Proton detection with the R^3B calorimeter,
The two layer solution.

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1. Introduction

The R3B experiment is part of the first stage of the FAIR project. In the R3B experiments, high energy nuclear beams, extracted from the Super FRS, are to interact in a secondary target surrounded by a complicated detector set-up for a complete study in inverse kinematics of all reaction products. The total absorption calorimeter will be situated around the reaction target to determine the total gamma energy disintegration, the cascade multiplicity and the individual gamma energies, as well as to detect and determine the energy of protons of up to 300 MeV.

The detection system will permit to carry out reaction studies with low intensity beams, to use beams with the maximum energy provided by the Super-FRS and to study nuclei with very short half life.

The objective of this report is to contribute to the design of the calorimeter by an alternative approach; studying different pixelated scintillators coupled with position sensitive photomultipliers to see if one can obtain the angular resolution necessary to detect gamma cascades from 1 to 10 MeV (in the centre-of-mass reference system). The calorimeter should be able to measure the total energy of the gammas, the multiplicities and the individual energies of each gamma.

However, the second objective of the spectrometer is to detect and determine the energy of protons of energies up to 300 MeV emitted in the reactions. In the case of protons, in comparison to the gammas, there are other detectors that will determine the angle and origin of emission, so the spectrometer just needs to determine the p-energy.

In this report is discussed the part of the work simulating the proton detection using the SRIM 2003 code and Geant4 programs. The SRIM code is being used for a first estimate while the Geant4 programs are made more appropriated to the final geometry.

2. Proton simulations with SRIM 2003 code

The objective of these simulations are to determine the energy resolution of the incident protons for known emission directions. Initially there are protons with energies up to 300 MeV in the laboratory system, and it is intended to seek a configuration of the crystal scintillators with which one can obtain an energy resolution better than 3%. Our approach is to use two scintillator layers as shown in figure 1.

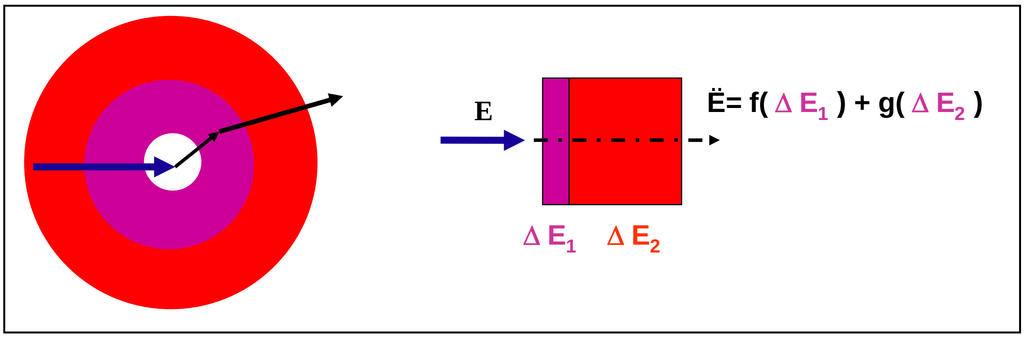

Figure 1: In the two layer detector approach, the estimated final energy is proportional to the energy deposited in each layer.

As it is well known, the deposited energy by a charged particle in a material is given by the Bethe-Bloch equation:

$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\log\frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2\right] \quad (1)$$

where $K=4\pi N_a r_e^2 m_e c^2=0.1535\ MeV\ cm^2/g$, m_e, e and r_e are the electron mass, the electron charge and the classical electron radius, N_a is the Avogadro's number, Z and A are the atomic number and atomic weight of the absorbing material, z is the charge of the incident particle in units of e, c is the velocity of the light, T_{max} is the maximum energy transfer in a single collision, I is an experimentally determined parameter and represents the mean excitation potential of the absorbing material, $\beta=v/c$ and v is the velocity of the incident particle.

Using the formula we can estimate the energy deposited in different detector materials of different thicknesses. Figure 2 shows the deposited energy in different thickness layers of the Brillance 380 scintillator, $LaBr_3$(Ce), in function of the incident energy of the protons. For example, a deposited energy of 70 MeV may correspond to protons with incident energy of 60 or 130 MeV for a 30 mm material thickness. In the first case the 60 MeV protons have been completely absorbed by the material, while in the second only part of their energy is absorbed. If we detect the deposited energy in each layer one can work out the energy of the incident particle even without fully stopping it.

