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Simulation of a signal in the beam loss monitors of the momentum cleaning for the new collimator design

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Summary

This work is concerned with the simulation of a signal in the beam loss monitors for the new collimator design. The comparison of results for the different design of the collimator jaws and setups are presented. Some peculiar properties of the signal formation in the momentum cleaning are discussed.

1 Introduction

1.1 Initial setup

A signal in the beam loss monitors is simulated in the model of the momentum cleaning insertion with reduced shielding [1]. The position of the elements and their length correspond to the optics version V6.2 [2]. One-half of the cleaning insertion with reduced shielding is illustrated schematically in Figure 1.

The primary losses are shared between 1 primary and 6 secondary collimators for each ring. In contrast to work [3] the primary collimator jaws (TCP) and the secondary collimator jaws (TCS) jaws are made of double density carbon. At injection the collimator jaws position were saved (n_1=6, n_2=7), at top energy, the collimator opening come n_1=10 and n_2=11.67. An individual skew angle and radius of each collimator present in table 1.

2 Simulation strategy

The K2 code [4] is used to prepare a map of primary inelastic interactions in the collimators jaws. The full map of inelastic interactions is obtained by tracking 500000 protons.

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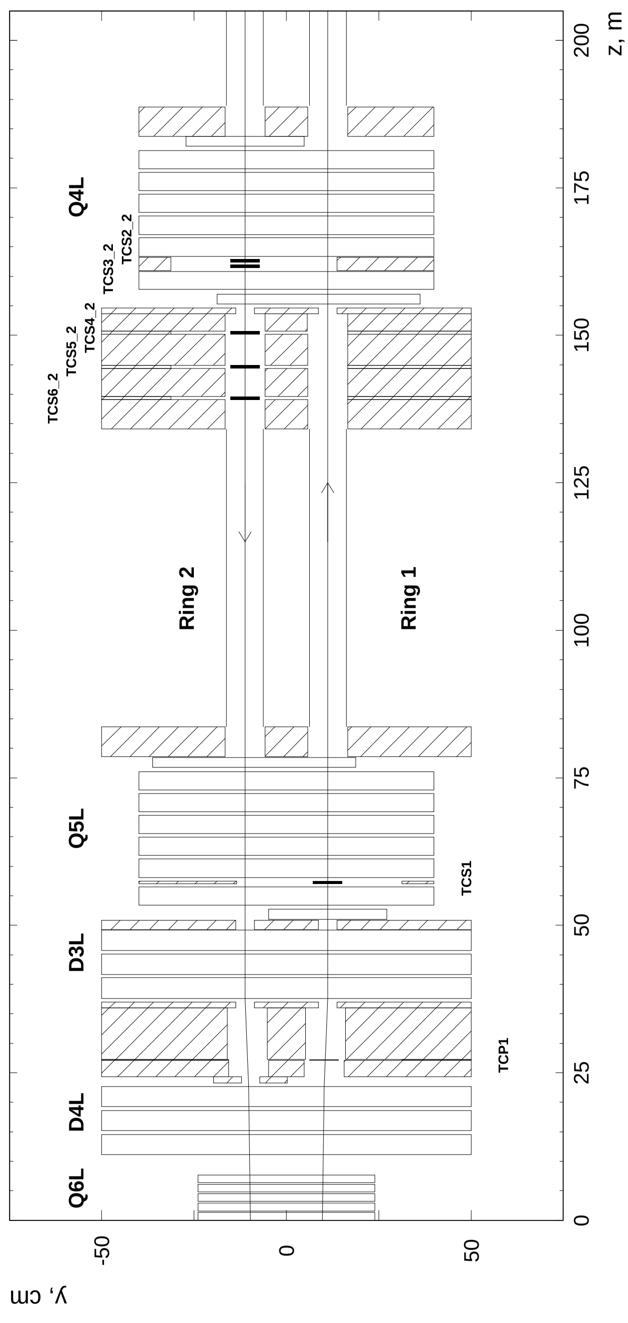

Figure 1: Longitudinal section through one half of the cleaning section for the reduced shielding configuration.

Table 1: Individual collimator parameters of the momentum cleaning

Collimator	Length	Injection		Collision	
	(cm)	skew angle (mrad)	radius (cm)	skew angle (mrad)	radius (cm)
TCP1	20	0.00000	0.5880	0.00000	0.2484
TCS1	50	0.00000	0.4204	0.00000	0.1776
TCS2	50	0.07959	0.3322	0.07959	0.1403
TCS3	50	-0.07841	0.3315	-0.07841	0.1401
TCS4	50	-0.15341	0.3894	-0.15341	0.1645
TCS5	50	0.16559	0.4290	0.16559	0.1796
TCS6	50	-0.15441	0.4554	-0.15441	0.1924

The calculated relative rates (quotes) of the inelastic interactions in the collimators jaws for two operation regimes and setup of the LHC are presented in Table 2.

Table 2: The relative rates of inelastic interactions in the collimator jaws. The sum over the collimators is equal to 1.

Setup	Collimator	TCP1	TCS1	TCS2	TCS3	TCS4	TCS5	TCS6
Injection	Al + Cu	0.431	0.211	0.183	0.104	0.034	0.030	0.007
Injection	2C + 2C	0.668	0.140	0.091	0.053	0.022	0.020	0.006
Collisions	Al + Cu	0.760	0.059	0.078	0.054	0.022	0.022	0.005
Collisions	2C + 2C	0.847	0.040	0.056	0.032	0.011	0.011	0.003

An air ionisation chamber of sizes 10x10x10 cm^3 is used as the beam loss monitor. All beam loss monitors are located at a distance of 30 cm downstream of the collimators (see Figure 2).

The both energy deposition density and fluence of all charged particles in the air cells of sizes 10x10x10 cm^3 are considered as a signal in the beam loss monitor.

Figure 3 presents the transverse cut of the cleaning section at the the beam loss monitor position.

The general equation for a signal in the beam loss monitor can be defined as a matrix form:

$$\overrightarrow{S^{f,e}} = \overrightarrow{M^{f,e}} \cdot \vec{r} \quad (1)$$

$$\vec{M} = \vec{M_1} + \overrightarrow{\Delta M_2} \quad (2)$$

where $\overrightarrow{S^{f,e}} = [s_{i1}]$ is a signal matrix, $\overrightarrow{M^{f,e}} = [m_{ij}]$ is a response matrix of the beam loss monitors and $\vec{r} = [r_{j1}]$ is a matrix of the the proton losses quote. $\vec{M_1}$ is corresponding to the response matrix of Ring 1, $\overrightarrow{\Delta M_2}$ is an response matrix induced by Ring 2.

The response of the ith beam loss monitor induced by one inelastic interacting proton with the jth collimator jaws can be calculated as

$$m^f_{ij} = \sum_{k=1} \Phi_k(i,j) \quad (3)$$

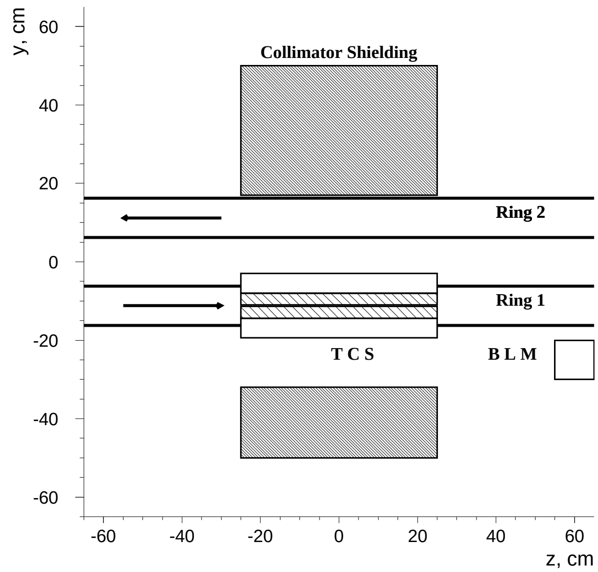

Figure 2: Position of the beam-loss monitor.

where $\Phi_k(i,j)$ - fluence of charged particles with energy above threshold.

In the case when a signal is a proportional to energy deposition, the response matrix has a shape as

$$m^e_{ij} = \sum_m \Delta E_m(i,j) \tag{4}$$

where $\Delta E_m(i,j)$ - partial energy deposition from particles with energy above threshold. Energy thresholds are a 10 MeV for charged hadrons and 1 MeV for electrons, respectively.

