Report on PARIS Calorimeter Simulations – reconstruction of high energy gamma

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Abstract

This report summarizes simulations for the PARIS calorimeter. Investigated set consisted of one- and two-shell cubic geometry. Materials used: LaBr3 and CsI. We focused on absorption coefficient, energy deposit and reconstruction algorithm. Whole simulation work presented in this report was done at Institute of Nuclear Physics of Polish Academy of Science in Krakow.

1. Introduction

Another step in PARIS simulation process was to work on a new geometry consisting of 200 LaBr3 cubic crystals forming shell which covers almost 4π angle. We performed basic simulations with crystals of two sizes 2"x2"x2" and 4"x2"x2". Characteristics investigated included efficiency of absorption and energy deposit for discreet gamma and for GDR-type emission. Next phase resulted in adding 200 CsI 6"x2"x2" crystals and performing the same set of simulation. We also focused on coming up with a reasonable reconstruction algorithm. The simulations are performed with the GEANT4 [1] package and data analysis is done with ROOT.

2. New geometry

The new geometry consisting of 200 LaBr3 crystals was constructed basing on an AutoCad file of John Strachan from Daresbury Laboratory, UK. The source file included coordinates of the center of the crystals as well as information about their rotation. All together this lead to creating ParisSegmentedDetectorConstructionNew.cc, another geometry in Paris package. In Fig.1 one can see the visualization of proposed geometry (we also implemented a beam pipe entrance which is not visible on this figure).

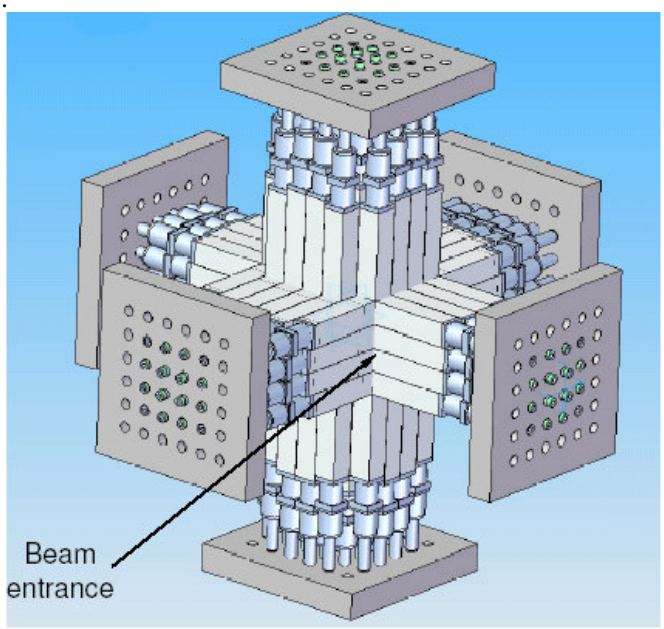


Fig.1 Visualization of geometry proposed by J.Strachan [2]

The main idea in constructing such geometry was to define a new structure *Labr3Crystal* which would hold information read from file about position coordinates and rotation. There would also be a vector *crystals* which items include above mentioned structures.\\

```
struct LaBr3Crystal{
G4double trans_cx;
G4double trans_cy;
G4double trans_cz;
G4double trans_vx;
G4double trans_vy;
G4double trans_vz;
G4int rotation;}
```

Coordinates cx,cy,cx indicate position of the center when vx,vy,vz are coordinates 1mm away from the center to give an axis to the crystal. So the difference between any two pairs of coordinates (for ex. cx and vx) implies that the main axis is in x direction in the frame of the world volume. The resulting geometries are shown in Fig.2

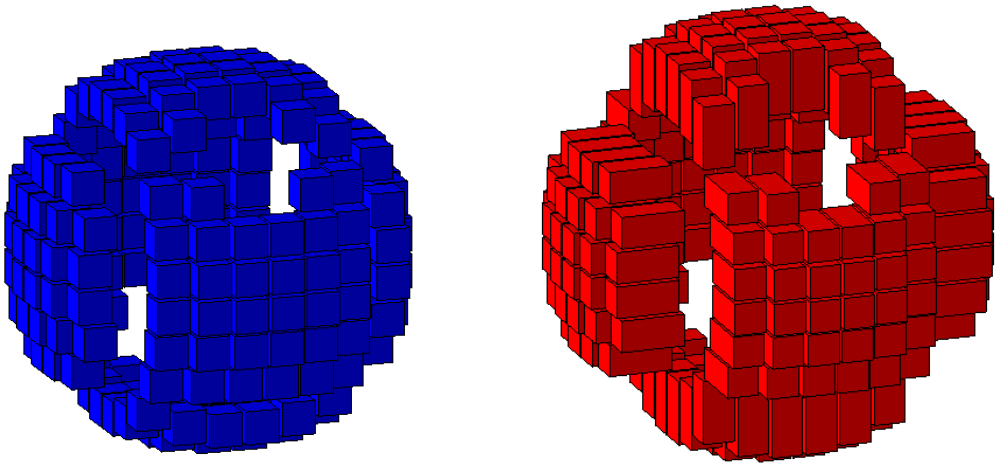


Fig.2 Geometries constructed from 200 2"x2"x2" LaBr3 (left) and 200 4"x2"x2" LaBr3 crystals (right, ParisSDCRotated.cc)

This kind of geometry covers almost whole 4π angle and it also provides an entrance for the beam pipe. Another upgrade consists in adding 200 6"x2"x2" CsI crystals, cf. Fig. 3.

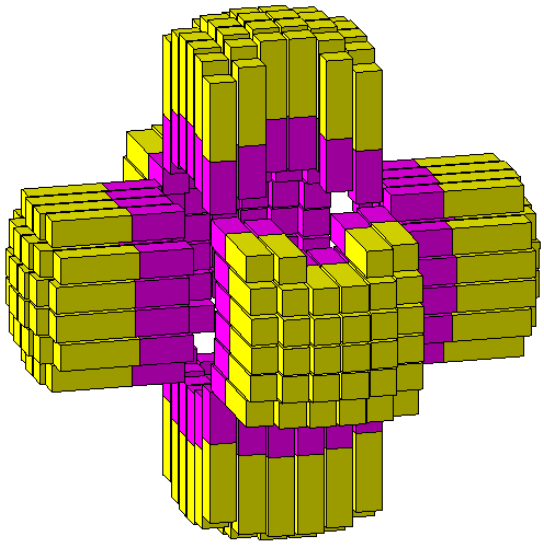


Fig.3 Geometry constructed from 200 4"x2"x2" LaBr3 and 200 6"x2"x2" CsI crystals, ParisSDCRotatedCsI.cc

As can be seen in the analysis and comparison in the next chapter, the latter geometry provides better parameters.

3. Simulation and analysis

To perform a simulation one needs to specify four basic aspects such as:

- Output Manager (analysis)
- Detector geometry
- Physics list
- γ generator

We used: output in the form of a ROOT file (holds information about primary gammas, energy accumulated in detectors etc.), geometry as specified before, standard EM physics and basic energy gamma generator (set of discreet energies propagating from the source point into 4π angle). The aim of the simulation was to see how γ-rays radiate in LaBr$_3$ and CsI, to calculate absorption coefficient and to obtain energy spectra. Fig. 4.

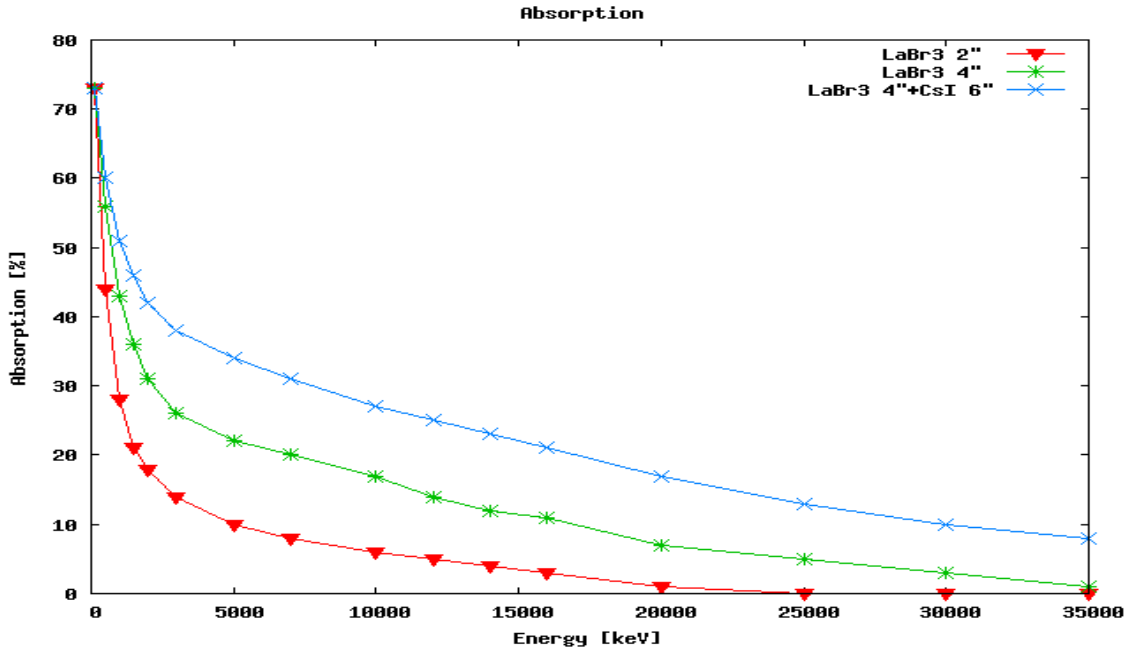


Fig. 4 Absorption coefficient depending on geometry and energy of γ-ray

This shows comparison in absorption coefficient for three different geometry configurations. Geometry with LaBr3+CsI is the most efficient but decreasing absorption with increasing energy trend stays the same for those three cases. For example: for energy 10 MeV absorption coefficient is 27%, 17% and 7% for 2", 4" and 6" CsI, whereas for 2 MeV it is 42%, 31% and 18% respectively. Corresponding energy spectra (obtained as a sum of energy from all detectors in 4π angle; that is why second escape peak is not visible and first escape peak is little intensive) look as follows. In this case simulation was performed with 10^6 events. Fig. 5.

