 146 TCSG.6R7.B1
- 148 TCLA.A6R7.B1
- 152 TCLA.C6R7.B1
- 158 TCLA.E6R7.B1
- 159 TCLA.F6R7.B1
- 167 TCLA.A7R7.B1
- 168 TCLA.B7R7.B1

• Column 12, writes the primary particle type (=1, protons).

• Column 13 and 14 show the region number and corresponding material code, respectively. As for the region number, these are the typical starting regions[5]:

420(2) TCSscaR(L)
421(3) TCSjawR(L)
367(8) TCPiskR(L)
374(6) TCPjawR(L)
373(5) TCPscaR(L)
461(5) TCLscaR(L)
462(6) TCLjawR(L)
463(4) TCLscaL(R)W
464(8) TCLjawR(L)W

The corresponding material code is the following:

2 Vacuum
3 Hydrogen
4 Helium
5 Beryllium
6 Carbon
7 Nitrogen
8 Oxygen
9 Magnesium
10 Aluminium
11 Iron
12 Copper
13 Silver
14 Silicon
15 Gold
16 Mercury
17 Lead
18 Tantalum
19 Sodium
20 Argon
21 Calcium
22 Tin
23 Tungsten
24 Titanium
25 Nickel

[5]The region naming code is:

isk skimmed region in the jaw (that shortens effective length jaw from 100 to 60 cm).

jawR(L) Right or Left jaw

scaR(L) scattering film in the Right or Left jaw.

scaR(L)W scattering film in the W insertion.

jawR(L)W W insertion beyond the scattering film.

- Column 15 displays the lost proton kinetic energy [GeV].
- In columns 16 through 18 the starting absolute coordinates [cm] are printed.

In the following example, a π^+ with the statistical weight of 8.7221 is detected in the absolute position $\{x, y, z\} = \{-27.63, -16039.35, -.5569\}[m]$ at the SEM chamber (horizontal detector) with a kinetic energy of 556.9 MeV, and the direction cosines $\{n_x, n_y, n_z\} = \{-.0648, -.4619, .8846\}$. This particle belongs to the shower originated by a proton (1), lost in lattice number 75 (TCP.C6L7.B1) in region 374 (the right hand side jaw, TCPjawR) made of material Carbon and at momentum 6999 GeV/c.

```
1 13      8.7221      7.402871     -27.635137  -16039.350000    -0.5569
    -.06481135  -.46188957  0.88456629   75    1  374   6    6999.061791
      9.873435       0.000016  -20326.968335
...
```

5 Acknowledgements

The authors would like to thank R. Assmann and the ABP group for their constant support and direct collaboration for this work. The careful calculation of the tracking loss patterns forms the basis of the here presented FLUKA application.

A BLM data extraction

A.1 Scoring cards

The energy spectra are generated with the USRTRACK command in the FLUKA input file. In total there are 18 USRTRACK (from unit 50 to 67), corresponding to the 9 sets of 2 detectors (BLM + SEM), 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 contains seven separate binnigs 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.   1248.35       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 with the USERWEIG card. The routine distinguishes every BLM from the lattice name that is indicated in the USRTRACK "SDUM".

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*.

A.3.1 The anBLM.sh script

This script should be run from the directory that contains all the runs relative to a given irradiation case (e.g. BLM/hori/TCPC6). There is no runtime input or specific input file other than the files resulting from simulations done with BLM settings. The script retrives the tracklength scorings, it produces *usrtrackh_* files containing tables for the track length estimators (by using *usrbdx.r*) and then it calls the PAW kumac *ustdum.kumac* to produce the plots with the spectra (*ustplo_*).

A.3.2 The ustdum.kumac

This PAW kumac produces the spectra plots. The script is used directly, it is called by *anBLM* (see A.3.1).

A.3.3 The anCROSS.sh script

The *anCROSS.sh* script can be called from /BLM/hori once all loss cases have been run and analyzed (with A.3.1). There is no specific runtime option or input file other than the previously obtained *LatticeWatt* files in each collimator loss case. The script computes the cross talk response of the BLM monitors in terms of total scored energy. The output is printed to the screen as a TEX formatted table.