The energy deposition and the fluence of charged particles with energy above threshold are simulated using the Monte Carlo code MARS [5]. An individual cascade starts from interaction of a proton insides one of the collimator jaws. The coordinates, angles and the momentum of the primary protons at their interaction point are selected from the map file. The initial map file contains a limited number of the interaction point (500000) therefore it was used many times per one simulation run in order to get small statistical errors of the energy deposition density calculation in the air ionisation chamber.

An individual cascade from inelastic proton interactions inside the jaws of each collimator (j) impacting on the beam loss monitor (i) collimator is considered separately to estimate a partial contribution to the BLM total signal from each source.

There are three different cases of decision of problem (see eq. 1):

- Case A (trivial solution)

$$\overrightarrow{\Delta S_2} \quad << \quad \overrightarrow{S_1} \tag{5}$$

$$\overrightarrow{S_1} \quad = \quad \overrightarrow{M_1} \cdot \overrightarrow{r} \tag{6}$$

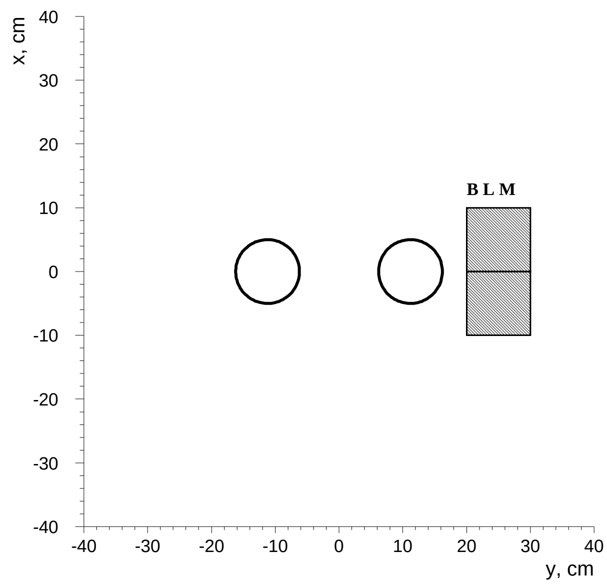

Figure 3: The transverse cut of the cleaning section at the the beam loss monitor position.

$$\overrightarrow{r} = \overrightarrow{M_1^{-1}} \cdot \overrightarrow{S} \tag{7}$$
$$\overrightarrow{r} \sim \overrightarrow{S}\ , \quad m_{ij} = 0 \ \ , \forall\ i \neq j \tag{8}$$

- Case B (no uncertainties $\vec{S}$ and $\vec{r}$)

$$\overrightarrow{S} = \overrightarrow{S_1} + \overrightarrow{\Delta S_2} \tag{9}$$
$$\overrightarrow{r} = \overrightarrow{M^{-1}} \cdot \overrightarrow{S} \tag{10}$$
$$\vec{r} = O(\vec{S})? \tag{11}$$

- Case C (yes uncertainties $\vec{S}$ and $\vec{r}$)

$$\overrightarrow{r} = \overrightarrow{V_r}(\overrightarrow{M^T} \cdot \overrightarrow{V_S^{-1}})\overrightarrow{S} \tag{12}$$
$$\overrightarrow{V_r} = (\overrightarrow{M^T} \cdot \overrightarrow{V_S} \cdot \overrightarrow{M})^{-1}, \tag{13}$$

where $\overrightarrow{V_r}$ *is a covariance matrix of relative loss rate,*
$\overrightarrow{V_S}$ *is a covariance matrix of a signal.*

3 Results and discussion

3.1 Top energy

The response matrix (fluence of all charged particles) of signal in the beam loss monitor per one inelastic interacting proton on the collimator jaws in the case of collisions is shown in Table 3.

Table 3: The responses (cm^{-2}) of the beam loss monitors per one lost inelastic proton in each collimators at top energy.

Beam loss monitor	Collimator (j)						
(i)	TCP1(1)	TCS1(2)	TCS2(3)	TCS3(4)	TCS4(5)	TCS5(6)	TCS6(7)
BLM1	0.0391	0.0	0.0	0.0	0.0	0.0	0.0
BLM2	0.5260	0.4635	0.0	0.0	0.0	0.0	0.0
BLM3	0.0205	0.0925	0.4316	0.0019	0.0	0.0	0.0
BLM4	0.0556	0.1736	1.3837	0.4400	0.0	0.0	0.0
BLM5	0.0156	0.0156	0.3689	0.4711	0.2148	0.0	0.0
BLM6	0.0216	0.0181	0.4512	0.6257	0.8341	0.2368	0.0
BLM7	0.0148	0.0123	0.2344	0.3438	0.7082	0.8491	0.1995

The Table 4 gives ratios of fluence of charged particles for collimators (2C) to fluence for collimators (Al + Cu).

Table 4: The ratio of charged particles fluence in the case of the double density carbon collimators (2C) to fluence for collimators (Al + Cu).

Beam loss monitor	Collimator (j)						
(i)	TCP1(1)	TCS1(2)	TCS2(3)	TCS3(4)	TCS4(5)	TCS5(6)	TCS6(7)
BLM1	2.20	0.0	0.0	0.0	0.0	0.0	0.0
BLM2	1.12	0.39	0.0	0.0	0.0	0.0	0.0
BLM3	0.76	3.12	0.40	4.87	0.0	0.0	0.0
BLM4	1.29	4.46	1.28	0.42	0.0	0.0	0.0
BLM5	1.97	4.32	2.67	1.45	0.22	0.0	0.0
BLM6	5.98	10.23	11.70	5.27	1.63	0.24	0.0
BLM7	12.03	17.83	23.63	9.84	4.31	1.67	0.21

By using the definition of the partial signal,

$$p^e_{ij} \quad = \quad m^e_{ij} \cdot r_j \tag{14}$$

it is possible to estimate a size of the "good" signal and the total.

The Table 6 and Figure 4 give the signal size in the beam loss monitors at top energy .

At top energy, size of the "good" signal varies from $1.7 \cdot 10^{-9}$ GeV·cm^{-3} (BLM7) up to $1.2 \cdot 10^{-7}$ GeV·cm^{-3} (BLM1). In contrast to the "good" signal, the range of the total signal has only one order of magnitude. The total reaches minimum value of $1.2 \cdot 10^{-7}$ GeV·cm^{-3} in the BLM1 and maximum value of $1.4 \cdot 10^{-6}$ GeV·cm^{-3} in the BLM2.

By using the definition of the relative partial signal,

$$c^e_{ij} \quad = \quad p^e_{ij}/s_i \tag{15}$$

values of the relative partial contribution for each beam loss monitor of Ring 1 at top energy are presented in Table 7 and in Figure 5.

The BLM1 has "good" spatial resolution (100%), BLM3 (close to TCS2) is only 57.4%. The contribution of "good" signal to the total is

Table 5: The responses (10^{-7}·GeV·cm^{-3}) of the beam loss monitors per one lost inelastic proton in each collimator at top energy.

Beam loss monitor	Collimator (j)						
(i)	TCP1(1)	TCS1(2)	TCS2(3)	TCS3(4)	TCS4(5)	TCS5(6)	TCS6(7)
BLM1	1.383	0.0	0.0	0.0	0.0	0.0	0.0
BLM2	16.075	15.190	0.0	0.0	0.0	0.0	0.0
BLM3	0.609	2.605	14.960	0.078	0.0	0.0	0.0
BLM4	1.939	4.785	43.305	13.790	0.0	0.0	0.0
BLM5	0.512	0.459	11.605	15.540	7.083	0.0	0.0
BLM6	0.581	0.480	14.37	17.250	24.720	8.103	0.0
BLM7	0.393	0.309	7.423	11.510	20.780	26.270	5.824

Table 6: The signal size (GeV·cm^{-3}) in the beam loss monitors per one lost inelastic proton in the momentum cleaning at top energy.

