# Position sensitive scintillator detectors for gamma ray imaging

Tasks and results

November 2023

## 1 Tasks:

1. Introducere
   - Build and run example TestEM4 in batch mode also in visualization mode. Save and plot results
   - Define new materials: CsI (Tl), BGO, LYSO
   - Define a panel scintillator of 4 cm 4 cm x 2 mm
   - Simulate the deposited energy in each type of scintillator for photon energies: 0.1 MeV, 0.5 MeV, 1 MeV, 3 MeV, 5 MeV, 10 MeV
   - Plot all results
2. Calcularea energiei depuse
   - Sursa — fascicul dicrectionat pe axa z, fara deschidere unghiulara
   - Pentru mai multe grosimi ale scintilatorului, calculeaza energia depusa
   - Scrie un cod in Python care sa calculeze Edep
   - $E_{dep} = \sum_i entries_i \cdot E_i$
   - Plot all results
3. Optical yield
   - Materiale: [BGO, CsI (Tl), BGO]; grosimi: [0.5, 1, 2] mm; energii: [0.1, 0.5, 1, 3, 5, 10] MeV
   - Calculand probabilitatea de interactie, afla numarul de fotoni care interactioneaza si compara cu numarul de entries dat de G4
   - Interactii = $N_0(1 - e^{-\mu x})$
   - Coeficientii de atenuare liniara — din baza de date nist xcom
   - Pentru fiecare energie depusa calculata, sa se calculeze si numarul de scintilatii (numarul de fotoni optici creati) cunoscand light yield-ul fiecarui material
   - Scrie un cod care sa parcurga toate fisierele, care sunt denumite in forma: `MATERIAL_ENERGY_WIDTH.root`
   - Plot all results
4. Suprafata in care s-a depus energia
   - Studiaza depunerea de energie salvand datele intr-o histograma 2D: poxitia (x,y) + Edep
   - Facand proiectia pe axele x si y, calculeaza FWHM din profilul 1D

- Realizeaza graficul FWHM in functie de energie si grosime/scintilator
  * Realizeaza un fit in python cu o functie Lorentziana/Super Gaussiana
  * Pentru funcția Lorentziana, FWHM $= 2 \cdot \gamma$.
  * Realizeaza simulari pentru diferite energii, grosimi si scintilatori
  * Mareste numarul de bini din histograma (redu dimensiunile scintilatorului)
  * Analitic, afla FWHM si FWTM.

5. Optimizarea pixelului
   - Studiaza depunerea de energie totala si in zona FWTM
   - Raportul eFWTM/eTot
   - Semnal/zgomot

# 2 Results

## 2.1 Task 1. Photon energy deposition in a scintillator panel made of CsI (Tl), BGO or LYSO

```
// Definition of CsI(Tl) crystal

// construct Cs and I

G4Element *Cs = new G4Element("Cesium"  ,"Cs" , z=55. , a= 132.91*g/mole);
G4Element *I = new G4Element("Iodine"  ,"I" , z=53. , a= 126.90*g/mole);

// construct CsI material
G4Material *CsI = new G4Material("CsI", density= 4.51*g/cm3, ncomponents=2);
CsI->AddElement(Cs, 1);
CsI->AddElement(I, 1);

// dope with Thallium

G4Element *Tl = new G4Element("Thallium"  ,"Tl" , z=81. , a= 204.38*g/mole);
G4Material *doppedCsI = new G4Material("CsITl", density= 4.51*g/cm3, ncomponents=2);
doppedCsI->AddElement(Tl, concentrationOfTl = 0.001*perCent);
doppedCsI->AddMaterial(CsI, 100*perCent - concentrationOfTl);

// we can also add the optical properties if needed
```

Figure 1: Define material — CsI (Tl)

```
// construct BGO

G4NistManager* manager = G4NistManager::Instance();

G4Element *O = manager->FindOrBuildElement(8);
G4Element *Bi = manager->FindOrBuildElement(83);
G4Element* Ge = manager->FindOrBuildElement(32);

G4Material *BGO = new G4Material("BGO", density= 7.10*g/cm3, ncomponents=3);
BGO->AddElement(O , natoms=12);
BGO->AddElement(Ge, natoms= 3);
BGO->AddElement(Bi, natoms= 4);
```

Figure 2: Define material - BGO

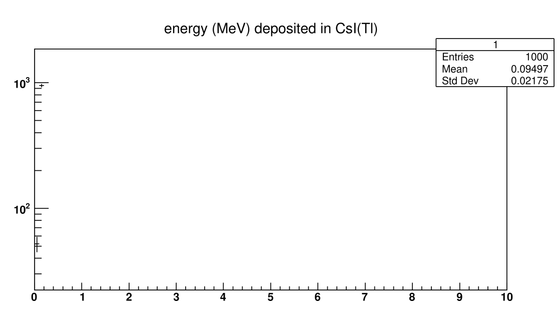
```
// cosntruct LYSO

G4Element *Lu = manager->FindOrBuildElement(71);
G4Element *Si = manager->FindOrBuildElement(14);
G4Element *Y = manager->FindOrBuildElement(39);

G4Material *LYSO = new G4Material("LYSO", density= 7.4*g/cm3, ncomponents=4);
LYSO->AddElement(Lu,71*perCent);
LYSO->AddElement(Si,7*perCent);
LYSO->AddElement(O, 18*perCent);
LYSO->AddElement(Y, 4*perCent);
```