The simulation was performed using a Monte Carlo code together with the SRIM 2003 code. It was studied the energy deposited by protons with incident energies between 100 and 300 MeV in two layers of material. A total of 121 simulations in steps of 10 MeV were performed.

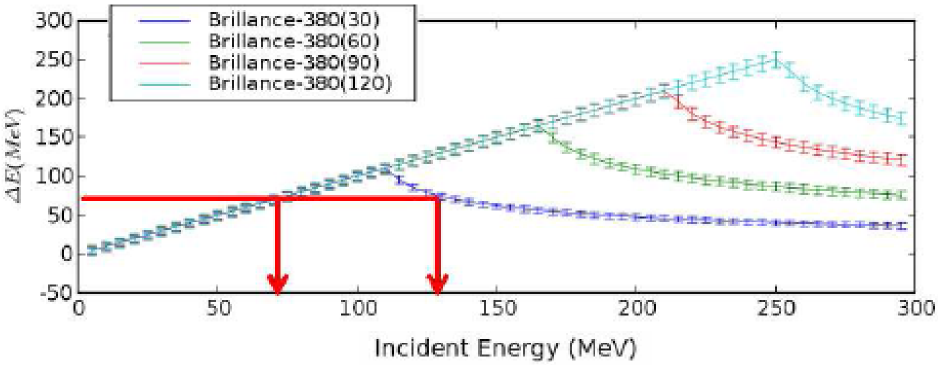

Figure 2: Deposited energy in different thickness layers of the Brillance 380 scintillator, $LaBr_3$(:Ce), in function of the incident energy of the protons, following the Bethe-Bloch expression (1)

In each case ten thousand protons were launched in the simulation and the results were fitted to a gaussian function with a constant background

$$y = y_0 + a\, e^{-\left(\frac{x-x_0}{\sqrt{2\sigma}}\right)^2}$$

the offset x_0 and the full width at half maximum (FWHM= 2.35σ) were obtained. For each incident energy of protons, the average energy deposited in the first and the second layers of the detector are obtained with their associated uncertainties. The energy deposited in the second detector is determined as the difference between the total energy of the emitted proton and that deposited in the first layer. In this way, the same value for the incident energy is always obtained. But we can invert the reasoning; if the energies absorbed by the first and the second detectors are known, it is possible to obtain the incident energy with a certain error.

This study has been carried out with two layers of materials with the condition of being optically compatibles, to avoid the emitted light of the first to be reabsorbed by the second. As can be appreciated in the figure 3 for the LYSO material, the emission and absorption spectra of a material do not overlaps, the emission is always shifted to lower energies.

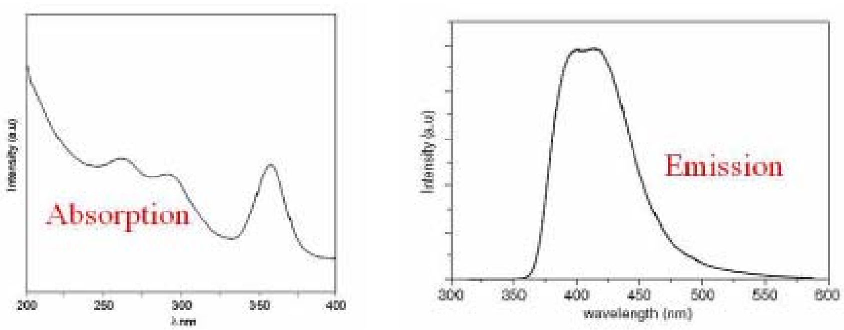

Figure 3: Absorption and emission spectra for the LYSO material [1].

In table 1 are shown the emission wavelengths of different scintillation materials and their reaction times. As the absorption spectrum is shifted to higher wavelengths, it is possible to choose a good combination of materials to avoid the overlap of the signals from the first and the second detector layers.

Material	**Density (g/cm^3)**	**Hygroscopic**	**Max $\lambda_{emission}$ [nm]**	**Decay time[ns]**
BGO	7.13	no	478	300
LYSO	7.10	no	420	45-60
CsI(Tl)	4.51	slightly	550	1000
CsI(Na)	4.51	yes	420	630
NaI(Tl)	3.67	yes	400	230
$LaBr_3$(:Ce)	5.29	yes	380	16
$LaCl_3$(:Ce)	3.90	yes	350	28

Table 1: Wavelengths for the maximum emission of different scintillator materials.