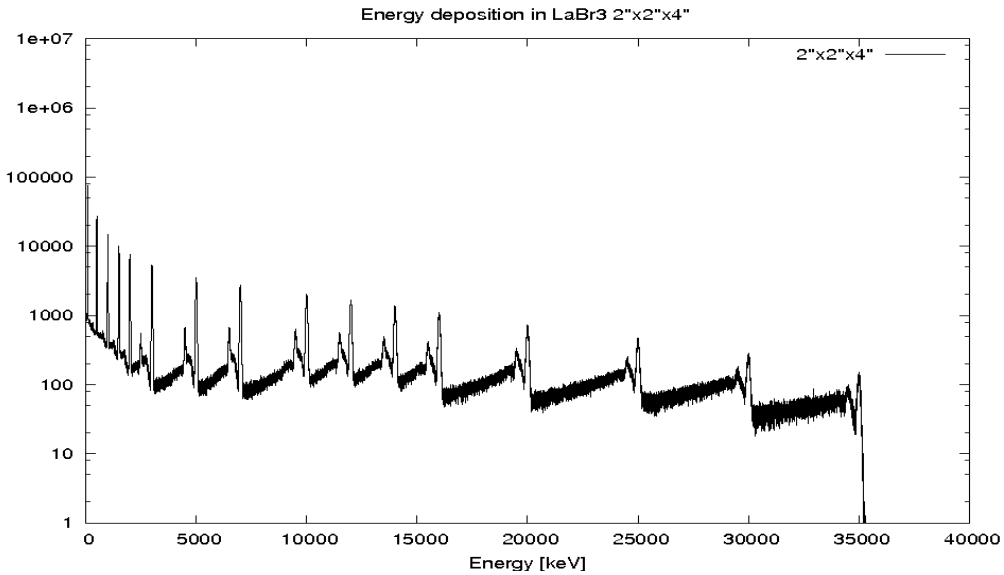


Fig. 5 Energy deposition in 2"x2"x4" LaBr3 crystals

More relevant would be to attach a comparison in energy deposition with respect to geometry type.

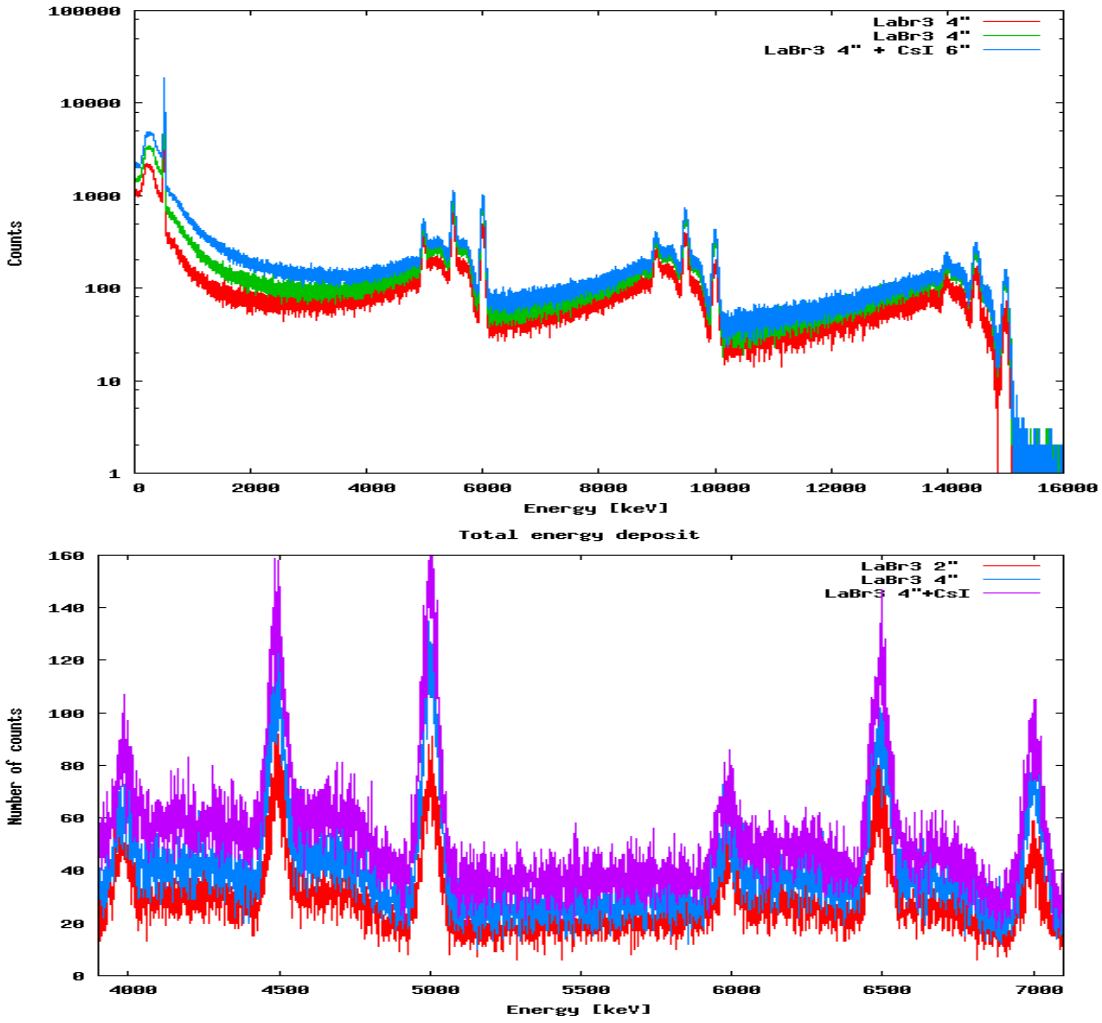


Fig. 6 Comparison in energy deposition for 5,10,15 MeV (top) and 5, 7 MeV gammas.

On the above spectra one can clearly see main peak, as well as first and second escape peaks and also a hump responsible for Compton scattering. It is also clearly visible that geometry including CsI provides best statistics.

3.1 Reconstruction algorithm

Another goal was to implement a reconstruction algorithm for scattered γ-rays (done in analysis phase). In the range of higher energies i.e. above 4 MeV, only cross section for pair creation plays an important role. Fig. 7.

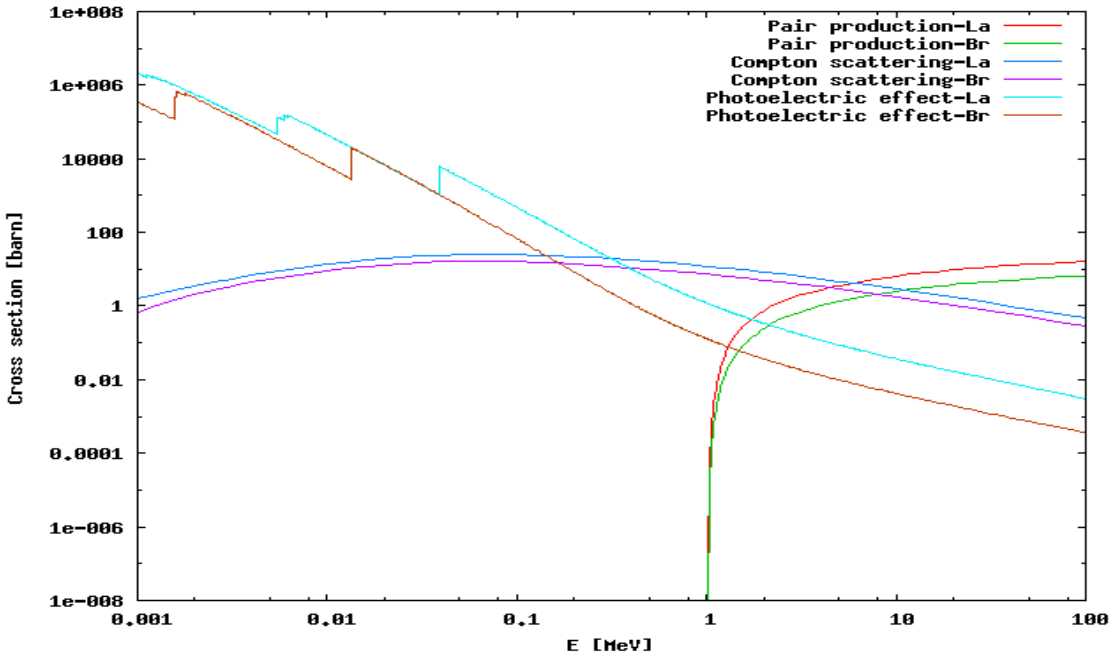


Fig.7 Cross section for interaction of γ with matter, for La(Z=57) and Br(Z=35)