Figure 3: Define material - LYSO

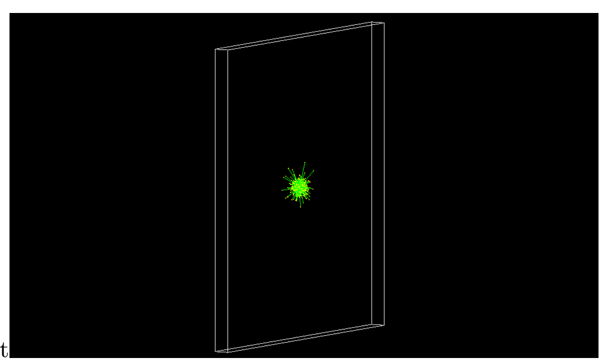
```
//
// Scintillator pannel 4cm x 4cm x 2mm
//

G4double x1 = 4*cm, x2 = 4*cm, x3 = 0.2*cm;

G4Box *scintilBox =  new G4Box("scintilBox", x1, x2, x3);

G4LogicalVolume *logicBox = new G4LogicalVolume(scintilBox, BGO, "logicBox");

G4VPhysicalVolume *physBox = new G4PVPlacement(0,                     //no rotation
                               G4ThreeVector(),        //at (0,0,0)
                             logicBox,                //its logical volume
                             "physBox",                //its name
                             0,
     //                        logicWorld,                     //its mother  volume
                             false,                       //no boolean operation
                             0, true);
return physBox;
```