A.4 Variance Reduction Scheme

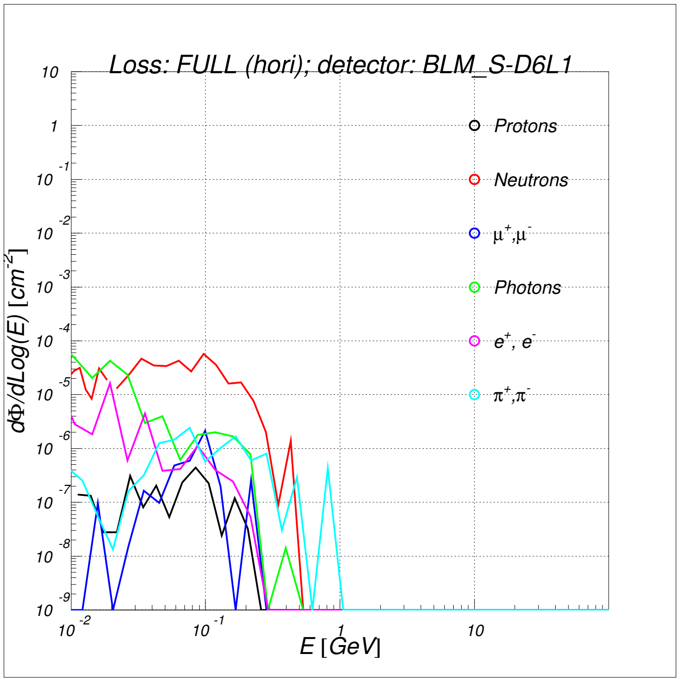
In order to reduce the CPU consumption, low energy particles where not transported in areas from which they could not possibly reach the BLM detectors. Therefore, the following EMF-CUT instructions were inserted into the input file:

```
* 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
```

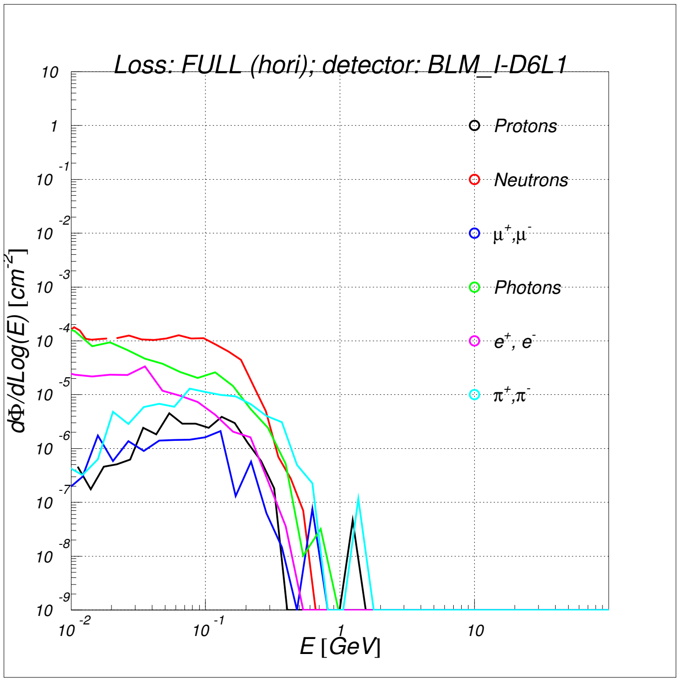
EMFCUT	0.0001	0.0004	0.00	TUNDAIR	
EMFCUT	0.0001	0.0004	0.00	TUNEAIR	
EMFCUT	0.0001	0.0004	0.00	PARK_AIR	
EMFCUT	0.0001	0.0004	0.00	Plat1BLM	airBLM
EMFCUT	0.0001	0.0004	0.00	TCPflaui	TCPexit
EMFCUT	0.0001	0.0004	0.00	TCPbox	
EMFCUT	0.0001	0.0004	0.00	TCPVO2	TCPVO1
EMFCUT	0.0001	0.0004	0.00	TCSflaui	TCSexit
EMFCUT	0.0001	0.0004	0.00	TCSbox	
EMFCUT	0.0001	0.0004	0.00	TCSVO2	TCSV01