Beam loss monitor	Collimator (j)						
(i)	TCP1(1)	TCS1(2)	TCS2(3)	TCS3(4)	TCS4(5)	TCS5(6)	TCS6(7)
BLM1	$1.171 \cdot 10^{-7}$	0.0	0.0	0.0	0.0	0.0	0.0
BLM2	$1.362 \cdot 10^{-6}$	$6.076 \cdot 10^{-8}$	0.0	0.0	0.0	0.0	0.0
BLM3	$5.158 \cdot 10^{-8}$	$1.042 \cdot 10^{-8}$	$8.378 \cdot 10^{-8}$	$2.504 \cdot 10^{-10}$	0.0	0.0	0.0
BLM4	$1.642 \cdot 10^{-7}$	$1.914 \cdot 10^{-8}$	$2.425 \cdot 10^{-7}$	$4.413 \cdot 10^{-8}$	0.0	0.0	0.0
BLM5	$4.337 \cdot 10^{-8}$	$1.836 \cdot 10^{-9}$	$6.499 \cdot 10^{-8}$	$4.493 \cdot 10^{-8}$	$7.791 \cdot 10^{-9}$	0.0	0.0
BLM6	$4.921 \cdot 10^{-8}$	$1.920 \cdot 10^{-9}$	$8.047 \cdot 10^{-8}$	$5.520 \cdot 10^{-8}$	$2.719 \cdot 10^{-8}$	$8.913 \cdot 10^{-9}$	0.0
BLM7	$3.329 \cdot 10^{-8}$	$1.236 \cdot 10^{-9}$	$4.157 \cdot 10^{-8}$	$3.683 \cdot 10^{-8}$	$2.286 \cdot 10^{-8}$	$2.890 \cdot 10^{-8}$	$1.747 \cdot 10^{-9}$

- 4% for BLM2
- 9% for BLM4
- 5% for BLM5
- 4% for BLM6
- 1% for BLM7

The TCP1 gives the major contribution to the background for the BLM2 (96%) and BLM7 (20%) monitors.

3.2 Signal from Ring 2

Let us try to estimate a signal size ($\Delta\vec{S}_2$) induced by Ring 2. The results presented in Figure 6 were obtained in approach B (see explanation above).

As it is simple to see from Figure 6, the signal size induced by Ring 2 does not exceed 1% (BLM3) from the total signal. However, the ratio of the total signal from Ring 2 to the "good" signal induced by Ring 1 can reach 21% for the BLM7.

Table 7: Ratio of partial signal to the total in the beam loss monitors at top energy.

Beam loss monitor	Collimator (j)						
(i)	TCP1(1)	TCS1(2)	TCS2(3)	TCS3(4)	TCS4(5)	TCS5(6)	TCS6(7)
BLM1	1.0000	0.0	0.0	0.0	0.0	0.0	0.0
BLM2	0.9573	0.0427	0.0	0.0	0.0	0.0	0.0
BLM3	0.3532	0.0714	0.5737	0.0017	0.0	0.0	0.0
BLM4	0.3494	0.0407	0.5160	0.0939	0.0	0.0	0.0
BLM5	0.2586	0.0111	0.3875	0.2965	0.0465	0.0	0.0
BLM6	0.2208	0.0086	0.3610	0.2476	0.1220	0.0400	0.0
BLM7	0.2000	0.0074	0.2498	0.2213	0.1373	0.1736	0.0105

By repeating the same arguments for left size position of the BLM, we can try to estimate a variation of the signal induced by Ring 2 (see Figure 7).

In this case the signal size induced by Ring 2 is about of 10% (BLM5-BLM7) from the total signal. The total signal from Ring 2 can exceed the "good" signal induced by Ring 1. For example, the "good" signal in the BLM7 is 7 times less than the signal induced by Ring 2.

During adjustment of the cleaning system mistakes are possible. We can consider a scenario when the the TCP1 collimator is mistuned. That is all primary halo is intercepted by the TCS1 collimator (see Figure 8). In this case the contribution to a signal from Ring 2 will make 100%.

3.3 Transverse distribution of signal

3.4 Whether there are other way to measure a proton losses ?

There is a correlation between partial energy deposition (temperature) in the collimator jaws and the partial signals in the beam loss monitors.

3.5 Injection

The Table 8 gives the response matrix (signal is a proportional energy deposition density) in the case of injection.

Values of the relative partial contribution for each beam loss monitor of Ring 1 at injection are presented in Table 10.

Table 8: The responses in GeV$\cdot$ cm^{-3} of the beam loss monitors per one lost inelastic proton in each collimator at injection.

Beam loss monitor	Collimator (j)						
(i)	TCP1(1)	TCS1(2)	TCS2(3)	TCS3(4)	TCS4(5)	TCS5(6)	TCS6(7)
BLM1	$5.42\cdot10^{-8}$	0.0	0.0	0.0	0.0	0.0	0.0
BLM2	$2.90\cdot10^{-8}$	$4.11\cdot10^{-7}$	0.0	0.0	0.0	0.0	0.0
BLM3	$3.03\cdot10^{-10}$	$2.27\cdot10^{-10}$	$2.87\cdot10^{-7}$	$2.38\cdot10^{-9}$	0.0	0.0	0.0
BLM4	$3.45\cdot10^{-10}$	$4.03\cdot10^{-10}$	$4.04\cdot10^{-7}$	$2.91\cdot10^{-7}$	0.0	0.0	0.0
BLM5	$1.80\cdot10^{-11}$	$8.57\cdot10^{-12}$	$2.77\cdot10^{-8}$	$4.82\cdot10^{-8}$	$1.57\cdot10^{-7}$	0.0	0.0
BLM6	$1.22\cdot10^{-11}$	$5.80\cdot10^{-12}$	$1.49\cdot10^{-8}$	$2.27\cdot10^{-8}$	$1.50\cdot10^{-7}$	$1.33\cdot10^{-7}$	0.0
BLM7	$1.05\cdot10^{-11}$	$3.41\cdot10^{-12}$	$4.18\cdot10^{-9}$	$9.94\cdot10^{-9}$	$5.19\cdot10^{-8}$	$1.50\cdot10^{-7}$	$1.16\cdot10^{-7}$

Table 9: The signal size (GeV$\cdot cm^{-3}$) in the beam loss monitors per one lost inelastic proton in the momentum cleaning at injection.

Beam loss monitor	Collimator (j)						
(i)	TCP1(1)	TCS1(2)	TCS2(3)	TCS3(4)	TCS4(5)	TCS5(6)	TCS6(7)
BLM1	$3.62\cdot10^{-8}$	0.0	0.0	0.0	0.0	0.0	0.0
BLM2	$1.94\cdot10^{-8}$	$5.75\cdot10^{-8}$	0.0	0.0	0.0	0.0	0.0
BLM3	$2.02\cdot10^{-10}$	$3.18\cdot10^{-11}$	$2.61\cdot10^{-8}$	$1.26\cdot10^{-10}$	0.0	0.0	0.0
BLM4	$2.30\cdot10^{-10}$	$5.65\cdot10^{-11}$	$3.68\cdot10^{-8}$	$1.54\cdot10^{-8}$	0.0	0.0	0.0
BLM5	$1.20\cdot10^{-11}$	$1.20\cdot10^{-12}$	$2.52\cdot10^{-9}$	$2.55\cdot10^{-9}$	$3.46\cdot10^{-9}$	0.0	0.0
BLM6	$8.17\cdot10^{-12}$	$8.12\cdot10^{-13}$	$1.35\cdot10^{-9}$	$1.20\cdot10^{-9}$	$3.30\cdot10^{-9}$	$2.67\cdot10^{-9}$	0.0
BLM7	$7.00\cdot10^{-12}$	$4.77\cdot10^{-13}$	$3.80\cdot10^{-10}$	$5.27\cdot10^{-10}$	$1.14\cdot10^{-9}$	$3.00\cdot10^{-9}$	$6.97\cdot10^{-10}$

4 Conclusions

Summarizing the main results we can mark the following:

- The response matrix has a triangular form only for Ring1
- The response matrix depends on impact parameters, layout (collimator + beam pipe + BLM + shielding), the BLM position and Z material.
- At top energy, the BLM1 has the "good" spatial resolution.
- At injection, the BLM1-BLM3 have the "good" spatial resolution
- At top energy, the TCP1 is one of major source of background in the BLMs (96% for BLM2)
- Background signal from the Ring2 depends on the BLM position. It does not exceed 1% (BLM3) in the case of the total. Background comes to 21% (BLM7) in the case of the "good" signal. Background from the Ring2 can exceed size of signal from Ring 1 more than in 7 times.