Figure 4: Panel dimensions

#### 2.1.1 CsI(Tl)

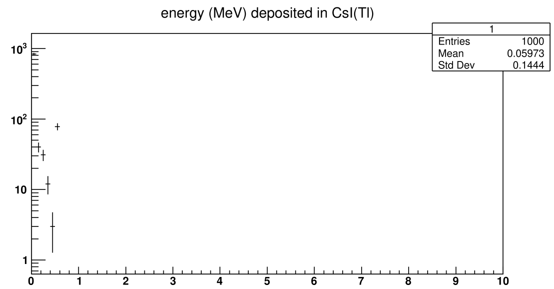



(a) Deposited energy in CsI(Tl) at 0.1 MeV incident energy

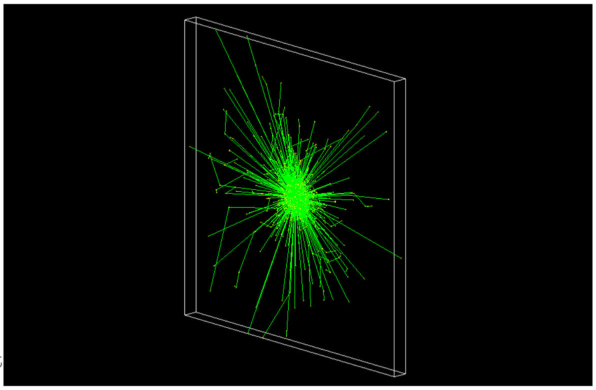


(b) Visualisation of the particle tracks

Figure 5: Results – CsI(Tl) – 0.1 MeV

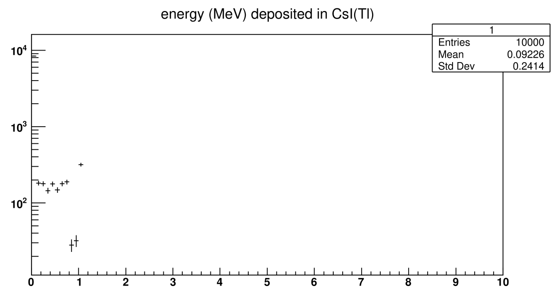



(a) Deposited energy in CsI(Tl) at 0.5 MeV incident energy

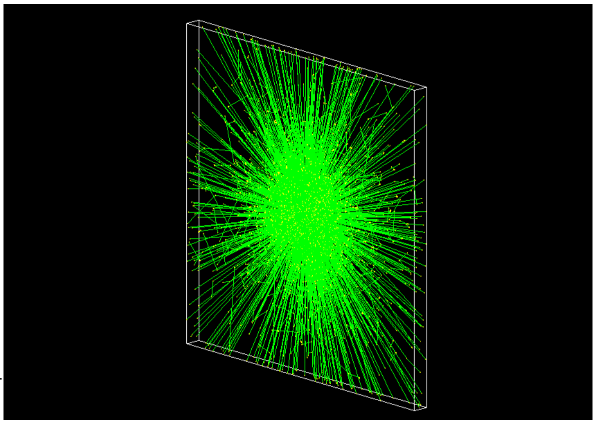


(b) Visualisation of the particle tracks

Figure 6: Results – CsI(Tl) – 0.5 MeV

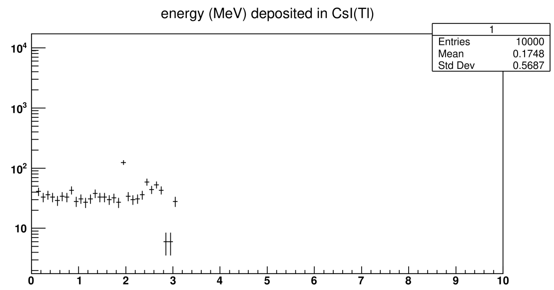



(a) Deposited energy in CsI(Tl) at 1 MeV incident energy

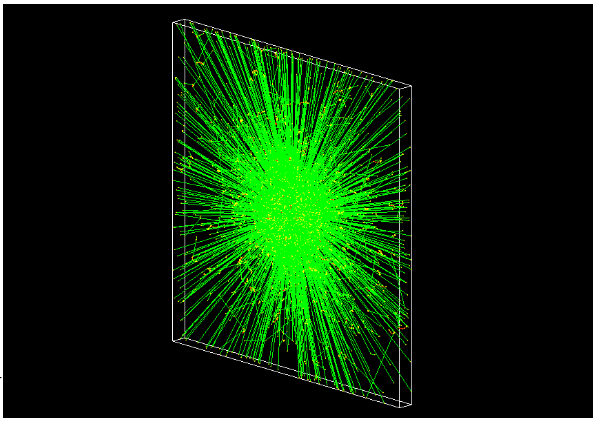


(b) Visualisation of the particle tracks