B Extra plots

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

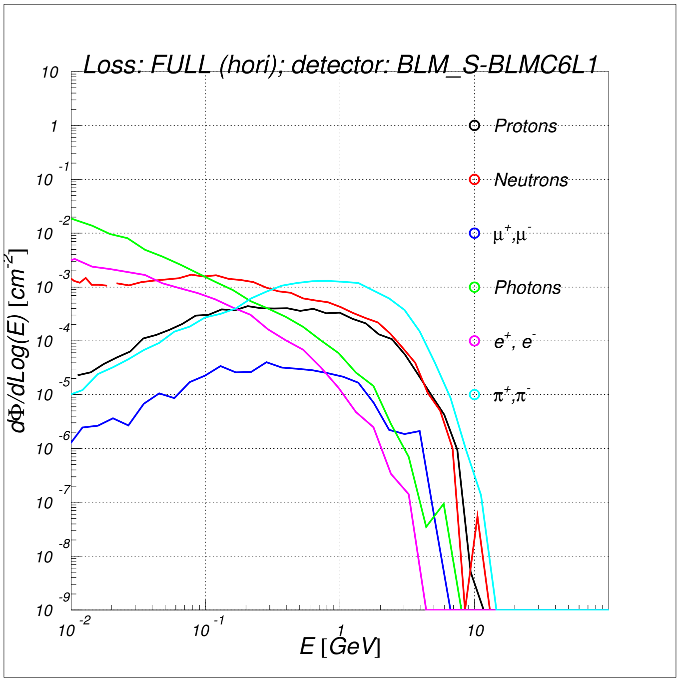


(a) **Horizontal detector**

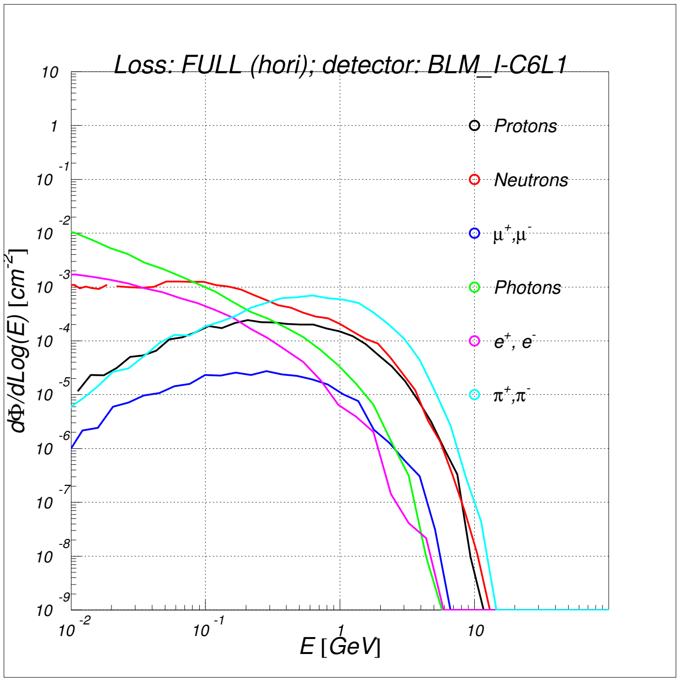


(b) **Vertical detector**

Figure 2: Fluence (per lost proton) in **BLMD6L1**

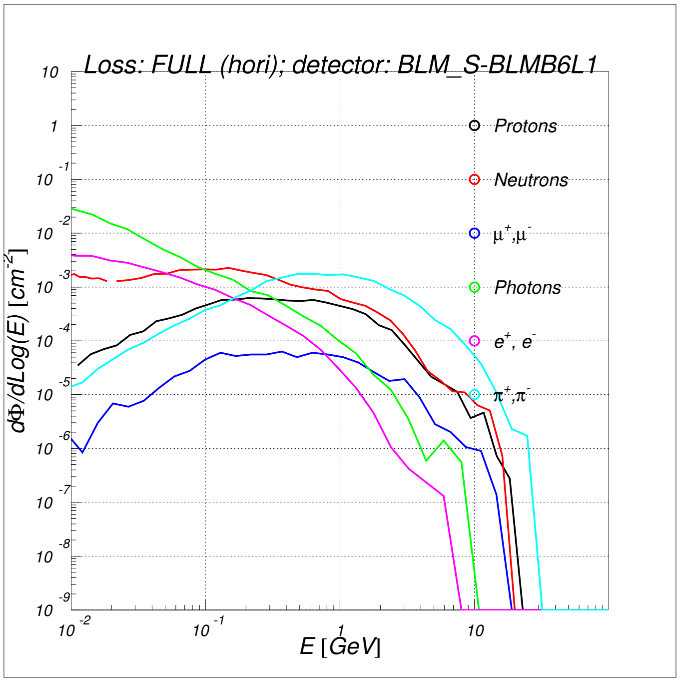