Because of that idea of reconstruction was simply to locate high energy gamma and sum two 511 keV energies found among their neighbours. Detailed algorithm is listed below:

- Construct list of neighbours for all crystals (radius based on crystals' dimensions)
- Find a crystal in which accumulated energy is higher than a threshold - 4 MeV
- Search for 511 keV energies among neighbours of the central crystal
- If two 511 keV are on opposite sides -> add them up to the main one (cf. physics of pair production)
- Continue usual procedure with remaining crystals(fill histogram separately with each energy)

After running couple of simulations it came clear that although the algorithm was proper and working well, the improvement itself wasn't very big. Below we present sample illustration of this algorithm.

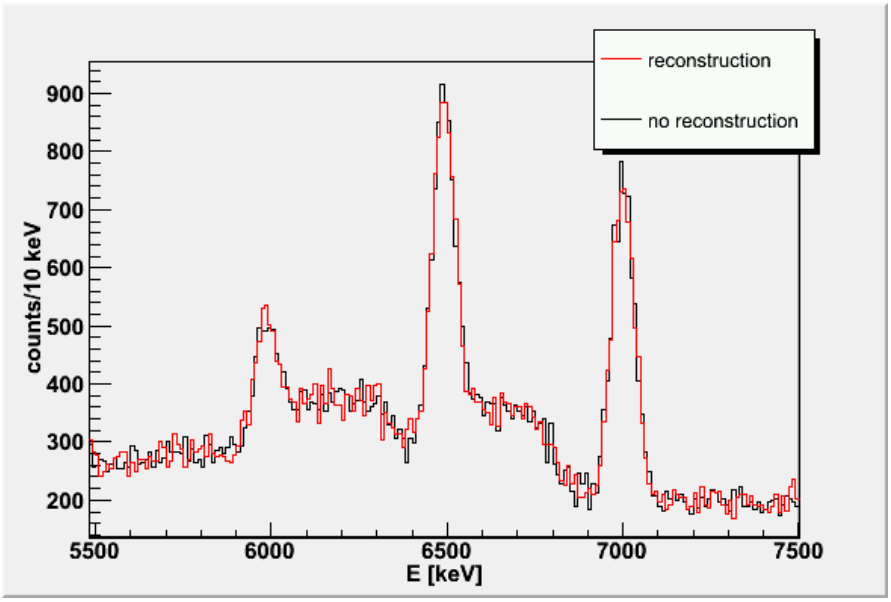
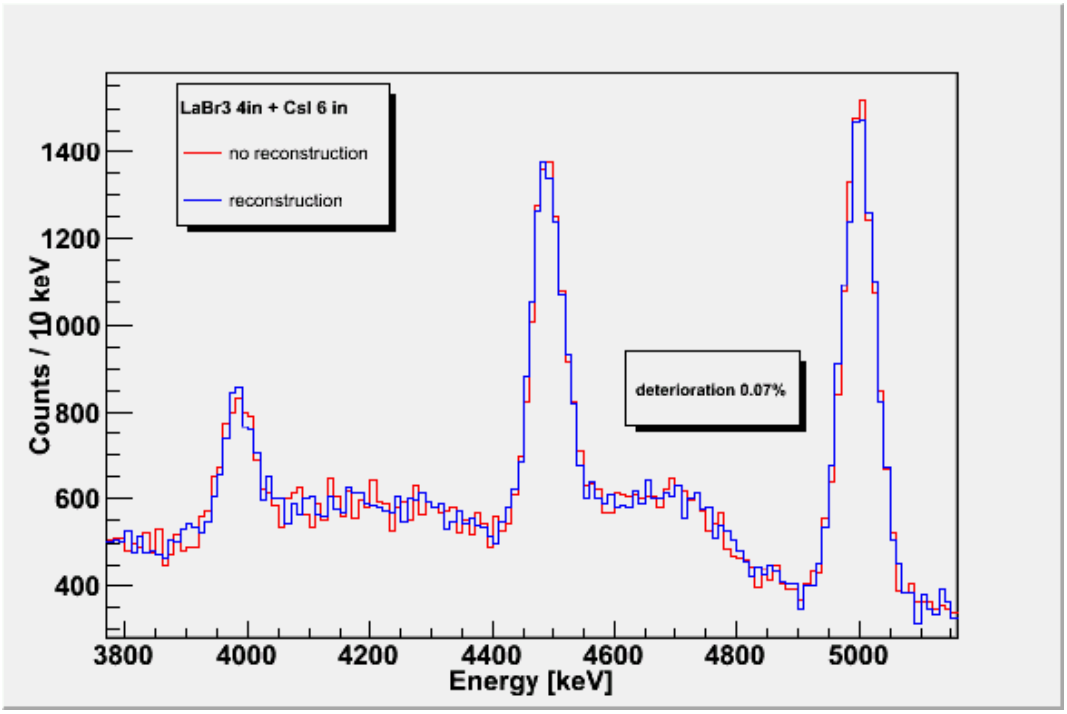
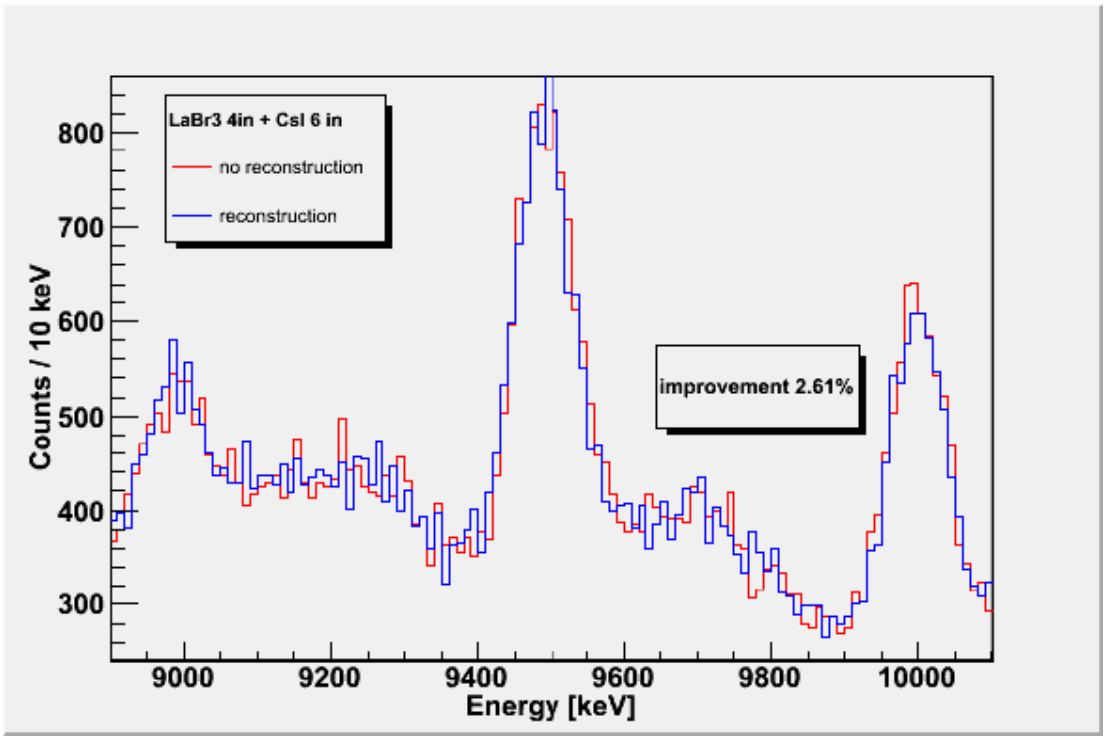
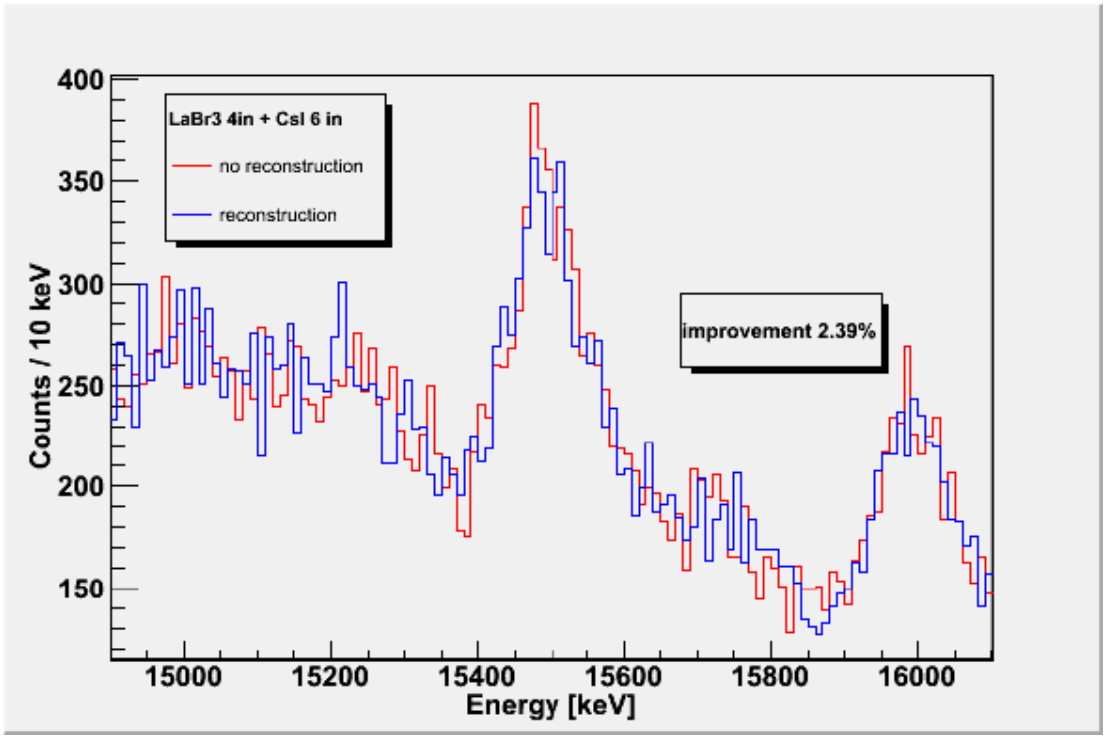