Figure 7: Results – CsI(Tl) – 1 MeV

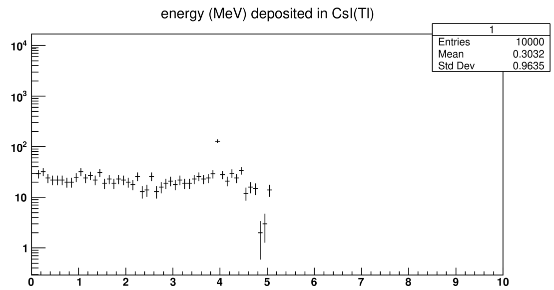



(a) Deposited energy in CsI(Tl) at 3 MeV incident energy

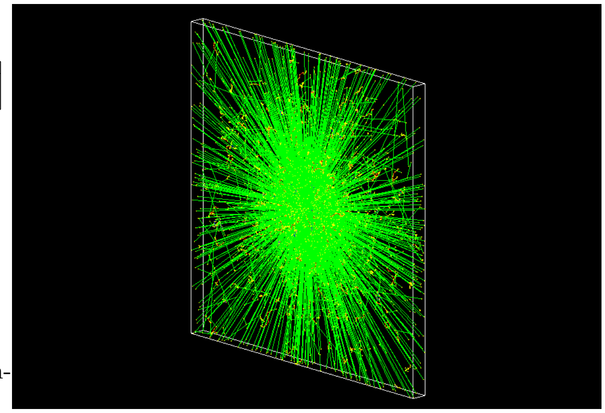


(b) Visualisation of the particle tracks

Figure 8: Results – CsI(Tl) – 3 MeV

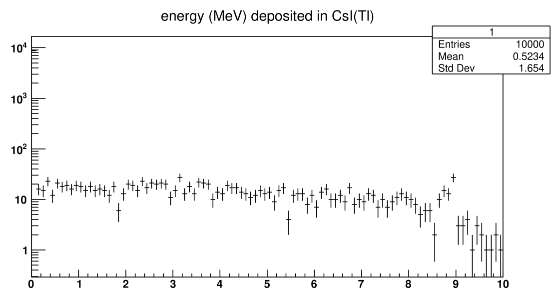



(a) Deposited energy in CsI(Tl) at 5 MeV incident energy

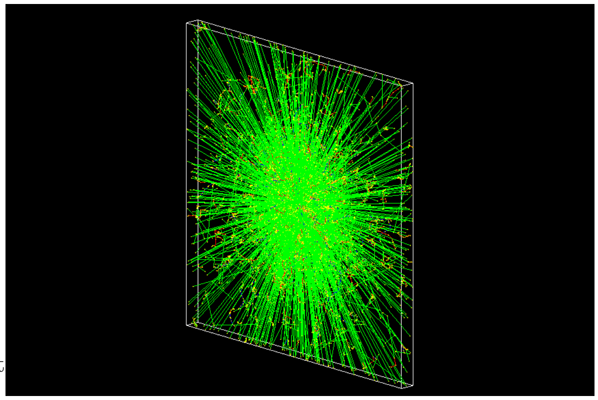


(b) Visualisation of the particle tracks

Figure 9: Results – CsI(Tl) – 5 MeV



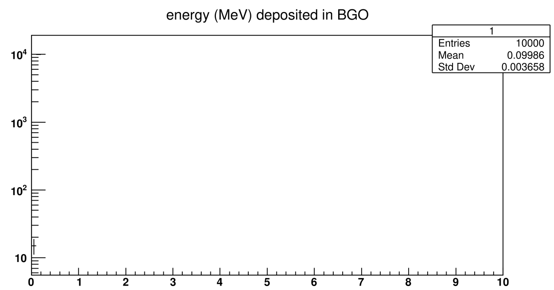

(a) Deposited energy in CsI(Tl) at 10 MeV incident energy



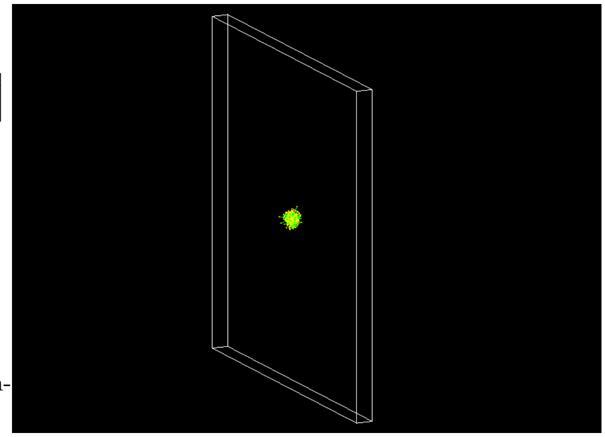
(b) Visualisation of the particle tracksy