(a) **Horizontal detector**

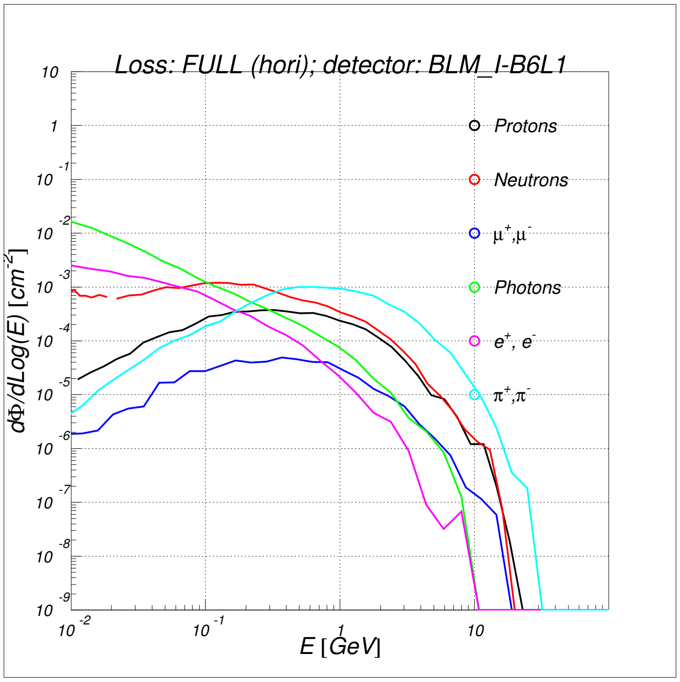


(b) **Vertical detector**

Figure 3: Fluence (per lost proton) in **BLMC6L1**

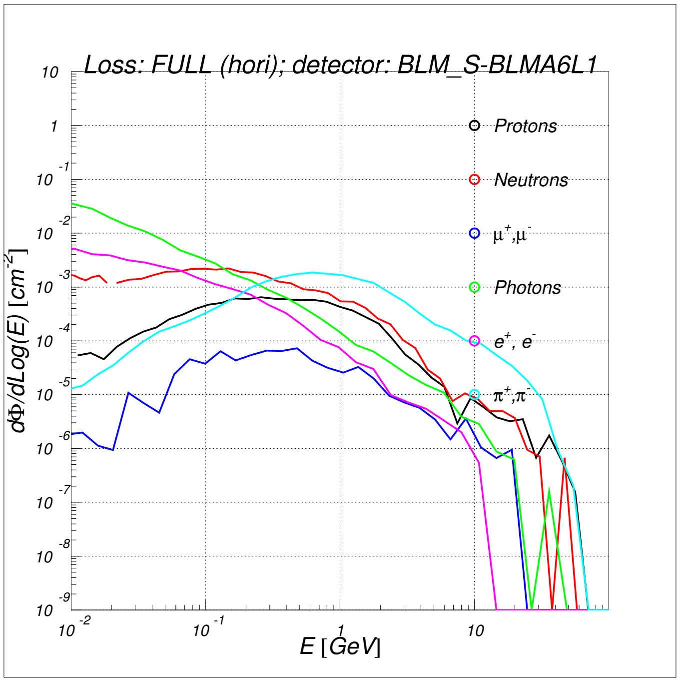


(a) **Horizontal detector**

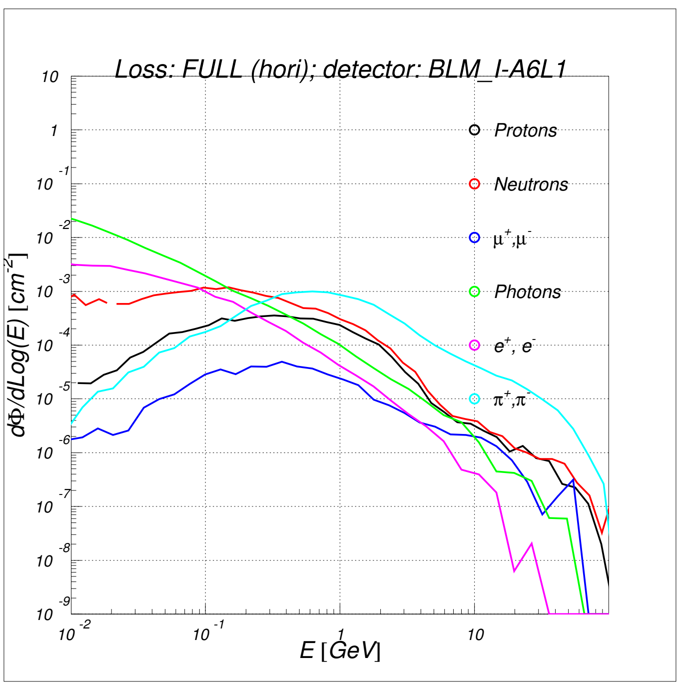


(b) **Vertical detector**