The combination of materials chosen and their thicknes were:

1. 1 mm $LaBr_3$(:Ce) + 20 mm $LaBr_3$(:Ce)
2. 20 mm $LaBr_3$(:Ce) + 30 mm LYSO(:Ce)
3. 30 mm $LaBr_3$(:Ce) + 150 mm $LaCl_3$(:Ce)

The results, energies deposited for each layer of the assembly detector and their errors in the cases 1) and 2) can be seen in tables 2 and 3. In the case 3) protons of 280 MeV are being fully stoped in the $LaCl_3$.

Energy [MeV]	dE(Brill_380)	Error(Brill_380)	dE(LYSO)	Error(LYSO)
170	75.437	7.51906	79.381	1.88769
180	56.962	3.92420	74.420	1.75688
190	49.043	3.42837	70.390	1.77703
200	43.498	3.10714	67.440	1.77173
210	40.300	2.95038	64.270	1.68221
220	37.460	2.87691	62.000	1.67457
230	34.870	2.88759	60.250	1.77095
240	33.490	2.79574	57.860	1.69133
250	31.670	2.80962	56.450	1.71572
260	30.130	2.78437	54.860	1.69840
270	29.460	2.77327	53.110	1.65894
280	28.700	2.75396	51.730	1.66283
290	26.960	2.83096	51.290	1.79966
300	26.730	2.72122	49.470	1.68702

Table 2: Deposited energy as function of the incident energy of the protons in the two layers, 30 mm of LYSO and 20mm of $LaBr_3$(:Ce), of the detector.

Energy [MeV]	dE(Brill_380)	Error(Brill_380)	dE(Brill_380)	Error(Brill_380)
100	2.37	0.212111	64.893	1.77027
110	2.22	0.208236	55.647	1.41470
120	2.09	0.211637	49.771	1.28713
130	1.98	0.221056	45.584	1.24123
140	1.88	0.219684	42.348	1.18445
150	1.80	0.219995	39.940	1.20167
160	1.72	0.222852	37.640	1.17143
170	1.65	0.223375	35.650	1.16397
180	1.59	0.222194	33.950	1.13217
190	1.53	0.227688	32.610	1.15918
200	1.49	0.233381	31.320	1.13297
210	1.45	0.235071	30.230	1.15484
220	1.40	0.282418	29.220	1.16856
230	1.36	0.239087	28.340	1.15214
240	1.32	0.249404	27.550	1.14949
250	1.30	0.238740	26.850	1.16847
260	1.27	0.249920	26.190	1.18123
270	1.24	0.251362	25.520	1.20573
280	1.22	0.248845	25.010	1.21725
290	1.19	0.251688	24.440	1.20407
300	1.17	0.259232	23.960	1.24050

Table 3: Deposited energy in function of the incident energy of the protons in the two layers, 1mm of $LaBr_3$(:Ce) and 20mm of $LaBr_3$(:Ce), of the detector.

Figures 4, 5, and 6 shows the incident energies respect to the deposited energies in each of the layers of the detector for the three cases studied. From these representations it is possible to estimate which is the incident energy deposited and with what resolution one can obtain this information, knowing the energy deposited in both layers of the detector. The results are presented in tables 3, 4 and 5.