Figure 10: Results – CsI(Tl) – 10 MeV

### 2.1.2 BGO

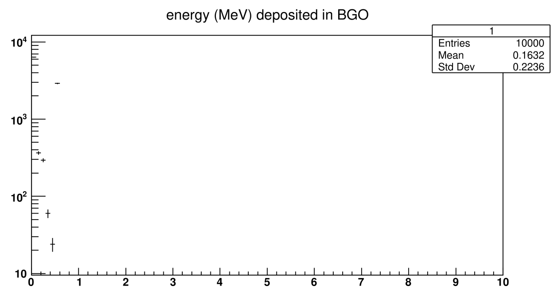



(a) Deposited energy in BGO at 0.1 MeV incident energy

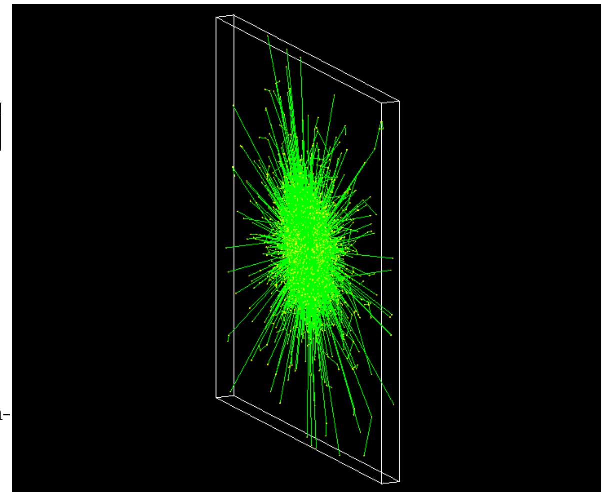


(b) Visualisation of the particle tracks

Figure 11: Results – BGO – 0.1 MeV

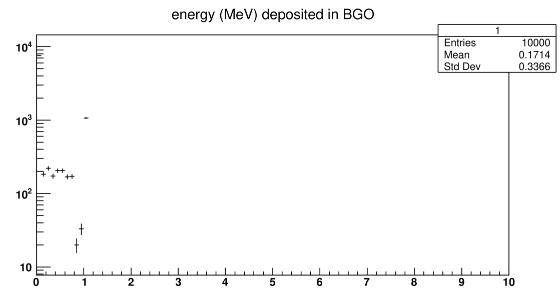



(a) Deposited energy in BGO at 0.5 MeV incident energy

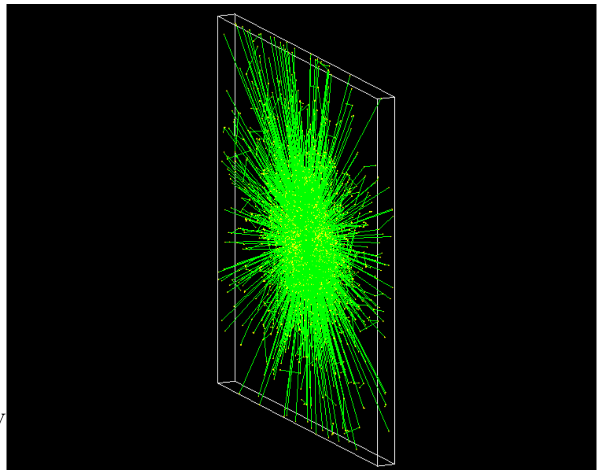


(b) Visualisation of the particle tracks

Figure 12: Results – BGO – 0.5 MeV

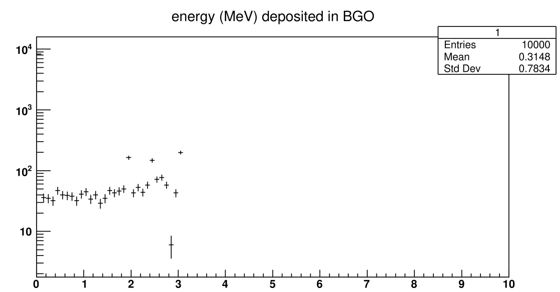



(a) Deposited energy in BGO at 1 MeV incident energy

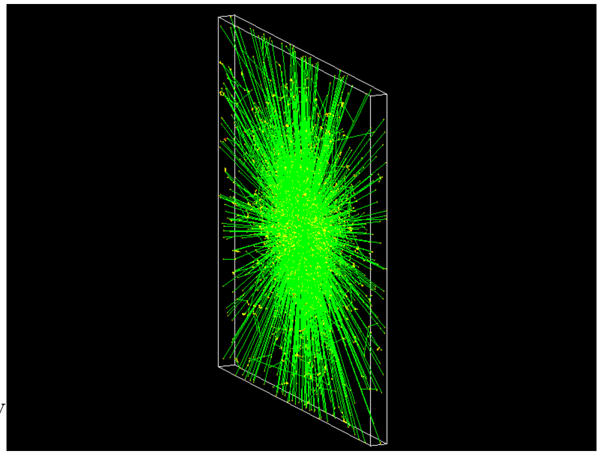


(b) Visualisation of the particle tracks

Figure 13: Results – BGO – 1 MeV

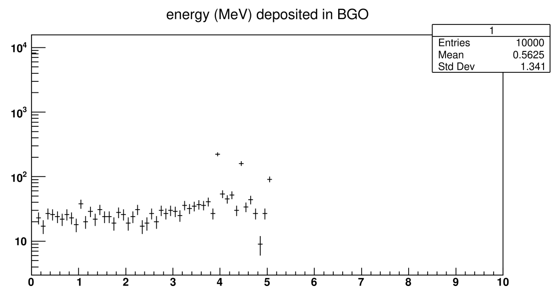



(a) Deposited energy in BGO at 3 MeV incident energy

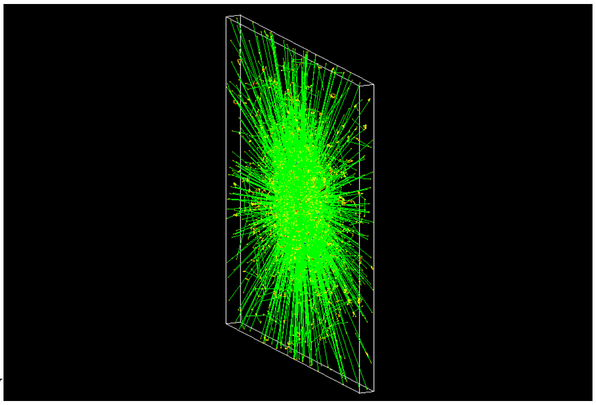


(b) Visualisation of the particle tracks

Figure 14: Results – BGO – 3 MeV

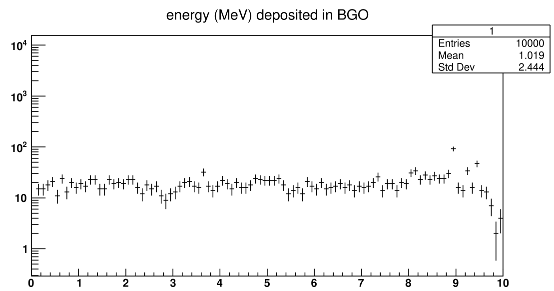



(a) Deposited energy in BGO at 5 MeV incident energy

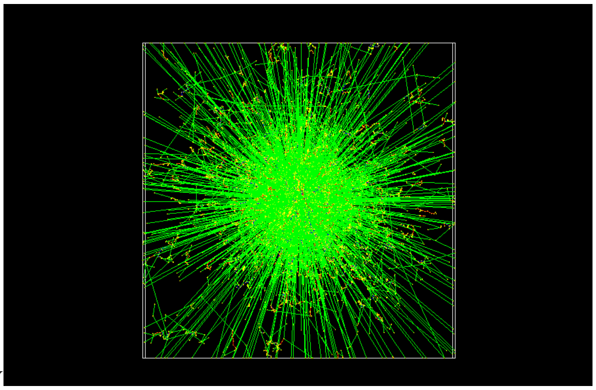


(b) Visualisation of the particle tracks

Figure 15: Results – BGO – 5 MeV



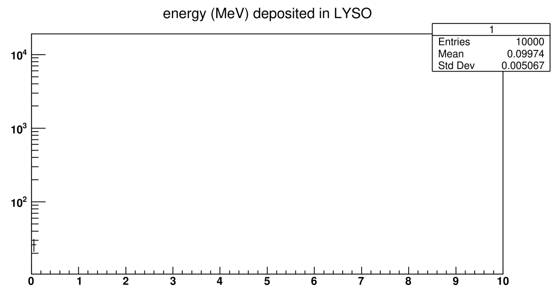

(a) Deposited energy in BGO at 10 MeV incident energy



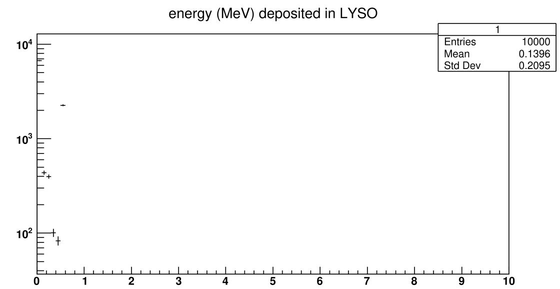
(b) Visualisation of the particle tracks