Figure 4: Fluence (per lost proton) in **BLMB6L1**

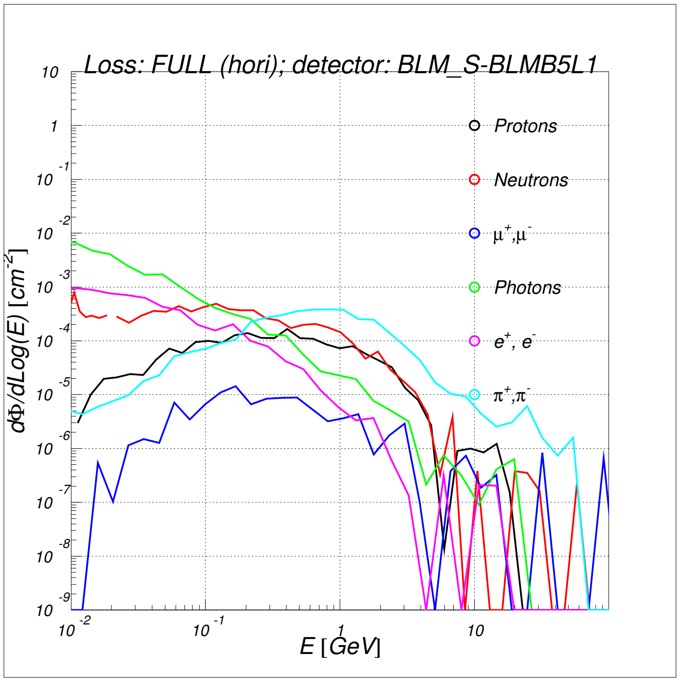


(a) **Horizontal detector**

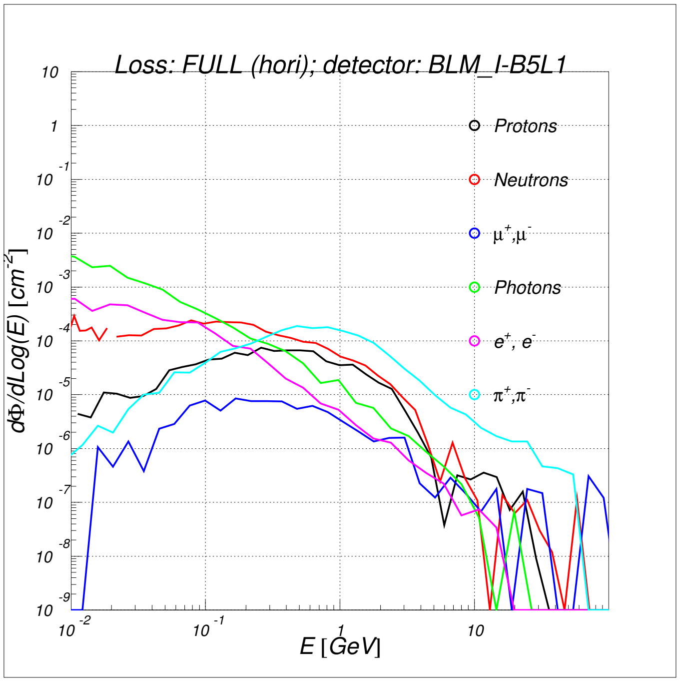


(b) **Vertical detector**

Figure 5: Fluence (per lost proton) in **BLMA6L1**

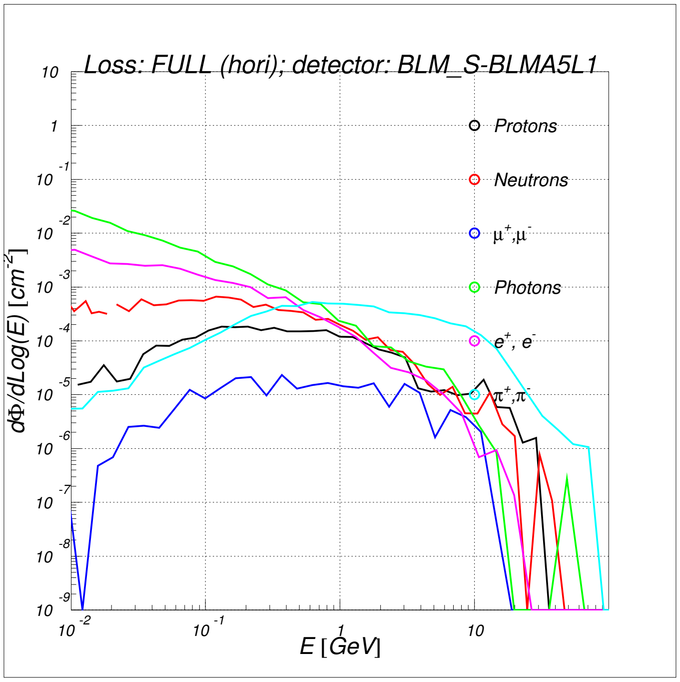