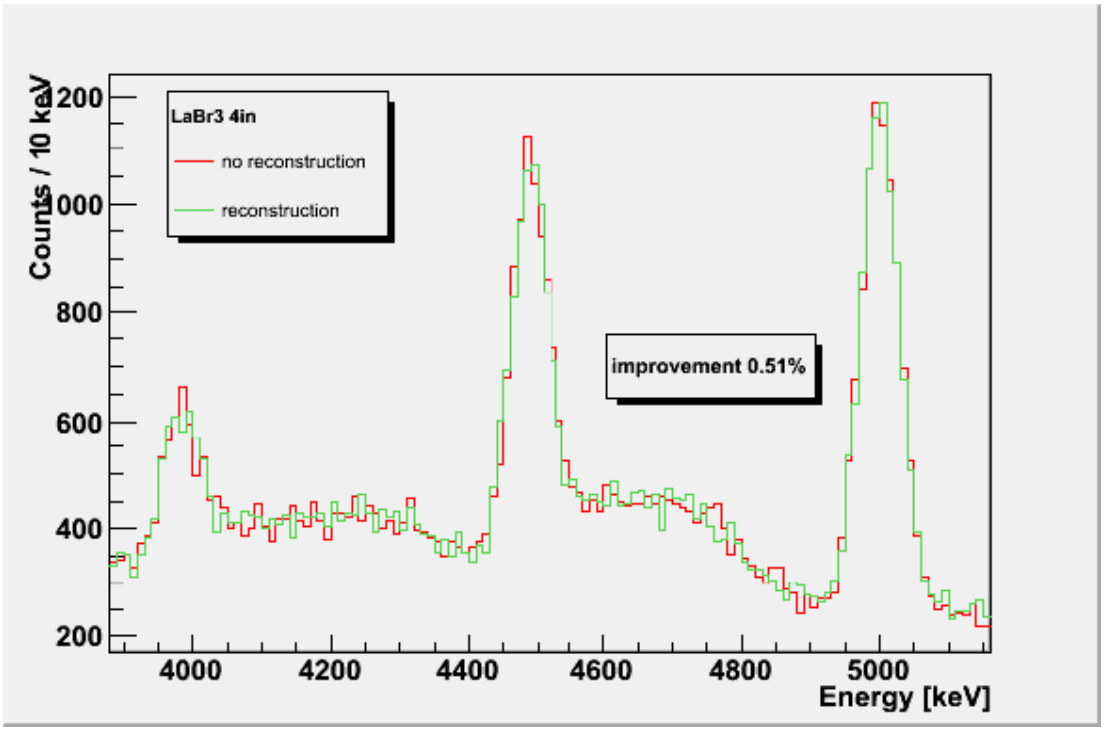
Fig. 8 Result of implementation of reconstruction algorithm

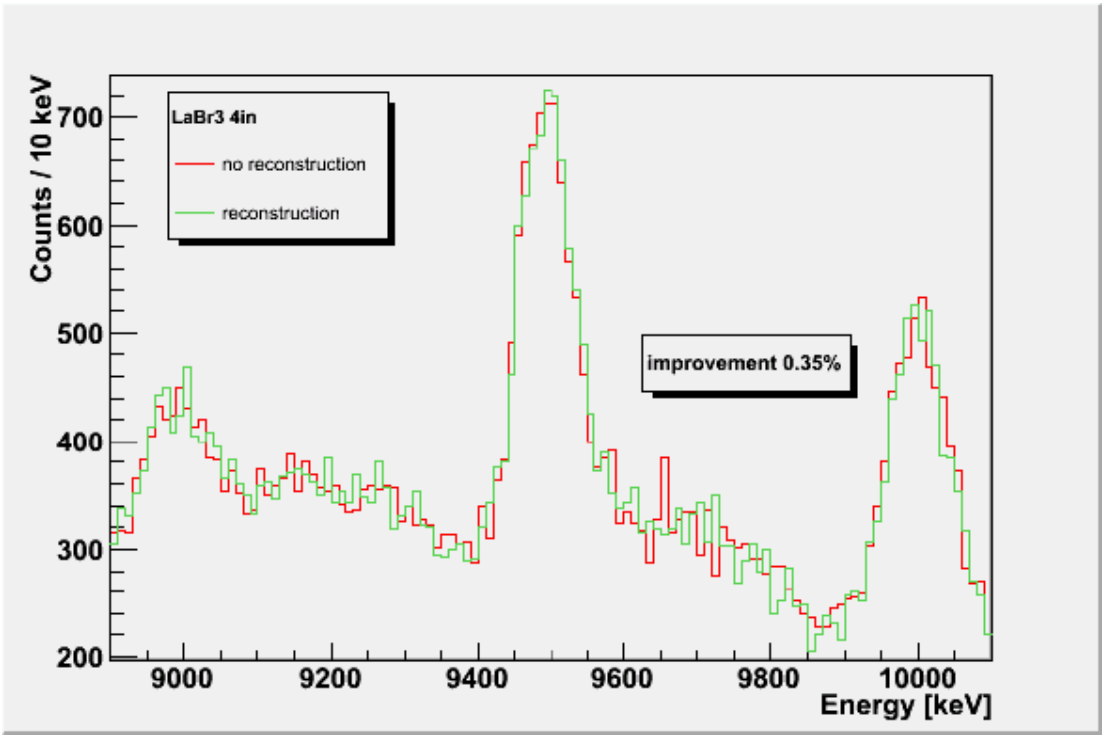
In the next 6 figures one can see detailed comparison in spectra for LaBr3 and CsI geomteries for a range of energies. Listed percentage gives improvement/deterioration in counts in peak for reconstructed spectra referred to non-reconstructed ones. Because of high fluctuations and low statistics (10^5 events) counts are listed per every 10 keV.Fig. 9.