Figure 16: Results – BGO – 10 MeV

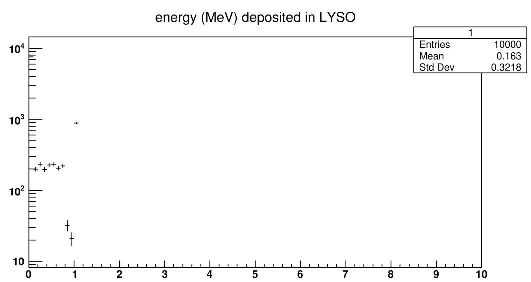
### 2.1.3 LYSO



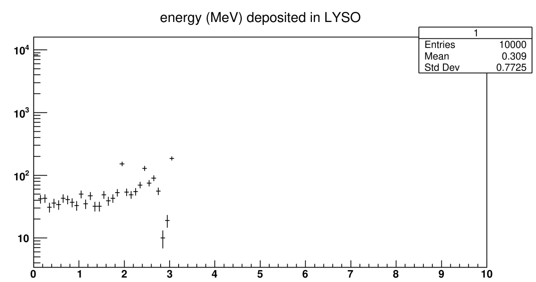

(a) LYSO - 0.1 MeV



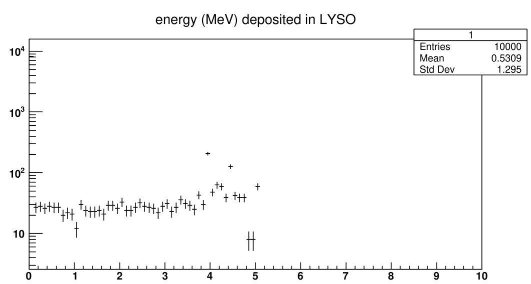

(b) LYSO - 0.5 MeV



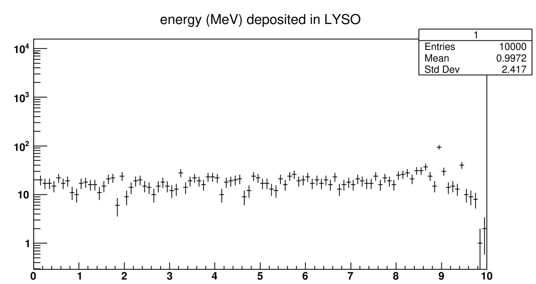

(c) LYSO - 1 MeV




(d) LYSO - 3 MeV



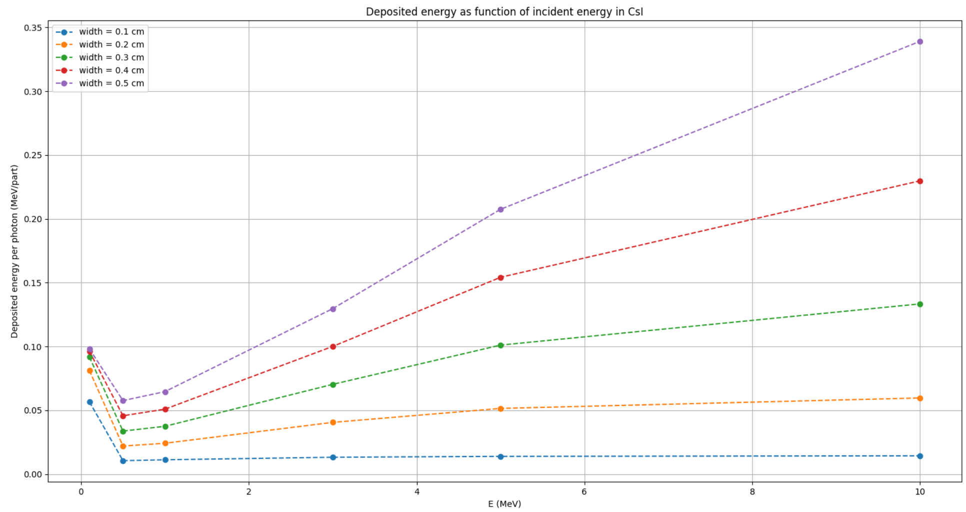

(e) LYSO - 5 MeV

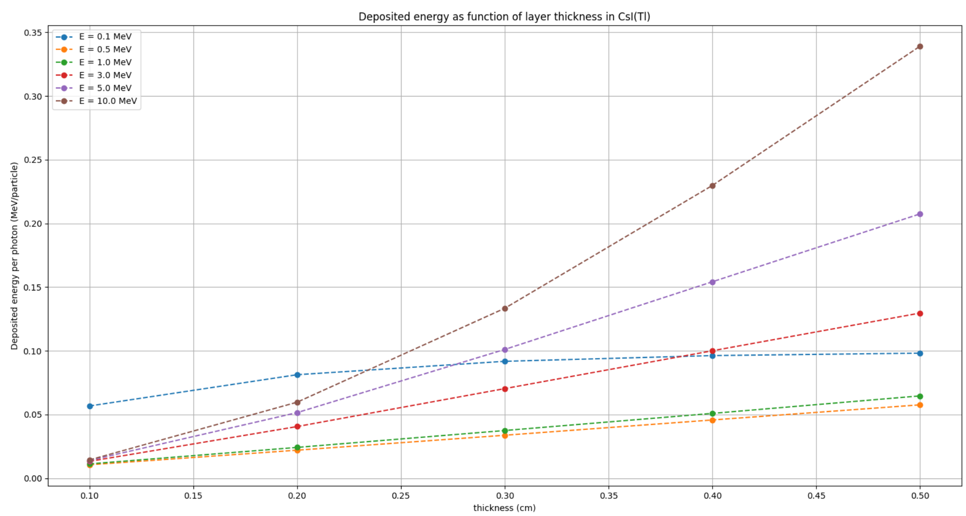


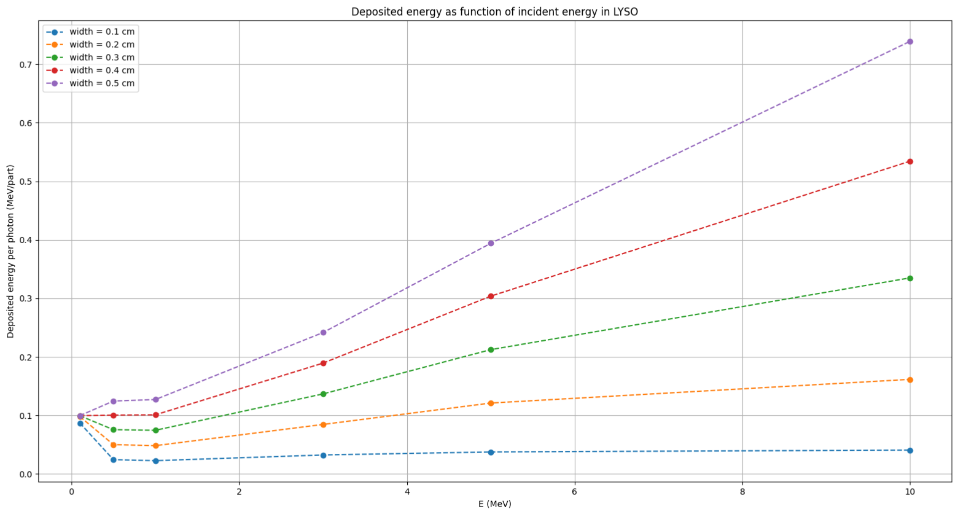

(f) LYSO - 10 MeV

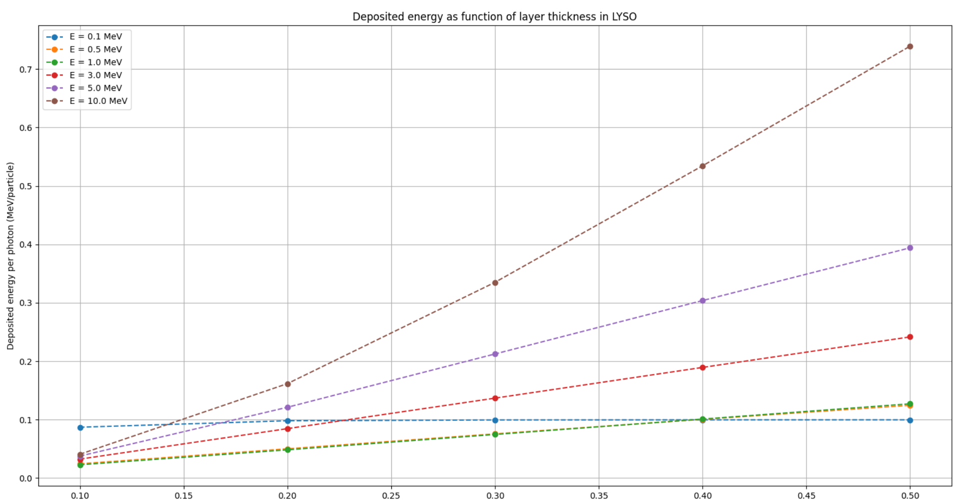
## 2.2 Task 2. Calculate the energy deposition (first)

Cum am calculat energia depusă din fiecare simulare: (link)


Deposited energy as function of incident energy in CsI
width = 0.1 cm
width = 0.2 cm
width = 0.3 cm
width = 0.4 cm
width = 0.5 cm
Deposited energy per photon (MeV/part)
E (MeV)


Deposited energy as function of layer thickness in CsI(Tl)
E = 0.1 MeV
E = 0.5 MeV
E = 1.0 MeV
E = 3.0 MeV
E = 5.0 MeV
E = 10.0 MeV
Deposited energy per photon (MeV/particle)
thickness (cm)




## 2.3 Task 3. Calculate the deposited energy and the number of scintillations produced in each material

The code that was used to obtain the results and plots in this section: link

The number of interacting photons can be obtained with the following formula. Further, we can use this to verify that the number of entries provided by GEANT4 is acceptable.

$$N_{interactions} = N_0(1 - \mathrm{e}^{-\mu \cdot x})$$

The number of optical photons (scintillations) produced by the interaction with gamma photons is given by:

$$\text{optical yield per interacting particle} = \frac{\text{deposited energy}}{\text{entries}} \cdot \text{light yield}$$

$$\text{total optical yield} = \text{deposited energy} \cdot \text{light yield}$$

| material | $\rho$ $(g/cm^3)$ | yield (ph/keV) | E (MeV) | $\mu$ (cm$^{-1}$) |
|---|---|---|---|---|
| CsI(Tl) | 4.51 | 54 | 0.1 | 9.17785 |
| | | | 0.5 | 0.4423859 |
| | | | 1 | 0.2637448 |
| | | | 3 | 0.1678171 |
| | | | 5 | 0.1633522 |