(a) **Horizontal detector**

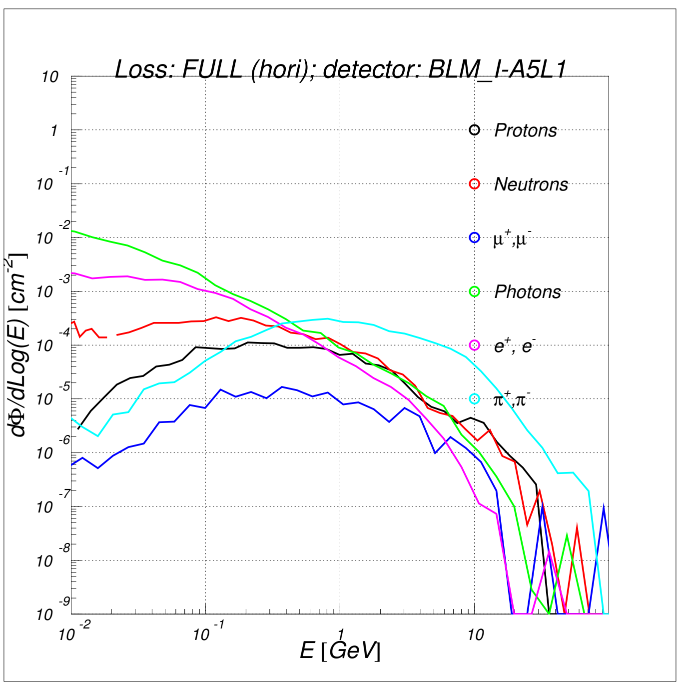


(b) **Vertical detector**

Figure 6: Fluence (per lost proton) in **BLMB5L1**

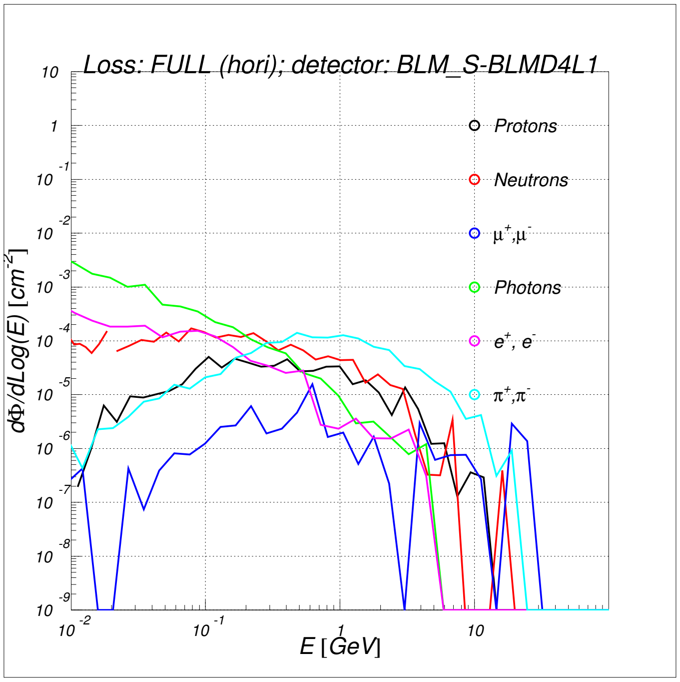


(a) **Horizontal detector**

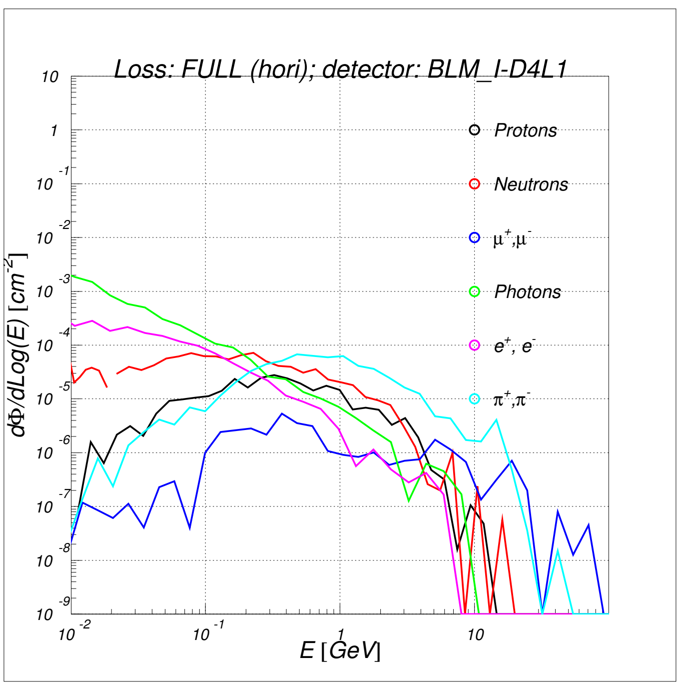


(b) **Vertical detector**