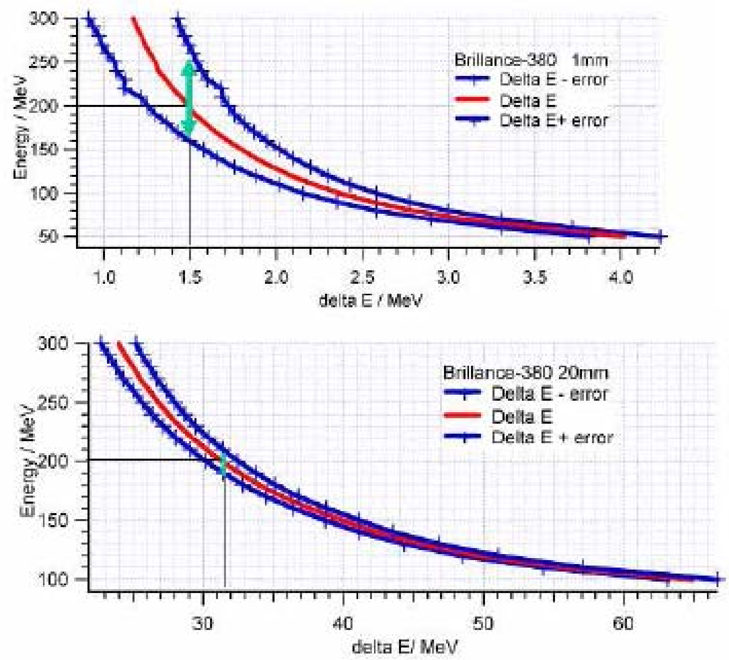

Figure 4: Incident energy vs. deposited energy in the 1 mm $LaBr_3$(:Ce) and 20 mm $LaBr_3$(:Ce) layers.

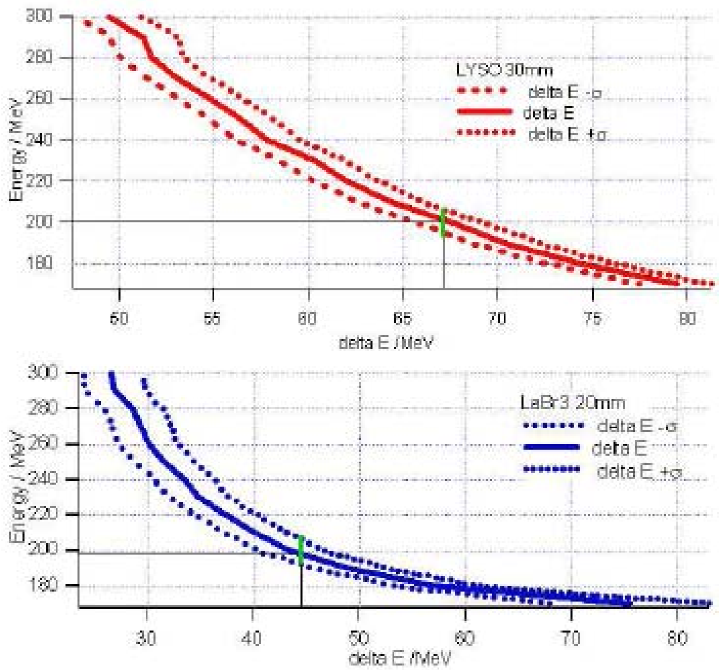

Figure 5: Incident energy vs. deposited energy in the 30 mm LYSO and 20 mm $LaBr_3$(:Ce) layers.

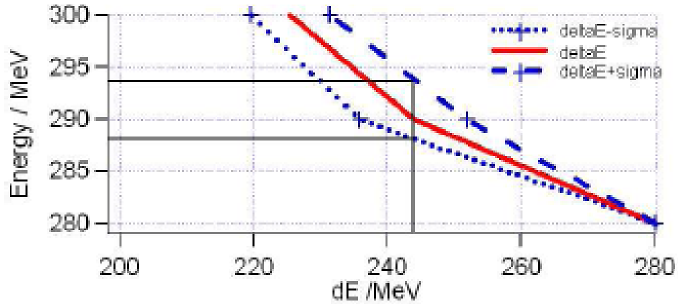

Figure 6: Incident energy vs. deposited energy in the 30 mm $LaBr_3$(:Ce) and 150 mm $LaCl_3$(:Ce) detector.

Deposited energy in 1mm $LaBr_3$(:Ce) [MeV]	Deposited energy in 20mm $LaBr_3$(:Ce) [MeV]	Incident energy [MeV]	σ(E)/E [%]
1.5	31.3	200	5

Table 4: Estimated incident energy from the known deposited energy in the 1 mm $LaBr_3$(:Ce) and 20 mm $LaBr_3$(:Ce) detector layers.

Deposited energy in 30mm LYSO(:Ce) [MeV]	Deposited energy in 20mm $LaBr_3$(:Ce) [MeV]	Incident energy [MeV]	σ(E)/E [%]
67.4	43.5	200	3.5

Table 5: Estimated incident energy from the known deposited energy in the 30 mm LYSO(:Ce) and 20 mm $LaBr_3$(:Ce) detector layers.