| | | | 10 | 0.181753 |
| BGO | 7.1 | 8 | 0.1 | 28.1941 |
| | | | 0.5 | 0.98619 |
| | | | 1 | 0.484504 |
| | | | 3 | 0.286982 |
| | | | 5 | 0.275267 |
| | | | 10 | 0.301466 |
| LYSO | 7.4 | 40 | 0.1 | 18.5 |
| | | | 0.5 | 0.81918 |
| | | | 1 | 0.463832 |
| | | | 3 | 0.284604 |
| | | | 5 | 0.26973 |
| | | | 10 | 0.290006 |

Table 1: The density, yield and linear coefficients corresponding to each material and incident energy

| E (MeV) | thickness (mm) | $N_{G4}$ | DE (MeV) | DE($\frac{MeV}{part}$) | $N_{int}$ | scintil. | total scintil. |
|---|---|---|---|---|---|---|---|
| 0.1 | 0.5 | 741700 | 73185.138 | 0.099 | 755784.684 | 789.377 | 585481107.200 |
| | 1 | 932826 | 92543.909 | 0.099 | 940358.879 | 793.665 | 740351270.560 |
| | 2 | 995378 | 98979.817 | 0.099 | 996442.937 | 795.515 | 791838532.320 |
| 0.5 | 0.5 | 48246 | 14631.719 | 0.303 | 48113.525 | 2426.186 | 117053755.280 |
| | 1 | 91330 | 30342.555 | 0.332 | 93912.138 | 2657.839 | 242740441.680 |
| | 2 | 171806 | 61453.63 | 0.358 | 179004.787 | 2861.536 | 491629037.680 |
| 1 | 0.5 | 25319 | 10948.519 | 0.432 | 23934.125 | 3459.384 | 87588155.160 |
| | 1 | 48203 | 24578.044 | 0.51 | 47295.408 | 4079.089 | 196624350.120 |
| | 2 | 92002 | 52352.935 | 0.569 | 92353.96 | 4552.330 | 418823482.880 |
| 3 | 0.5 | 15229 | 9840.736 | 0.646 | 14246.642 | 5169.472 | 78725888.120 |
| | 1 | 29244 | 32508.677 | 1.112 | 28290.318 | 8893.086 | 260069418.400 |
| | 2 | 56534 | 85053.088 | 1.504 | 55780.294 | 12035.672 | 680424703.200 |
| 5 | 0.5 | 14589 | 9844.073 | 0.675 | 13669.068 | 5398.080 | 78752585.560 |
| | 1 | 28260 | 38005.496 | 1.345 | 27151.293 | 10758.810 | 304043966.160 |
| | 2 | 54868 | 123440.796 | 2.25 | 53565.393 | 17998.221 | 987526364.880 |
| 10 | 0.5 | 15798 | 9917.915 | 0.628 | 14960.266 | 5022.365 | 79343322.960 |
| | 1 | 30807 | 41340.75 | 1.342 | 29696.723 | 10735.417 | 330725996.920 |
| | 2 | 59968 | 165331.96 | 2.757 | 58511.551 | 22056.024 | 1322655676.320 |