Figure 7: Fluence (per lost proton) in **BLMA5L1**

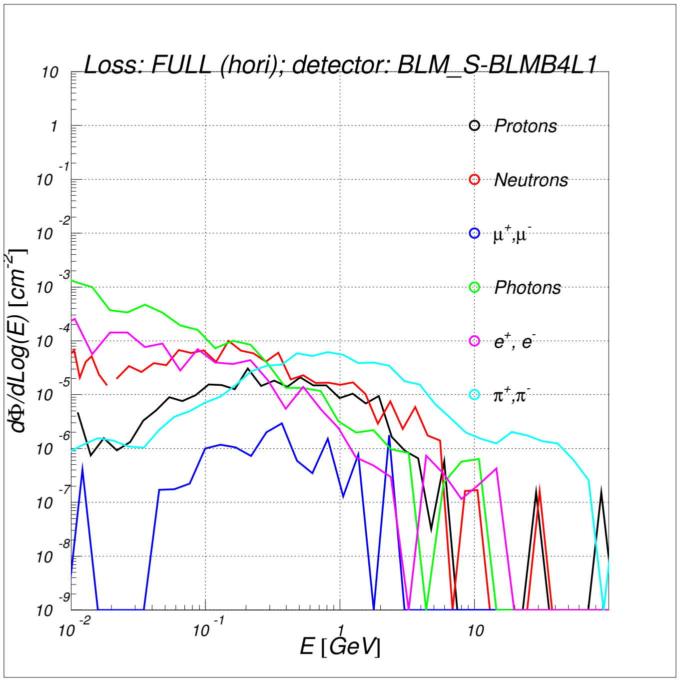


(a) **Horizontal detector**

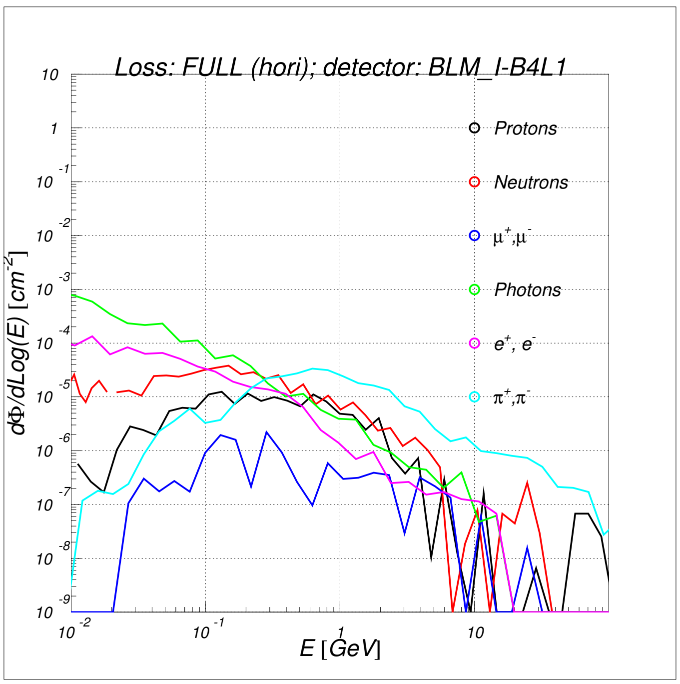


(b) **Vertical detector**

Figure 8: Fluence (per lost proton) in **BLMD4L1**

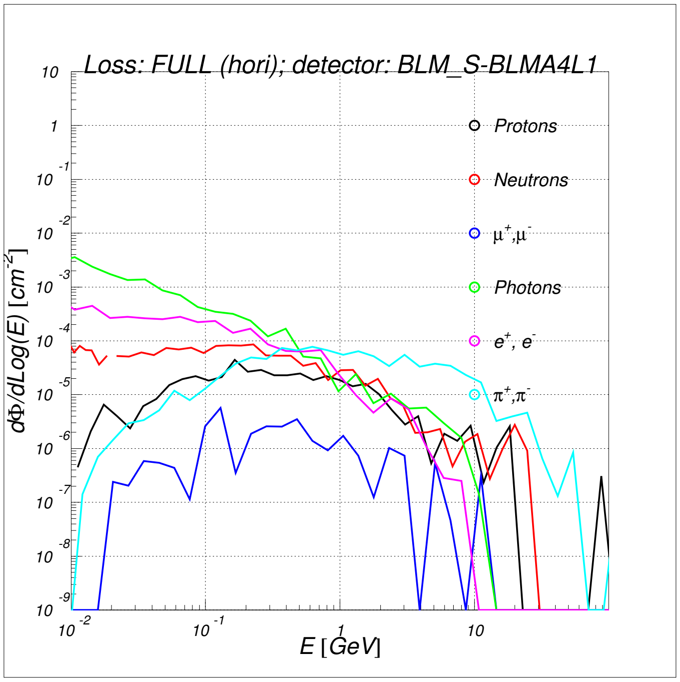


(a) **Horizontal detector**