LaBr3 4in + CsI 6 in
no reconstruction
reconstruction
improvement 2.61%
Counts / 10 keV
Energy [keV]
800
700
600
500
400
300
9000
9200
9400
9600
9800
10000


LaBr3 4in + CsI 6 in
no reconstruction
reconstruction
improvement 2.39%
Counts / 10 keV
Energy [keV]
400
350
300
250
200
150
15000
15200
15400
15600
15800
16000


LaBr3 4in
no reconstruction
reconstruction
improvement 0.51%
Counts / 10 keV
Energy [keV]
200
400
600
800
1000
4000
4200
4400
4600
4800
5000


LaBr3 4in
no reconstruction
reconstruction
improvement 0.35%
Counts / 10 keV
Energy [keV]
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300
400
500
600
700
9000
9200
9400
9600
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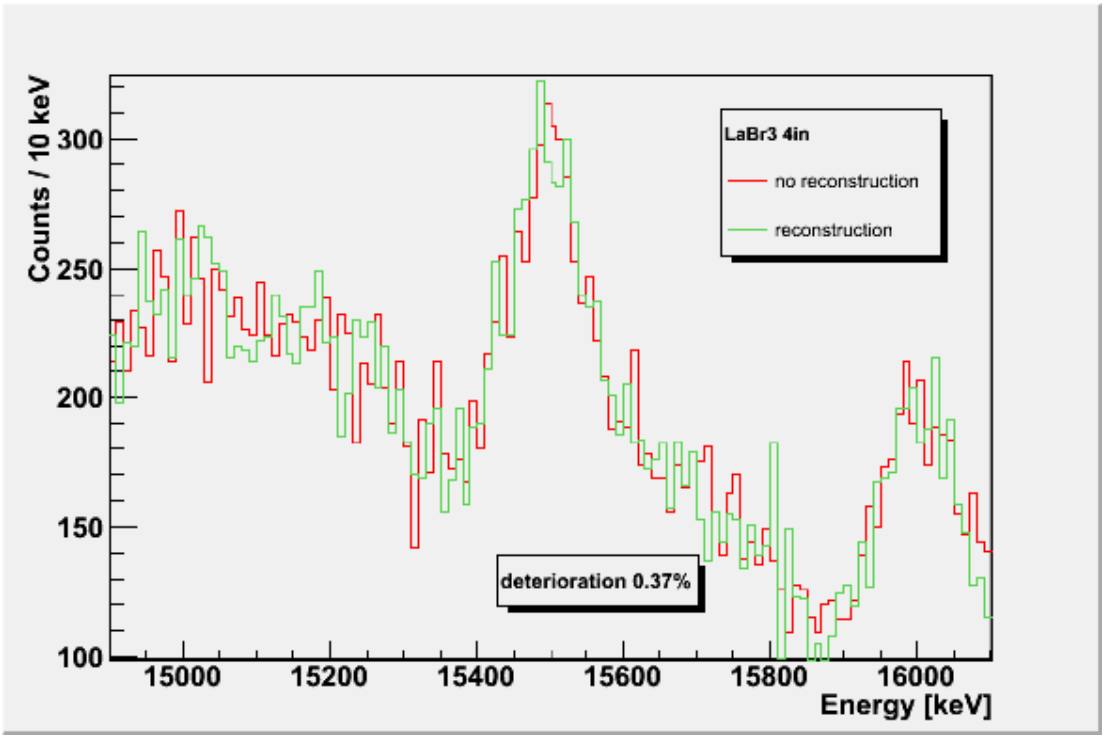


Fig.9 Illustration of reconstruction algorithm for primary gamma - 5,10 and 16 MeV in CsI and LaBr3

4. GDR simulation

Previous calculations were just a first step to perform GDR simulations. Giant Dipole Resonance is a collective excitation of a nucleus characterized by small amplitude and high frequency of oscillations. Excitation takes place when reaction between beam and target occurs. Impact parameter determines the value of spin and angular momentum of the complex nucleus. Complex nucleus is characterized by its spin and energy of excitation and it can deexcitate by evaporating neutrons,more rarely protons, αparticles and γ-rays. Most probable is the emission of neutrons; emitting GDR γ-rays is 10^(-3) less probable but if they occur they are highly energetic. Probability of emitting GDR -rays is the highest during first steps of decay which can give information about rotating and hot nuclei. [3]
Summing up, all nuclei that are above yrast line deexcitate by evaporating neutrons and then they diminish their spin by emitting a cascade of low energy gammas (in approximation emission of one gamma diminish spin by 2h, they move down the yrast line). Simulation of such process consisted on two points (one event simulated one deexcitation process, only γ-rays are considered) :

- emission of γ from energy range 500 keV - 2 MeV; multiplicity per event was a random number generated from triangular distribution (interval [1;30], with maximum at 30),
- emission of one high energy γ [5;20]MeV after every 10^3 low energy γ.

Simulation was performed for 10^6 events and for geometry with $LaBr_3$ and CsI. Resulting spectrum of emitted γ-rays in GDR process is presented in Fig. 10.

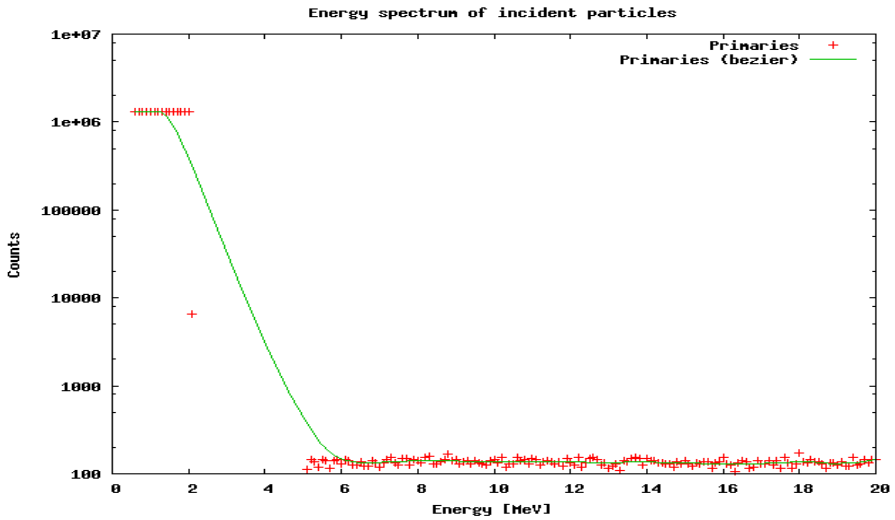
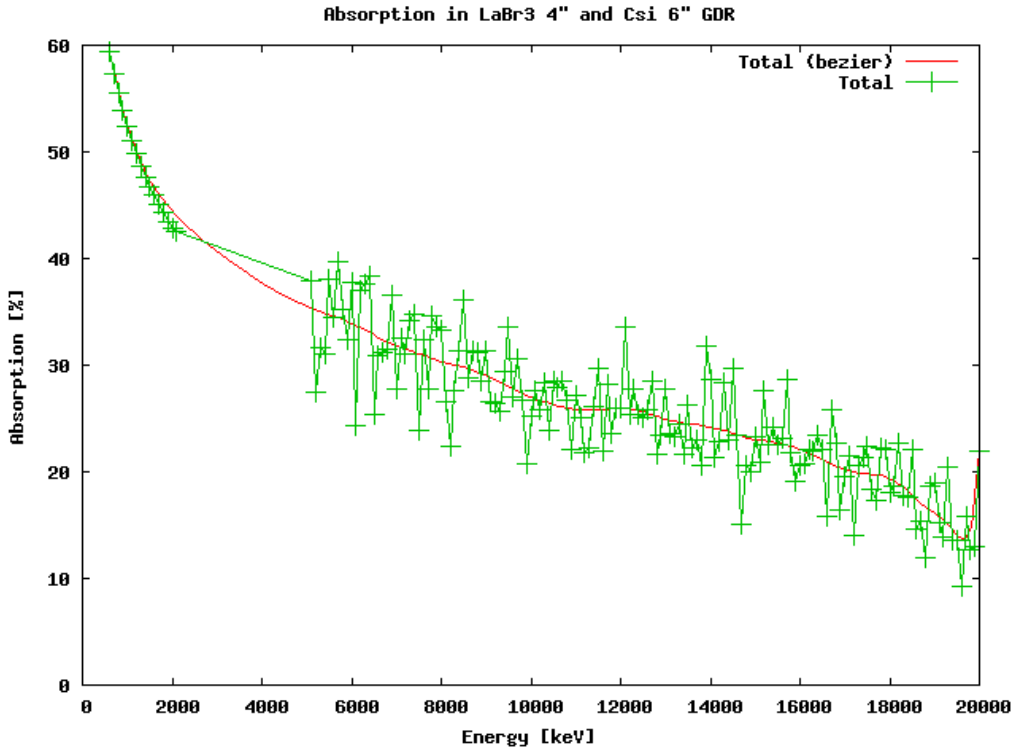


Fig.10 Energy spectrum of incident γ-rays in GDR simulation

According to previous considerations, one can see huge supremacy of low energy γ-rays over high energy ones. In following figures we present absorption coefficients calculated separately for two layers of detector: inner part $LaBr_3$ and outer part CsI. Fig. 11.