Table 10: Ratio of partial signal to the total in the beam loss monitors at injection.

Beam loss monitor	Collimator (j)						
(i)	TCP1(1)	TCS1(2)	TCS2(3)	TCS3(4)	TCS4(5)	TCS5(6)	TCS6(7)
BLM1	1.0000	0.0	0.0	0.0	0.0	0.0	0.0
BLM2	0.2519	0.7481	0.0	0.0	0.0	0.0	0.0
BLM3	0.0076	0.0012	0.9864	0.0048	0.0	0.0	0.0
BLM4	0.0044	0.0010	0.7004	0.2942	0.0	0.0	0.0
BLM5	0.0014	0.0001	0.2946	0.2989	0.4049	0.0	0.0
BLM6	0.0010	0.0001	0.1584	0.1407	0.3873	0.3125	0.0
BLM7	0.0012	0.0001	0.0660	0.0916	0.1984	0.5215	0.1212

- There is a correlation between partial energy deposition (temperature) in the collimator jaws and the partial signals in the beam loss monitors
- Actually, the dependence of a signal is more complex (see case C)
- For collimator jaws made of double density carbon, good signal is less than in the case of old design, but background is more.
- Besides, we can expect a fatal consequences in the momentum cleaning at top energy. The integrated efficiency of the momentum cleaning system defined as a flux of energy leaking from the insertion divided by the one proton intercepted by collimators is equal to $5.0 \cdot 10^{-3}$ for protons with energy above 5000 GeV. It can induce quenches in coils of the quadrupole Q7.

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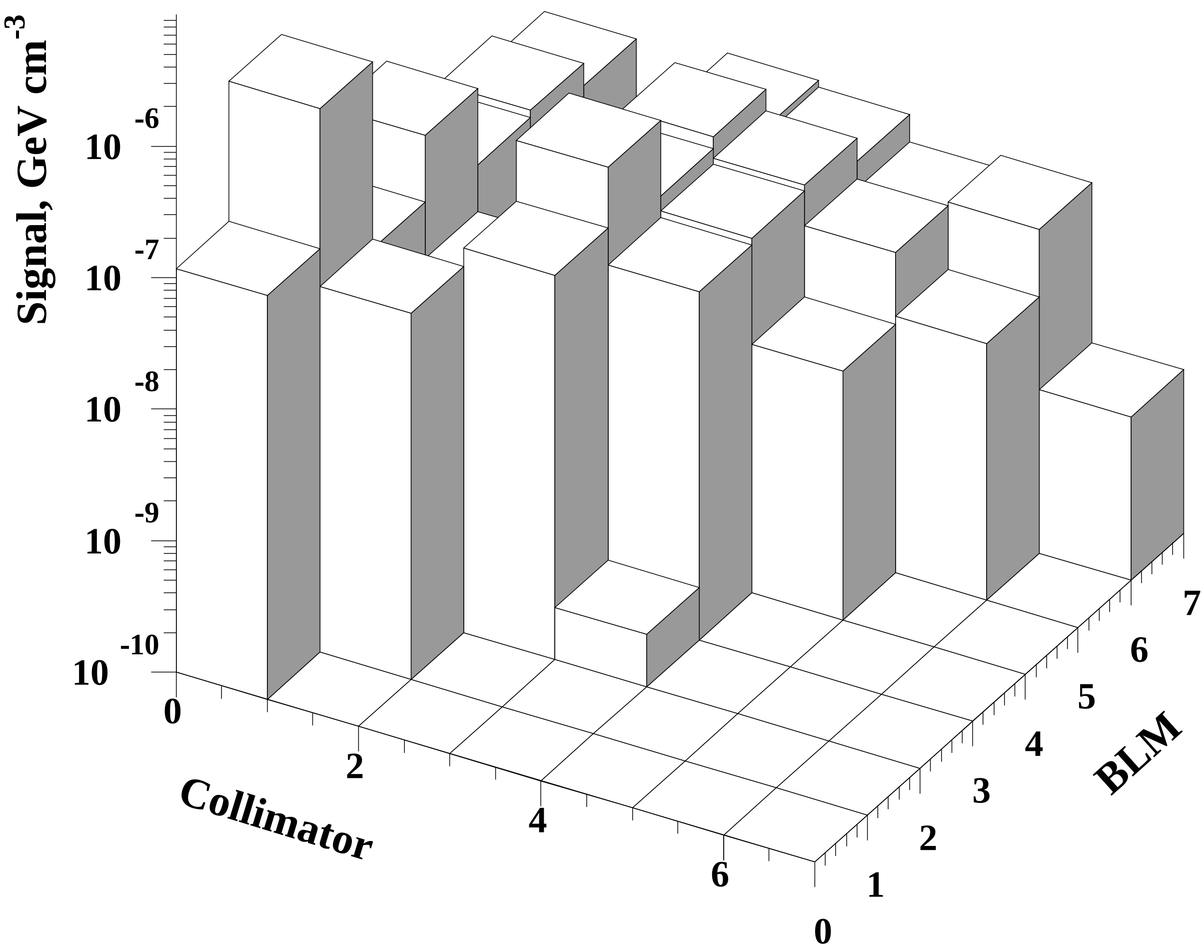

Figure 4: Partial signal (only from Ring 1) in the beam loss monitors at top energy.

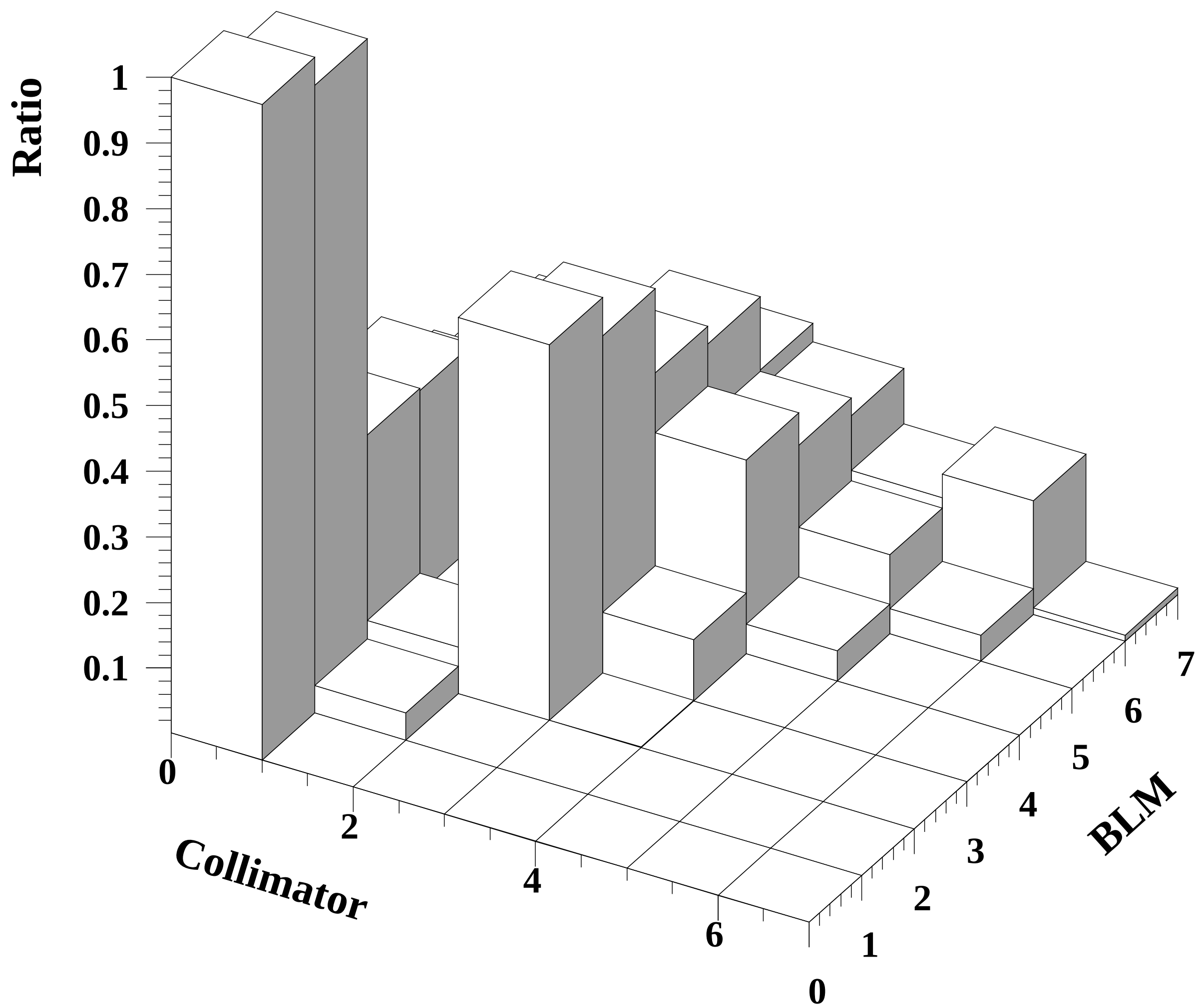

Figure 5: Relative partial contribution to the BLM signal from the momentum cleaning collimators at top energy.