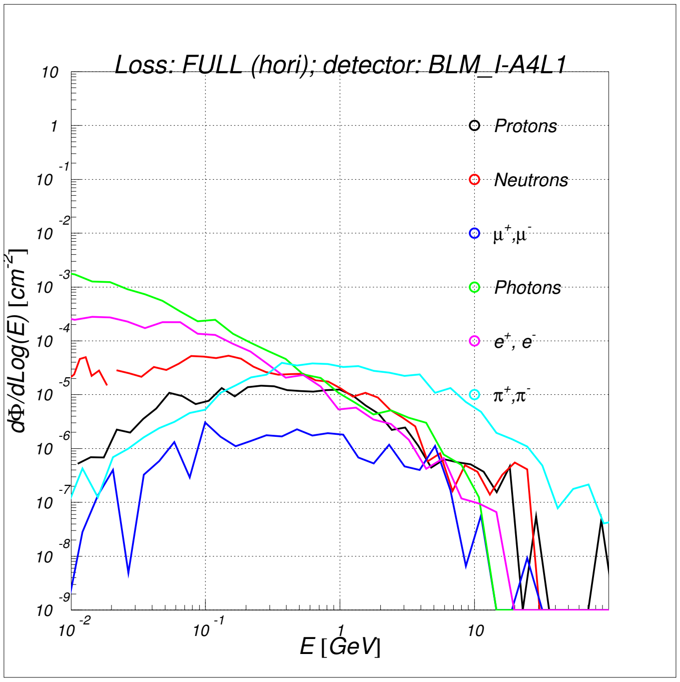


(b) **Vertical detector**

Figure 9: Fluence (per lost proton) in **BLMB4L1**



(a) **Horizontal detector**



(b) **Vertical detector**

Figure 10: Fluence (per lost proton) in **BLMA4L1**

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