Deposited energy in 30mm $LaBr_3$(:Ce) [MeV]	Deposited energy in 150mm $LaCl_3$(:Ce) [MeV]	Incident energy [MeV]	σ(E)/E [%]
36.8	243.9	290	1.4

Table 6: Estimated incident energy from the known deposited energy in the 30 mm $LaBr_3$(:Ce) and 150 mm $LaCl_3$(:Ce) detector layers.

We can thus conclude that:

1. If the proton is not not fully absorbed, two ΔE-detectors are needed to solve the ambiguity of the signal.
2. The gammas will deposit the most part of their energy close to the first impact, therefore, it is required for the first layer a material with a good resolution as $LaBr_3$(Ce), where the second layer can in case of gammas can be used as veto.
3. The incident proton energies can be estimated with an error of 3- 4% if the detector is formed by 30 mm LYSO and 20 mm $LaBr_3$(Ce). However, as the LYSO has relatively poor $E\gamma$ resolution 6%, it would be a waste of money to place a $LaBr_3$(Ce) behind it. If one can live with the resolution of LYSO one would in this case combine with LSO.

4. The detector formed by 30 mm $LaBr_3$(:Ce) and 150 mm $LaCl_3$(:Ce) detect protons up to 280 MeV of energy with a resolution better than 2%. This combination will have the sufficient E_γ as well as E_p resolution even if one take a much shorter LaCl crystal. The materials are however higroscopic and very expensive.
5. A relatively cheap solution would be to combine a detector formed by 30 mm $LaBr_3$(:Ce), for a good $E\gamma$ resolution and relatively high (50% up to 10 MeV) absorbtion of gammas, with a second layer of pure CsI. This would have the good combinations of wavelength one would have to work on separating the decay times though.

3. Geometry simulations with GEANT4 code

The preliminary calorimeter design is based in a simulation done with GEANT4+ROOT by Héctor Álvarez (hapol@fpddux.usc.es). This code is available in the web http://www.usc.es/genp/ . The proposal consists of 5025 scintillator crystals distributed in three zones covering the polar angles in this way:

- 1070 crystals between 133º and 90º (backward end cap)
- 1970 crystals between 90º and 50º (central barrel)
- 1985 crystals between 50º and 7º (forward end cap)

The scintillator material chosen in this design is CsI, the total volume of the detector would be 500.000 cm^3 and a weight of some 2.000 Kg.

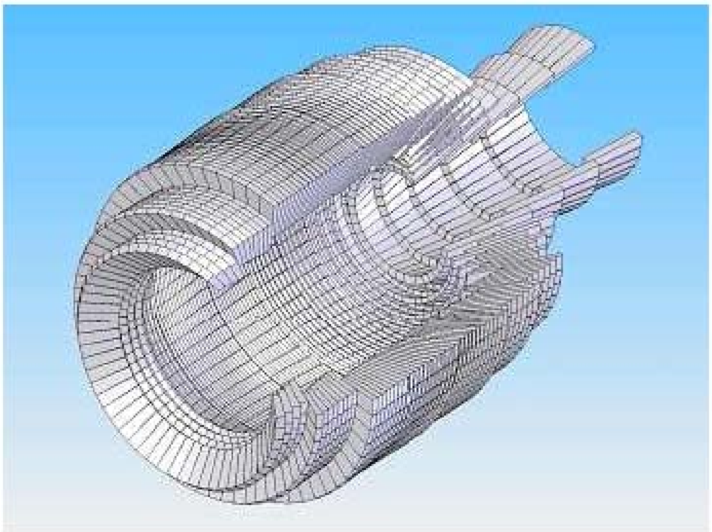

Figure 7: Shape of the calorimeter proposed by the Santiago de Compostela group.

To continue our work we have to study how our approach of using two layers of crystals can be incorporated in this design.

We propose the use of high density scintillators coupled in a telescope configuration. The first of the detectors, with high resolution for gammas, followed by the second crystal, to absorb the full energy of the photons. In case the “first” hit is detected in the second layer this event is discarded. While the most employed scintillator assemblies are NaI(Tl)/CsI(Na), NaI(Tl)/CsI(Tl) and NaI(Tl)/CaF_2(Eu) [2], we propose the use of new scintillator materials as lanthanum halides ($LaCl_3$(Ce) and $LaBr_3$(Ce)) or LYSO materials ($Lu_xY_ySiO_4$), due to their properties; high light emission, high density, fast time response and high energy resolution.