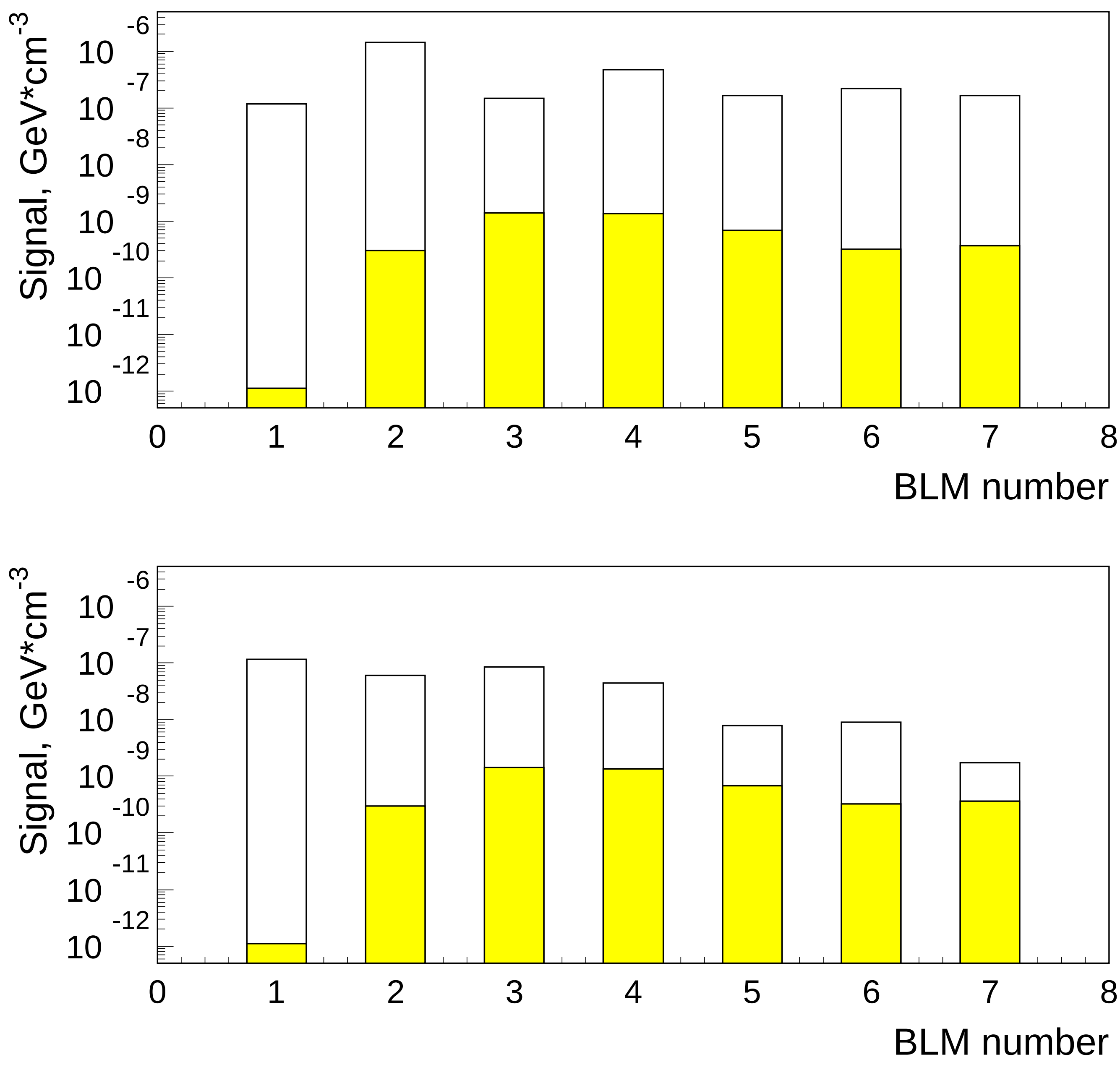

Figure 6: Signal size distribution along the beam loss monitors at top energy: (a) – the clear histogram is the total signal from Ring 1, the grey histogram - the total from Ring 2; (b) – the clear histogram is the "good" signal from Ring 1, the grey histogram - the total from Ring 2.

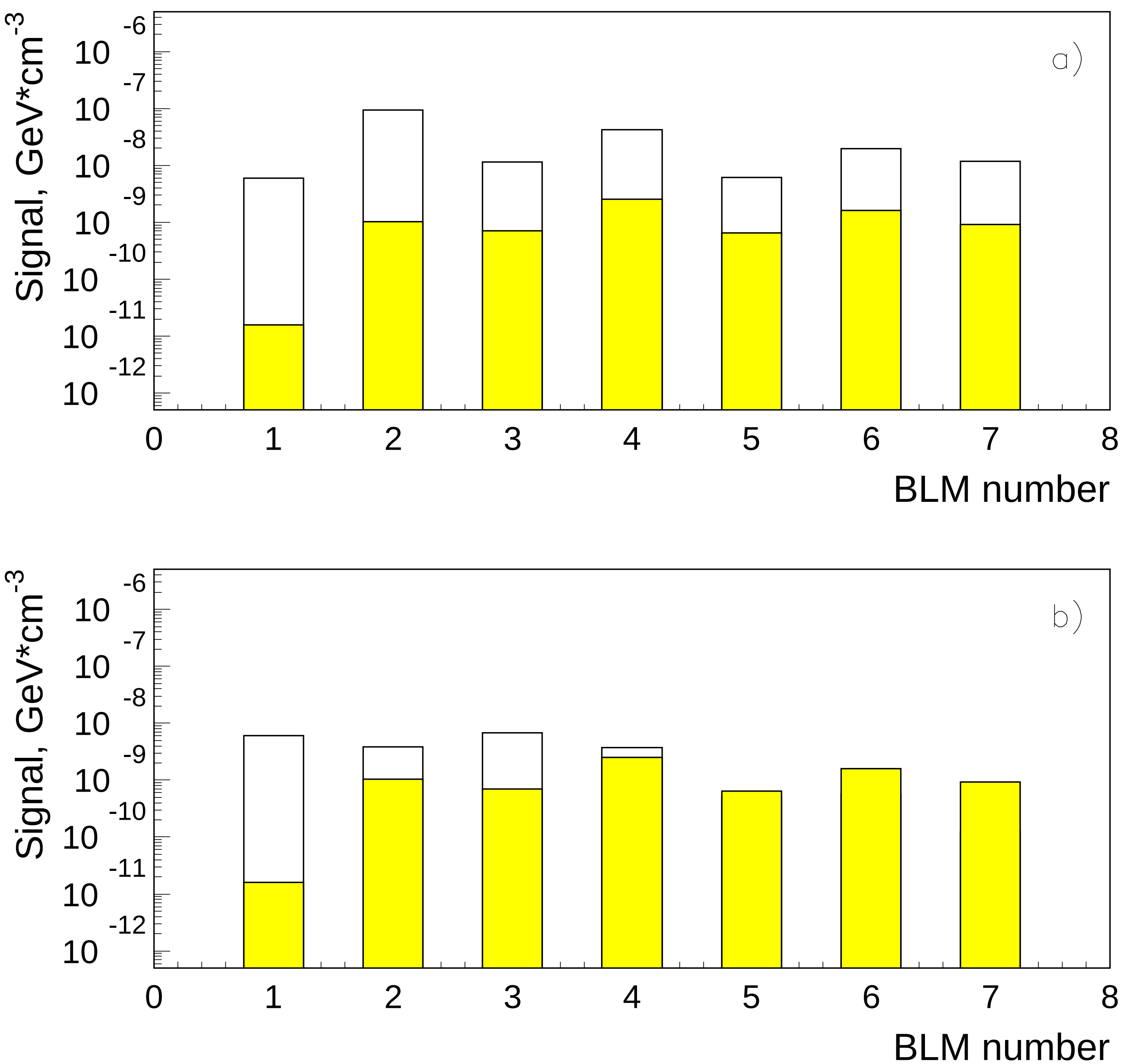

Figure 7: Signal size distribution along the beam loss monitors (left side position) at top energy: (a) – the clear histogram is the total signal from Ring 1, the grey histogram - the total from Ring 2; (b) – the clear histogram is the "good" signal from Ring 1, the grey histogram - the total from Ring 2.