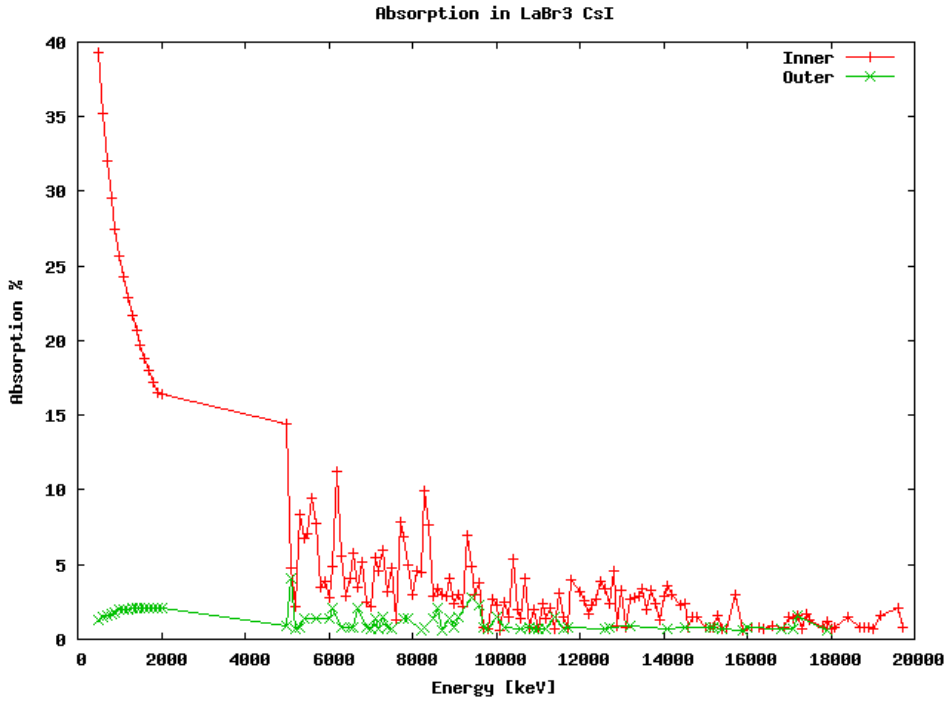
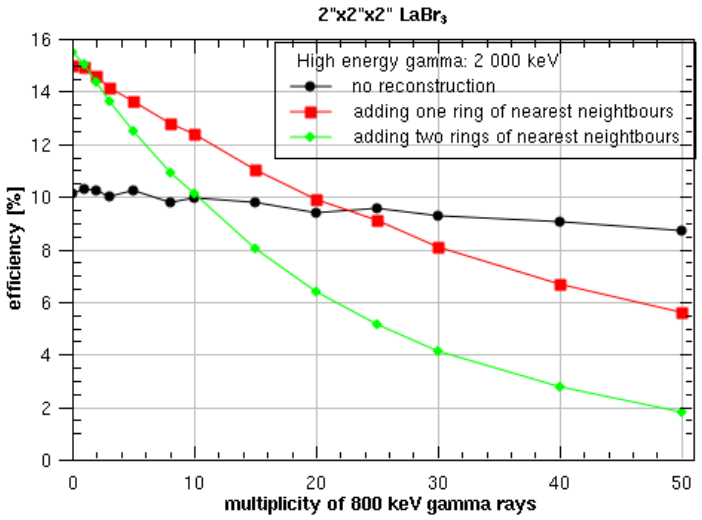


Fig. 11 Absorption coefficients: total (top), inner & outer (bottom)

This time we used another reconstruction algorithm simply basing on summing energies of all neighbours (regardless if it was 511 keV or not) to the main crystal with energy above threshold.
To compare obtained efficiencies using this algorithm we performed simulation with 800 keV low energy gamma. High energy gamma varied from simulation and was equal to 2, 5 and 15 MeV. Energy thresholds used were 900 keV, 3 MeV and 3 MeV respectively. Multiplicity of high energy gamma was 1 but varied for low energy gammas. There were 10^5 events per simulation.
We present results for two geometries i.e. $LaBr_3$ 2"x2"x2" and $LaBr_3$ 2"x2"x4". Fig. 12 and 13



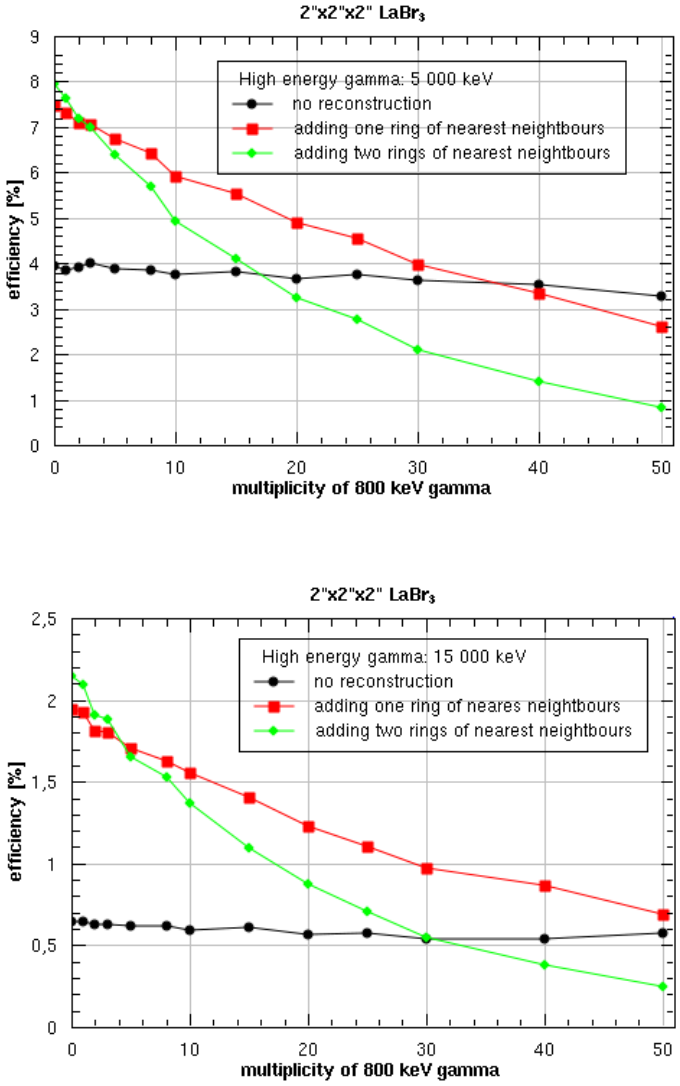


Fig.12 Absorption coefficients vs multiplicity of low energy gamma in LaBr3 2"x2"x2" for different values of high energy gamma

For simple analysis (without reconstruction) efficiency slightly decreases for higher multiplicities. Its level of course lowers while decreasing energy of high energy gamma.
One can also see a big improvement when reconstruction was used and also an advantage of adding only primary neighbours over adding primary and secondary. Only for very low multiplicities adding primary and secondary neighbours acts a little better. There exists certain boundary value of multiplicity for which reconstruction algorithm fails. It is smaller for lower energies of high energy gamma and it's due to adding up false results. It yields 25 for 2 MeV gamma and 40 for 5 MeV gamma. For 15 MeV reconstruction with adding primary neighbours is more efficient for whole range of multiplicity. The same results apply for LaBr3 2"x2"x4", furthermore efficiency is higher in each considered case.

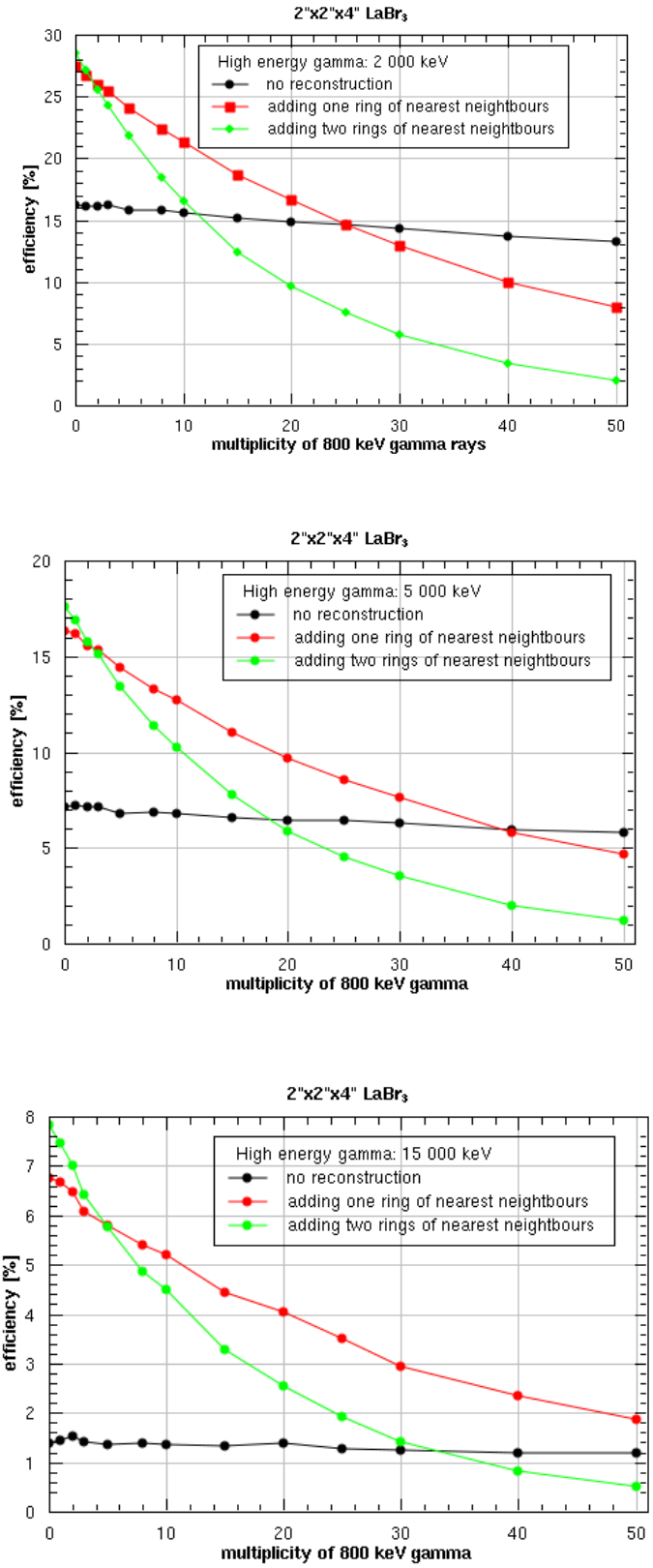


Fig.13 Absorption coefficients vs multiplicity of low energy gamma in LaBr3 2"x2"x4" for different values of high energy gamma