As, summarized in the previous section, it is possible to obtain resolutions in the order 2% for the energy determinations of protons when two lanthanum halide layers are chosen as scintillators. The simulations carried out with Geant4 consist in the study of the response to photons with energies up to 30 MeV using a planar geometry. As can be shown in the figure 8, the simplest geometry consist in a plane detector of dimensions 40 mm $\times$ 40 mm $\times$ 30 mm divided in 64 (=8$\times$8) boxes, displaced respect to the centre of the coordinate system. The emission of particles can be modified in PlanarPrimaryGeneratorAction.cc in direction (ParticleMomentumDirection) as in the position of the origin (ParticlePosition).

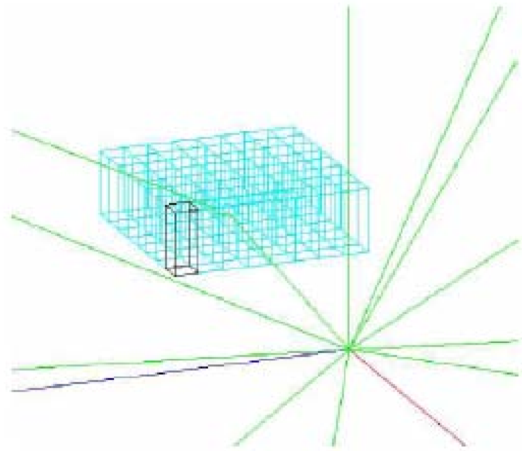

Figure 8: Simple planar geometry proposed to begin the simulations.

This part of the simulations are still in progress. In the appendix are described the steps and ideas so far reached.

Bibliography

[1] Hautefeuille et al. J. of Crystal Growth (in press)
[2] “A faster Phoswich” Saint Gobain Ceramics and Plastics, Inc. Report 2004
[3] I. Piqueras, F.A.Beck, E.Pachoud, G. Duchene; NIMA 516 (2004) 122

Appendix 1:

A1.1 Additional information about the events, hits and launched particles

The objective of this section is to explain the concepts of event, hit and step in the Geant4 code. An event represents the physic interactions a particle experiments with matter after being launched. Before finish, the information about the deposited energy by the particle in the path, number of interactions, etc…is collected. When the event finishes a new particle is launched and another event will be registered.

The sequence of events (carried out by RunAction) that happens when a particle is launched is:

- a particle is launched
- the path the particle travel in a instant (tracking) is followed
- the step is defined as the path the particle travel in the same direction; so, a step finish when the particle changes its direction

The information is registered by the hits. The hit is like a picture of the physic interactions of a track in a sensitive region of the detector (definition from the 4.4 Hits chapter of Geant User´s Guide For Application Developers). Therefore, a detailed time analysis of the evolution of the path's particle is done. And the information about a G4Step object as:

- time and position of the step
- energy and momentum of the track
- deposited energy of the step
- information about the geometry

or any combination of them, is stored in the hit array. So, the information about the step and the tracking of an event is registered in the hit.

A1.2 Histograms: probabilistic tracking method

The objective is to obtain the information about the spatial and energy resolutions of a detector in a unique run.

Following the probabilistic tracking method developed by I. Piqueras et. al. [3], it is possible to completely reconstruct the absorbed events in the detector knowing the centre of gravity of the touched segments of the detector and the partial energy deposited in each in them. Furthermore, the total energy is obtained from the deposited energies in the segments.

The histograms must describe the number of segments touched and the sequence of them the particle has crossed until it looses all its energy. This is important to determine the centre of gravity of the segments the particle crosses. We need to know in which impact (maybe the first or the last one) the particle deposits the most part of its energy.

The information about the deposited energy and the hits must be stored for each event in all the events. The number of events launched must be highly enough to get a good statistic, around 10000 in each run.

The necessary histograms are:

- deposited energy in each detector
- deposited energy in each segment
- sequence of segments in which the particle has deposited the energy (the number of segments touched by the particle)