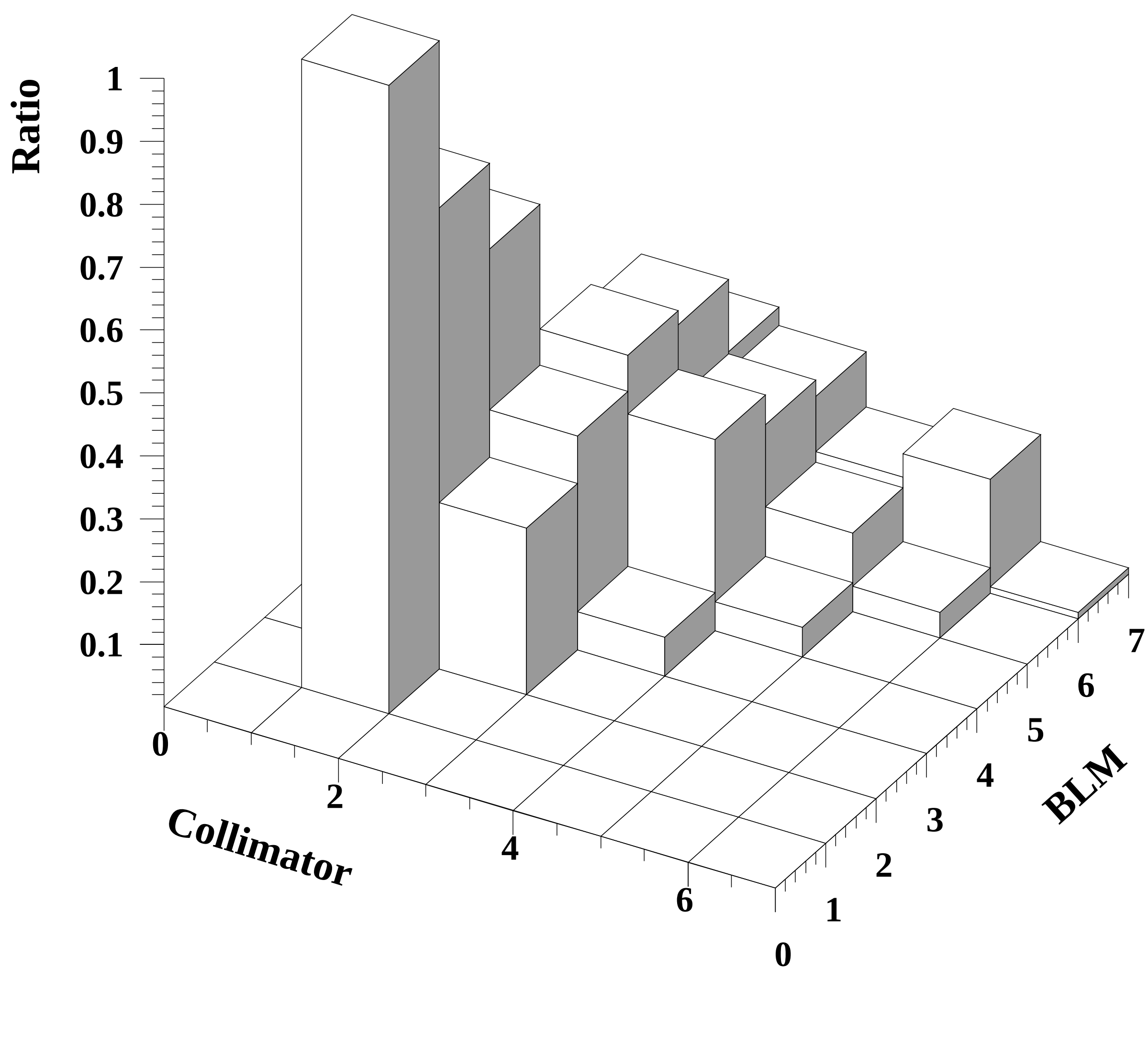

Figure 8: Relative partial contribution to the BLM signal from all collimators in the case of mistuning. All pripary halo is intercepted by the TCS1 collimator.

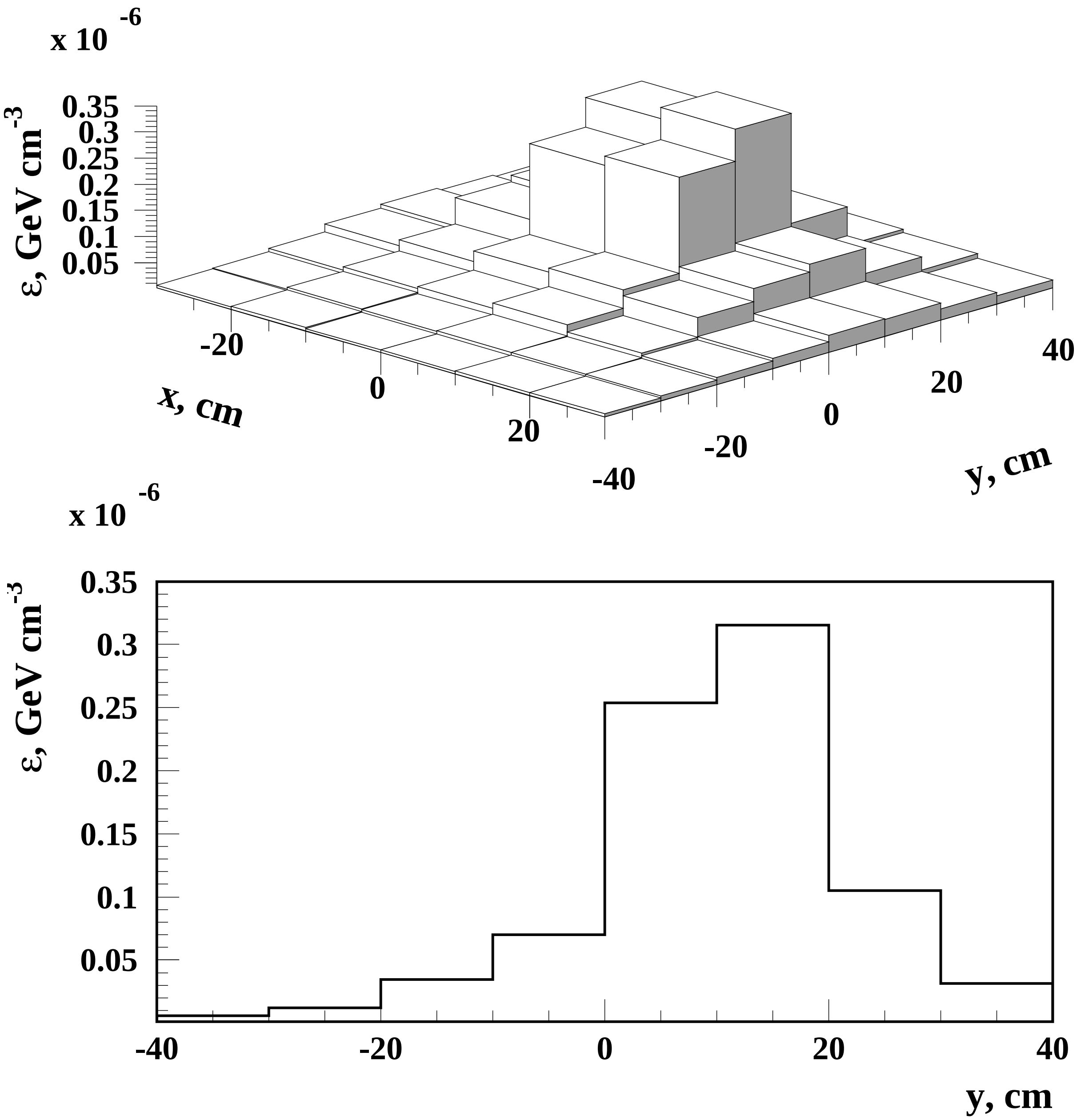

Figure 9: Transverse distribution of energy deposition density in air at position of beam loss monitor close to TCP1 from proton interactions on primary collimators.