The shape of GDR resonance i.e. shape of cross section for photoabsorption is described by Lorentz distribution. We performed another set of simulations, generating per event low energy gammas (800 keV) of two chosen multiplicities and one high energy gamma taken from Lorentz distribution. Parameters of distribution were: mean value 15 MeV, width 8 MeV and cutoff 15 MeV. Fig. 14

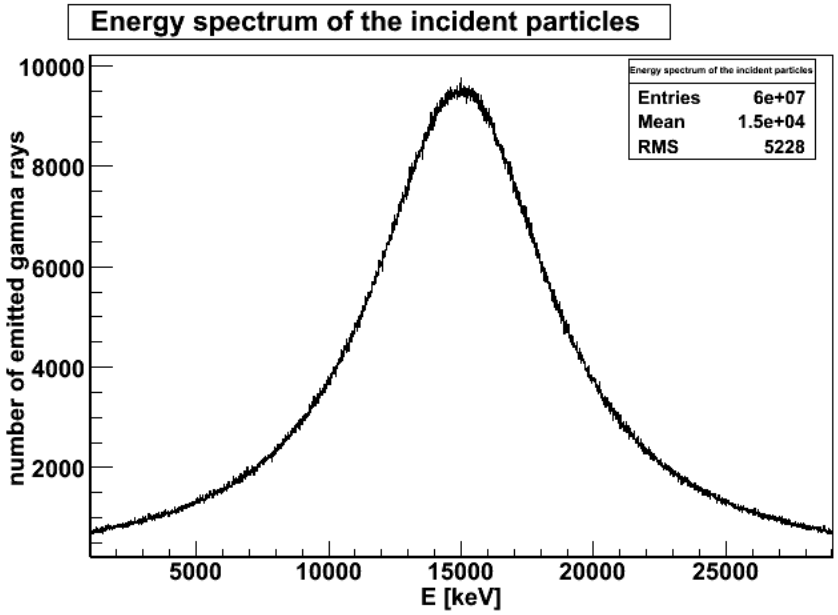
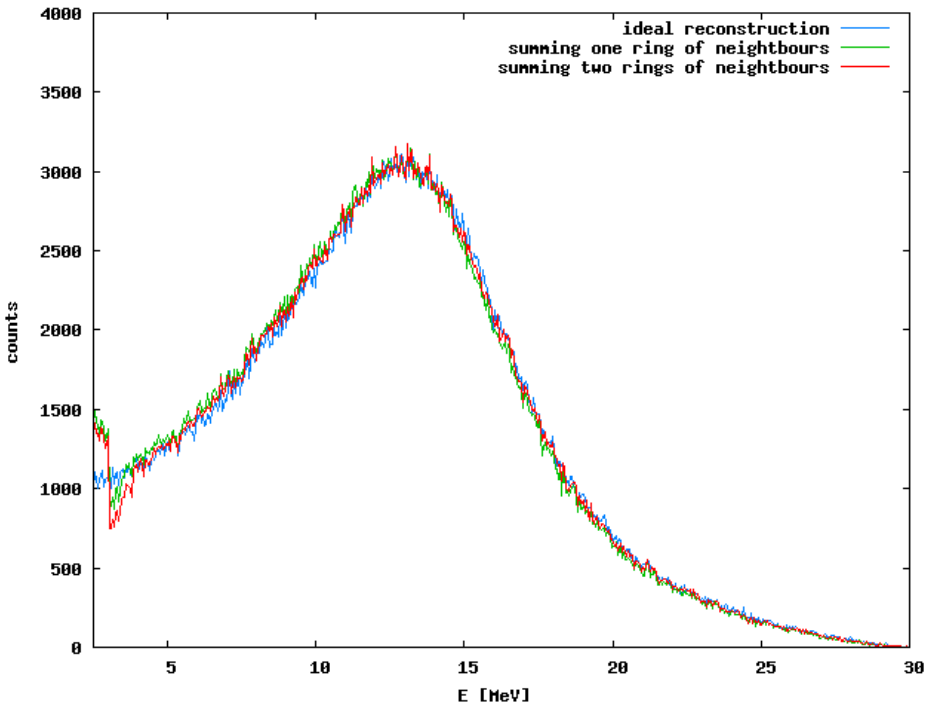


Fig.14 Lorentz distribution of incident high energy gammas

Next we present resulting energy spectra for multiplicity 5 (10^7 events), 15 (10^7 events) and 30 (0.5x10^6 events) for two sizes of $LaBr_3$ crystal. Because of different number of events spectra for multiplicity 5 and 15 have 10 keV/bin and those for multiplicity 30 have 200 keV/bin. Energy threshold in summing algorithm was set to 3 MeV. Fig. 15 and 16