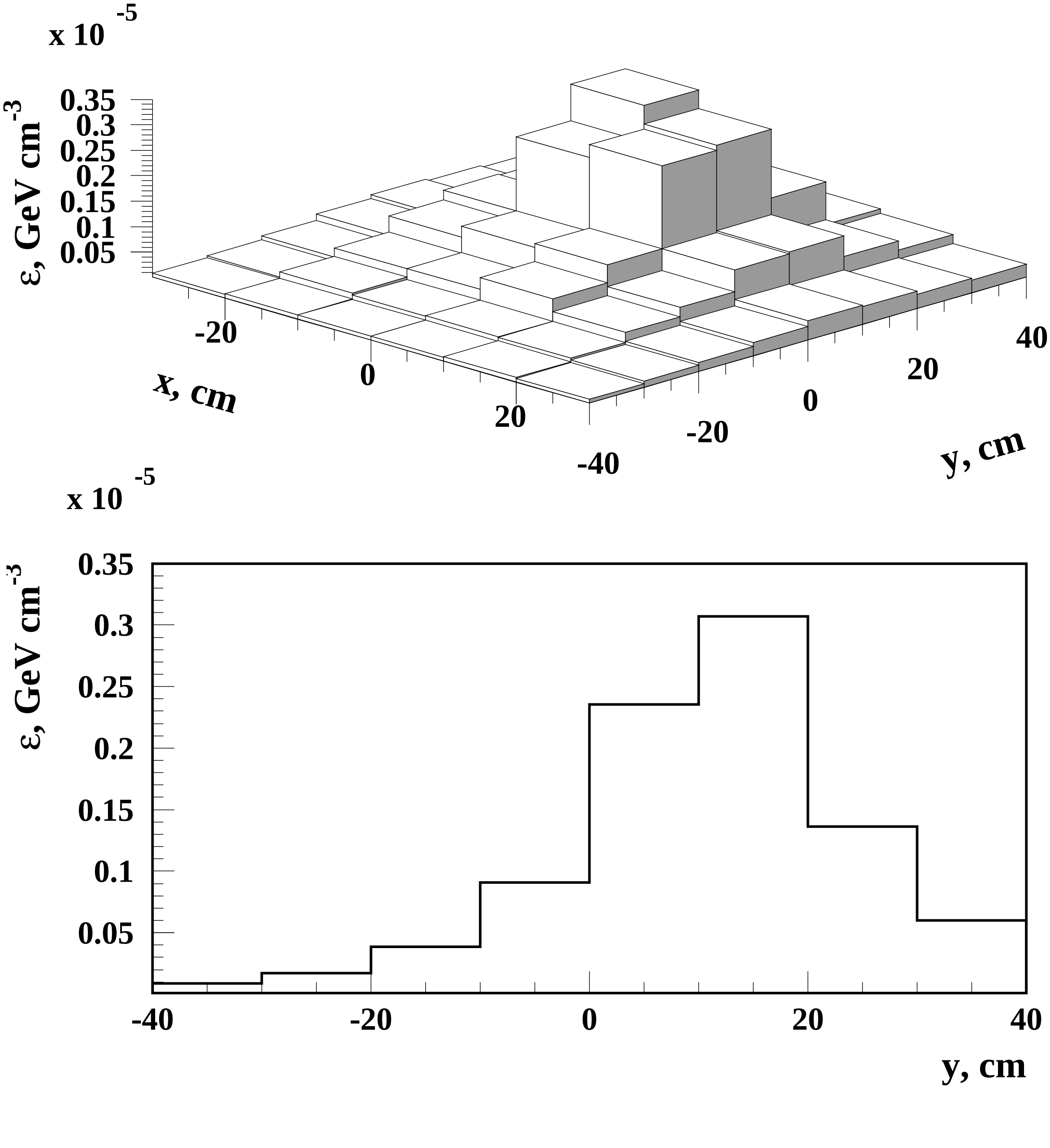

Figure 10: Transverse distribution of energy deposition density in air at position of beam loss monitor close to TCS1 from proton interactions on primary collimators.

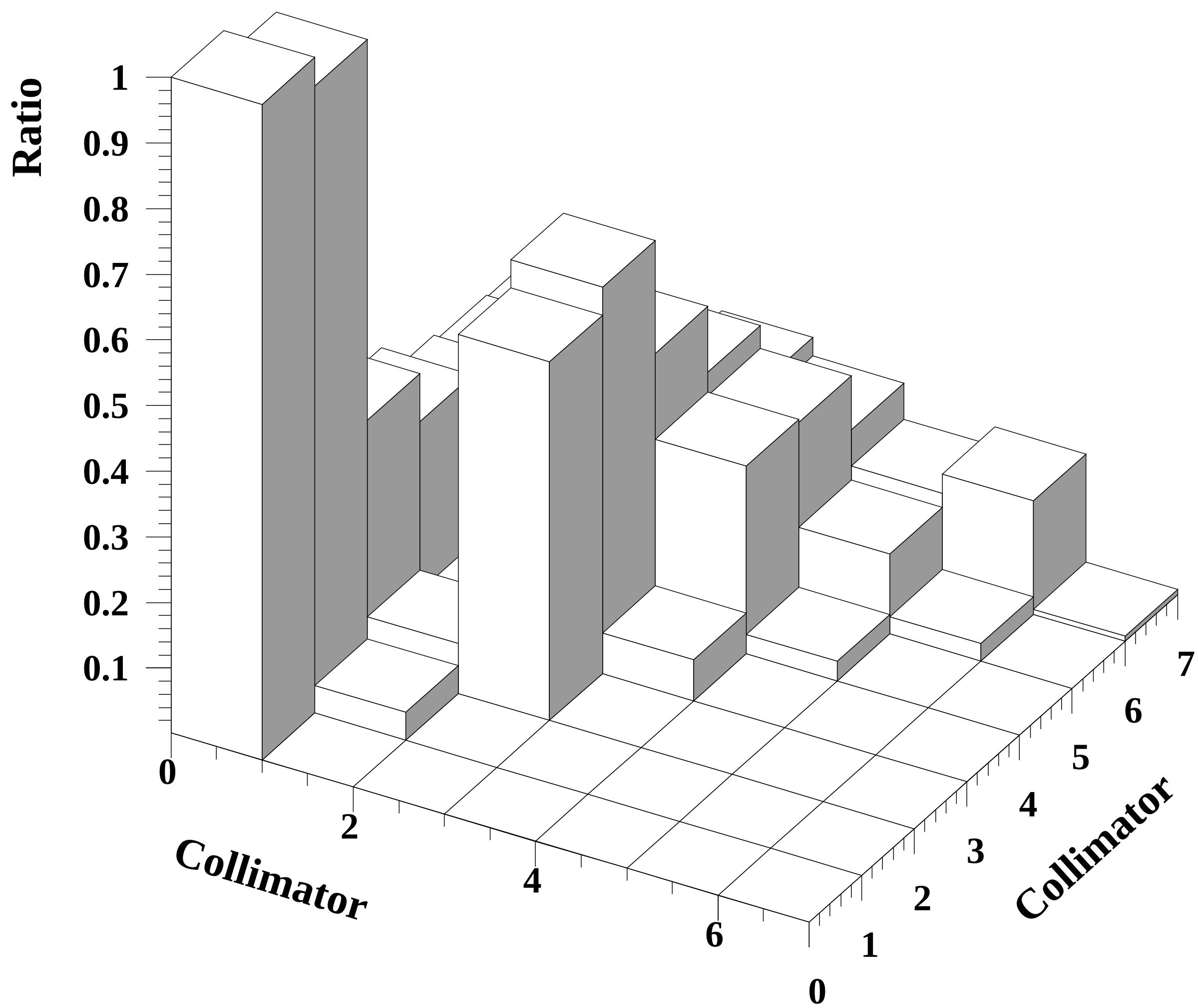

Figure 11: Relative partial contribution to the energy deposition in jaws from all collimators at top energy.

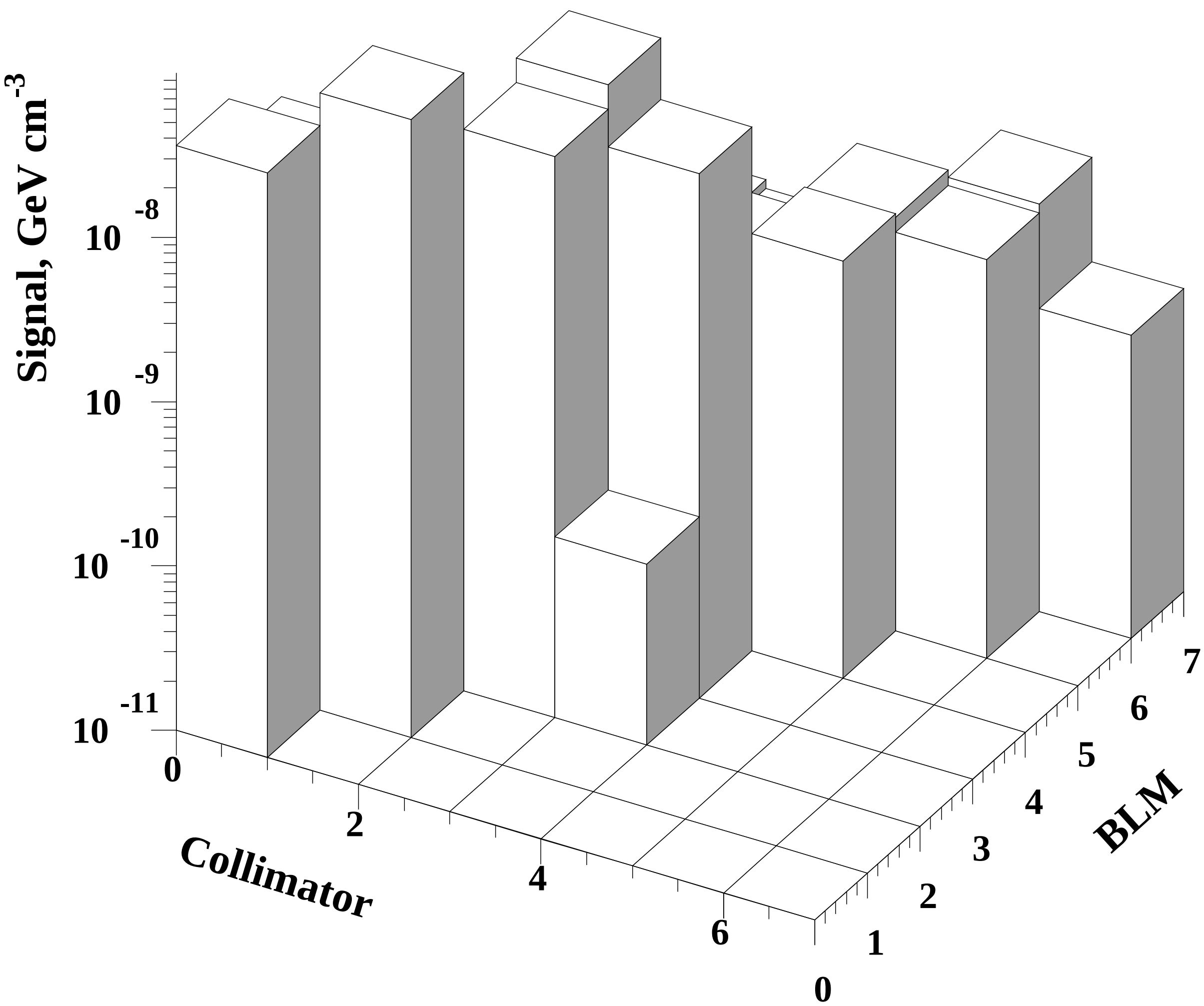

Figure 12: Partial signal in the beam loss monitors of Ring 1 at injection.

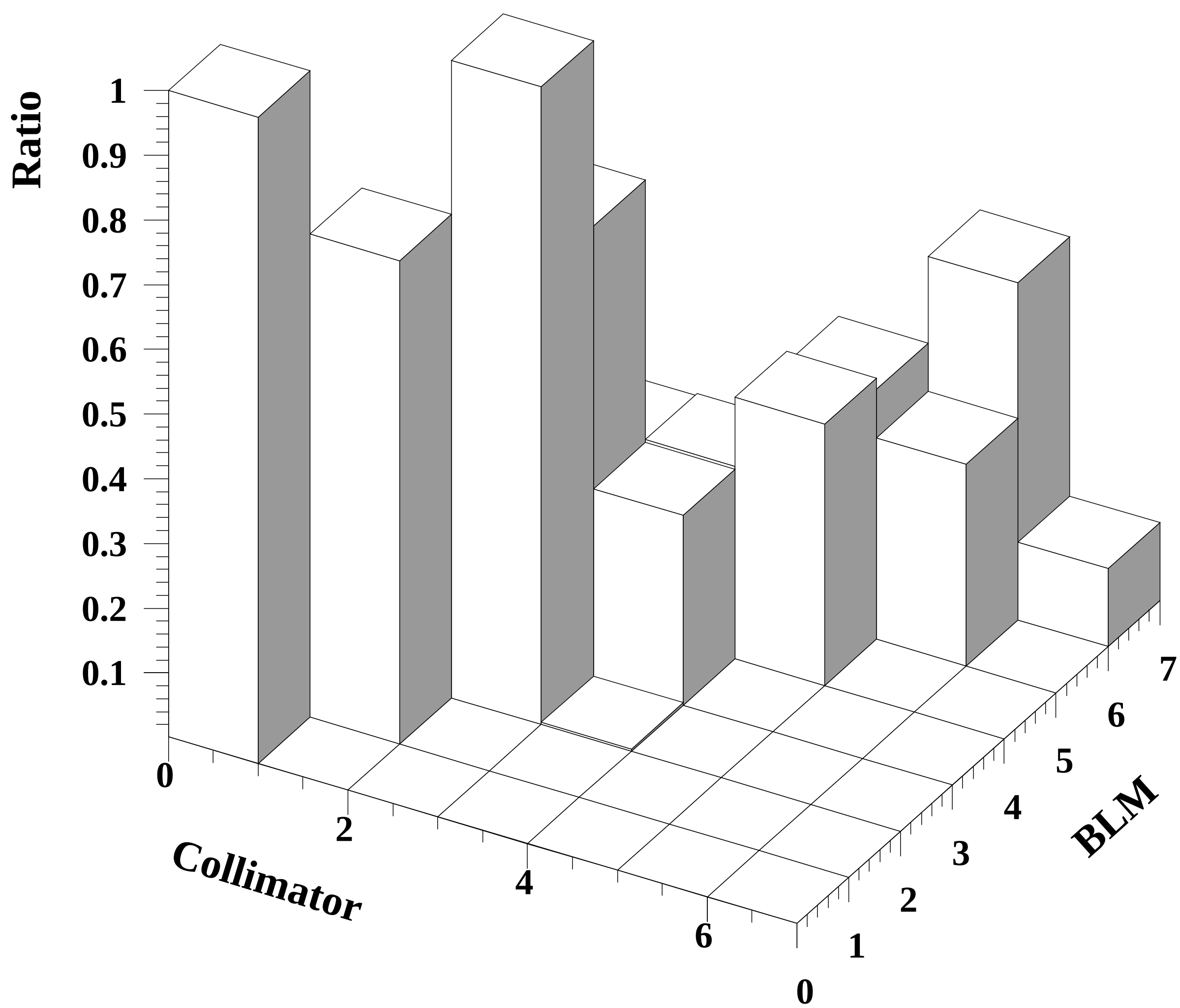

Figure 13: Relative partial contribution to the BLM signal from all collimators at injection.