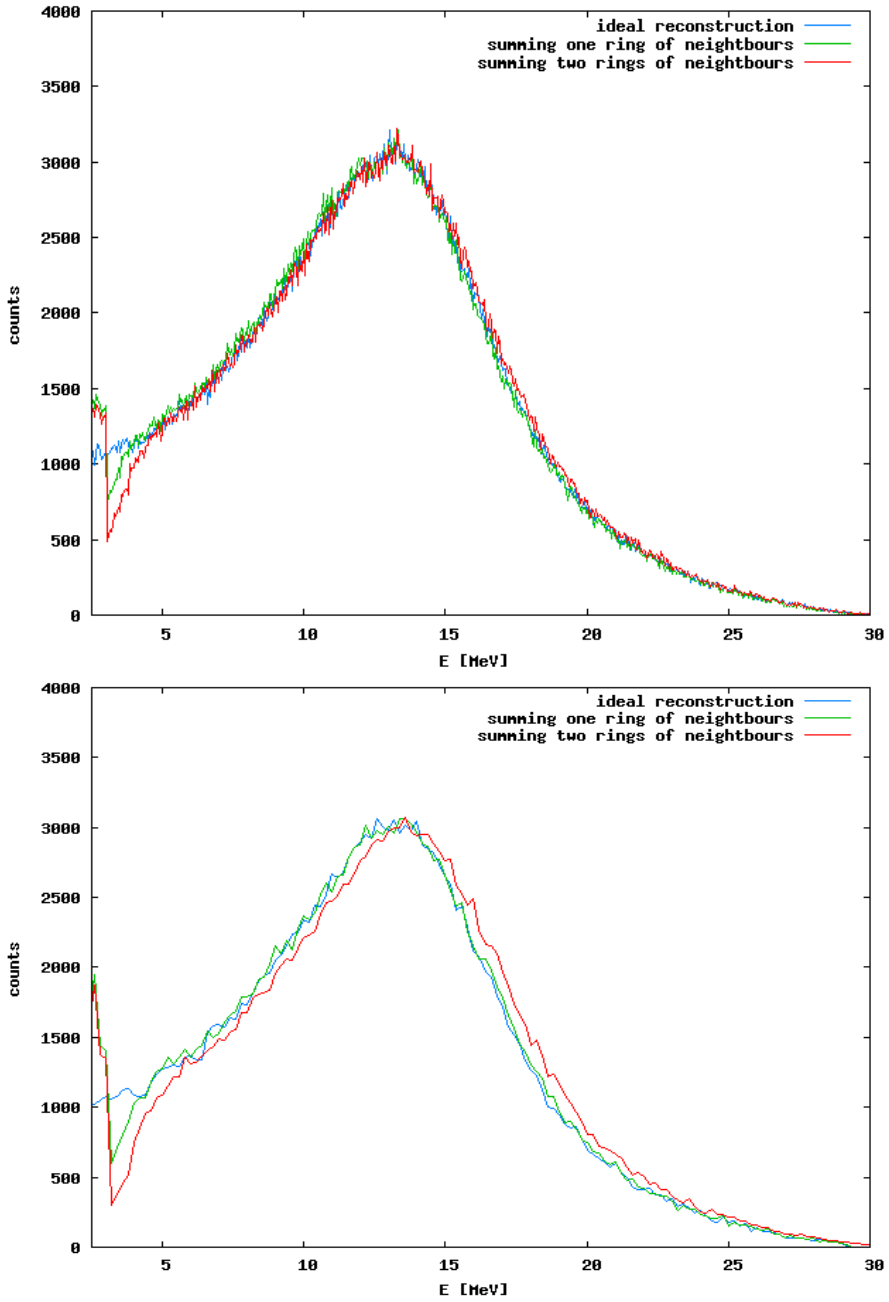
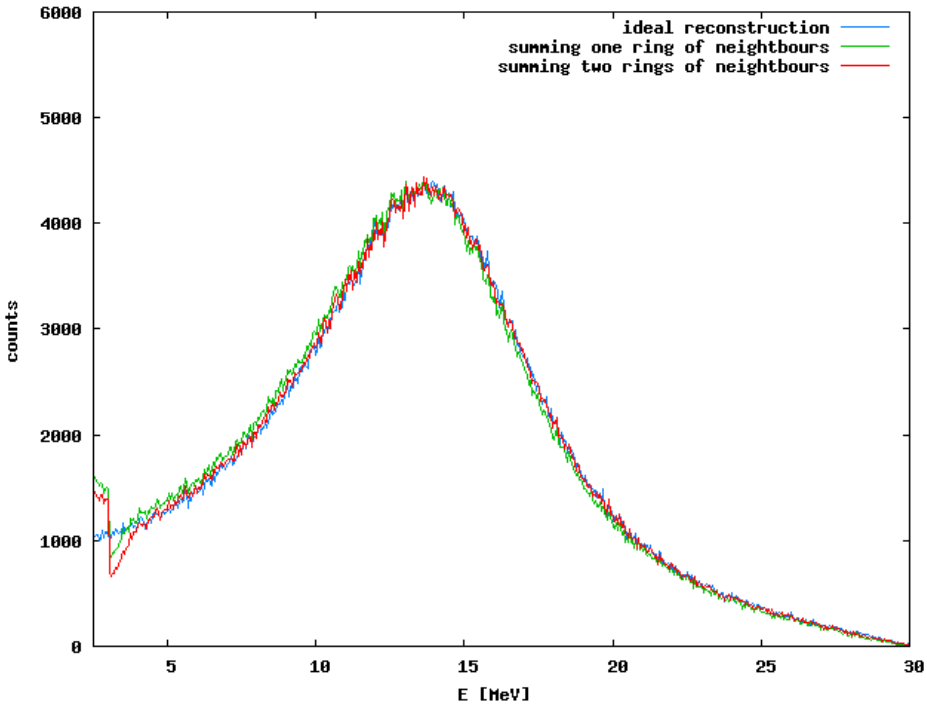
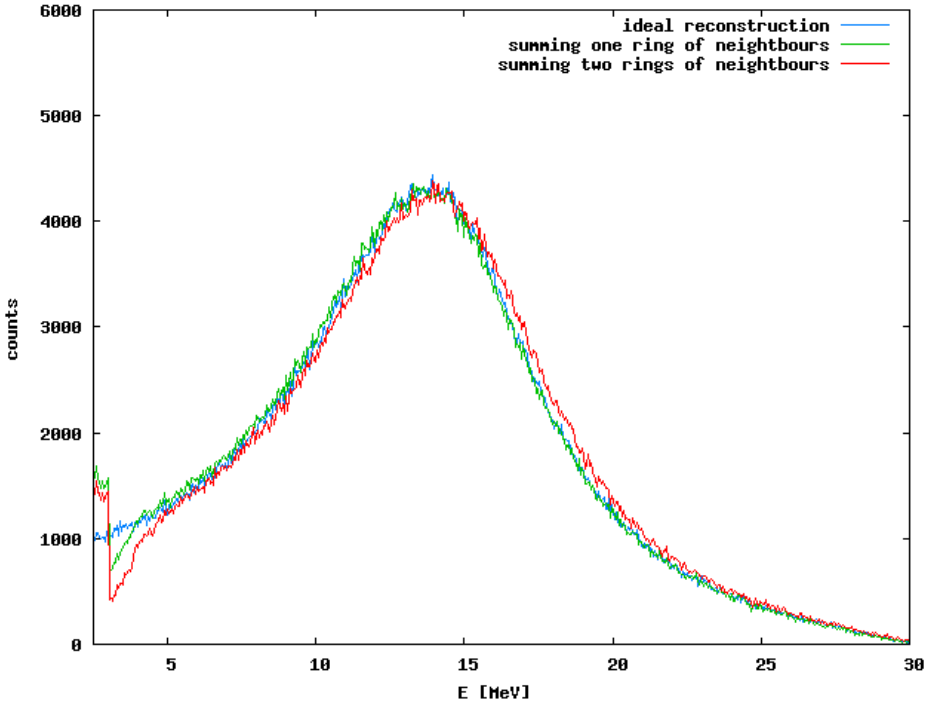


Fig. 15 Energy spectra for LaBr3 2"x2"x2" with multiplicity 5 (top), 15 (middle) and 30 (bottom)

Distribution of incident gammas was highly symmetric while on obtained figures one can see non symmetric answer. That is because coefficient of absorption increases when energy decreases - maximum is shifted to the left. We tried to compare proposed reconstruction algorithms to the ideal one in which we assume to know where each gamma leaves its trace. For multiplicity 5 both algorithms (summing only primary neighbours and summing primary as well as secondary ones) return almost the same results as ideal reconstruction algorithm. For higher multiplicities spectrum obtained from summing primary and secondary neighobours is visibly shifted to the right. That is because there were more low energy gammas taken into the sum. In case of summing only primary neighbours this shifting is visible starting from multiplicty 30. Probably for even higher multiplicities difference between two proposed algorithms will be even bigger. Sudden breakdown near 3 MeV results from value of threshold energy.


ideal reconstruction
summing one ring of neightbours
summing two rings of neightbours
counts
E [MeV]
0
1000
2000
3000
4000
5000
6000
5
10
15
20
25
30


ideal reconstruction
summing one ring of neightbours
summing two rings of neightbours
counts
E [MeV]
0
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2000
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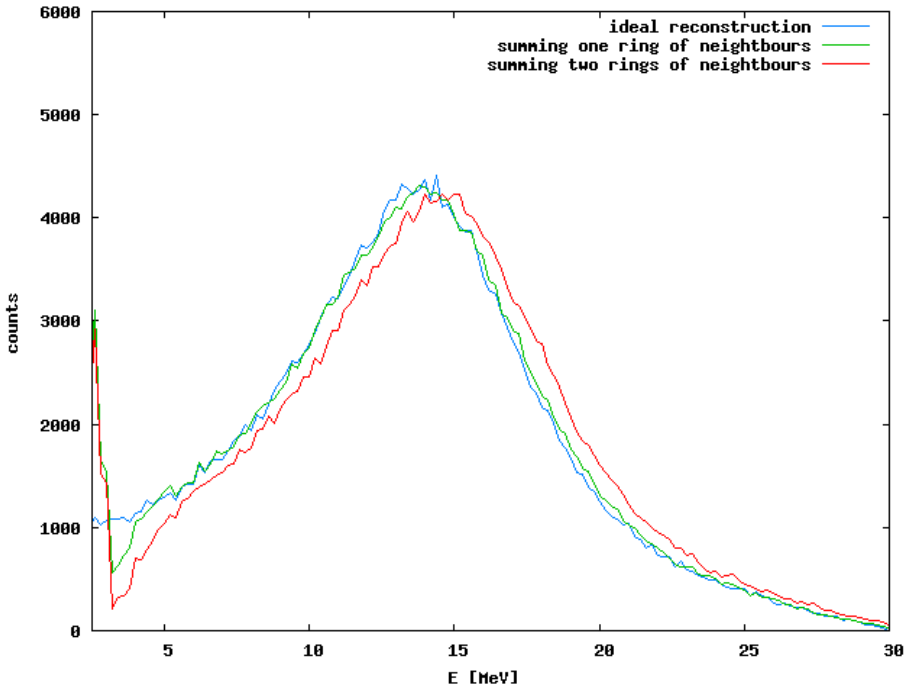

Fig.16 Energy spectra for LaBr3 2"x2"x4" with multiplicity 5 (top), 15 (middle) and 30 (bottom)

Situation for LaBr3 2"x2"x4" is exactly the same as explained before with only one difference in counts - higher coefficient of absorption.

5. Future perspectives

Things to be done in the future:

- Upgrade reconstruction algorithm (maybe?)
- Further simulations with GDR emission including neutron interactions with matter
- Realistic reaction simulation

6. Acknowledgments

This work would have not be done without help of our supervisors. Therefore we thank prof. Adam Maj and dr Maria Kmiecik from IFJ Kraków.

7. Bibliography

[1] geant4.cern.ch, User guides
[2] *Strachan J.*, Possible scenarios for the PARIS mechanical design.
PARIS collaboration meeting in York, 2008
[3] *Kmiecik M.*, Properties of nuclei and nuclear reactions studied with Giant Dipole Resonance, PhD Thesis
[4] *Ciemała M.*, Multichannel set for high energetic gamma measurement – simulation in GEANT4, M.Sc. Thesis