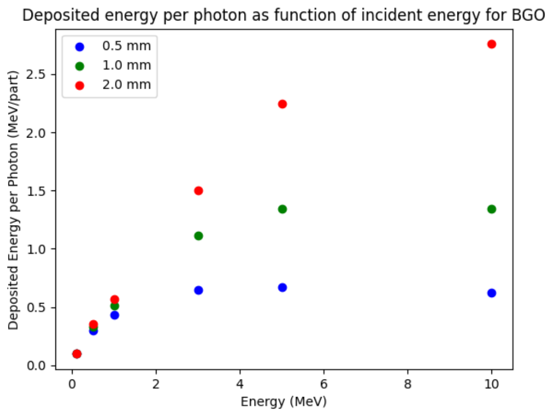
Table 2: Results obtained for $10^6$ incident photons in BGO material. Yield(BGO) = 8 photons/keV. The number of scintillations is calculated for the interacting particles. The column "scintil." represents scintillations per interacting particles, while the column "total scintil." refers to the entire beam.

| E (MeV) | thickness (mm) | $N_{G4}$ | DE (MeV) | DE($\frac{MeV}{part}$) | $N_{int}$ | scintil. | total scintil. |
|---|---|---|---|---|---|---|---|
| 0.1 | 0.5 | 352969 | 34075.292 | 0.097 | 368016.821 | 5213.109 | 1840065754.230 |
| | 1 | 579259 | 56672.02 | 0.098 | 600597.261 | 5283.110 | 3060289054.350 |
| | 2 | 821944 | 81223.12 | 0.099 | 840477.452 | 5336.189 | 4386048480.000 |
| 0.5 | 0.5 | 23387 | 4950.17 | 0.212 | 21876.457 | 11429.820 | 267309192.150 |
| | 1 | 43855 | 10482.999 | 0.239 | 43274.335 | 12908.036 | 566081931.690 |
| | 2 | 83162 | 21941.315 | 0.264 | 84676.002 | 14247.264 | 1184830992.180 |
| 1 | 0.5 | 14934 | 4732.622 | 0.317 | 13100.669 | 17112.733 | 255561562.080 |
| | 1 | 27736 | 11179.311 | 0.403 | 26029.711 | 21765.316 | 603682799.940 |
| | 2 | 52465 | 24125.558 | 0.46 | 51381.876 | 24831.414 | 1302780125.790 |
| 3 | 0.5 | 9426 | 3599.809 | 0.382 | 8355.75 | 20622.715 | 194389707.600 |
| | 1 | 17726 | 13174.569 | 0.743 | 16641.682 | 40134.645 | 711426713.580 |
| | 2 | 34165 | 40490.142 | 1.185 | 33006.417 | 63997.297 | 2186467653.150 |
| 5 | 0.5 | 8920 | 3406.614 | 0.382 | 8134.346 | 20622.999 | 183957148.980 |
| | 1 | 17075 | 13853.369 | 0.811 | 16202.524 | 43811.532 | 748081904.130 |
| | 2 | 33068 | 51422.718 | 1.555 | 32142.526 | 83973.231 | 2776826786.580 |
| 10 | 0.5 | 9638 | 3566.448 | 0.37 | 9046.482 | 19982.175 | 192588200.640 |
| | 1 | 18664 | 14282.154 | 0.765 | 18011.125 | 41322.134 | 771236318.160 |
| | 2 | 36402 | 59606.751 | 1.637 | 35697.85 | 88422.739 | 3218764544.820 |

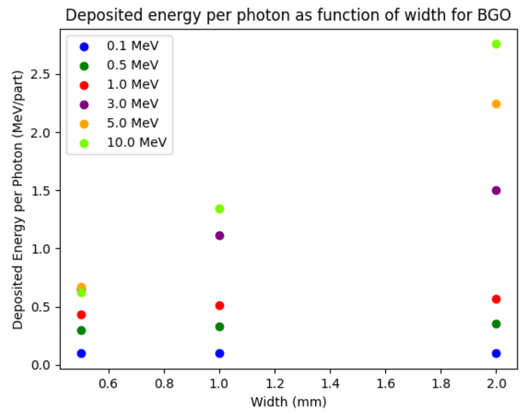
Table 3: Results obtained for $10^6$ incident photons in CsI(Tl) material. Yield(CsI(Tl)) = 54 photons/keV. The number of scintillations is calculated for the interacting particles. The column "scintil." represents scintillations per interacting particles, while the column "total scintil." refers to the entire beam.

| E (MeV) | thickness (mm) | $N_{G4}$ | DE (MeV) | DE($\frac{MeV}{part}$) | $N_{int}$ | scintil. | total scintil. |
|---|---|---|---|---|---|---|---|
| 0.1 | 0.5 | 649348 | 64026.83 | 0.099 | 603468.581 | 3944.069 | 2561073200.400 |
| | 1 | 876529 | 87007.819 | 0.099 | 842762.834 | 3970.562 | 3480312759.000 |
| | 2 | 984653 | 98081.232 | 0.1 | 975276.474 | 3984.398 | 3923249279.400 |
| 0.5 | 0.5 | 43382 | 11683.406 | 0.269 | 40131.516 | 10772.584 | 467336258.400 |
| | 1 | 82313 | 24397.032 | 0.296 | 78652.494 | 11855.737 | 975881299.800 |
| | 2 | 155127 | 50073.508 | 0.323 | 151118.773 | 12911.616 | 2002940308.600 |
| 1 | 0.5 | 25101 | 10253.969 | 0.409 | 22924.742 | 16340.336 | 410158775.400 |
| | 1 | 47560 | 22667.121 | 0.477 | 45323.94 | 19064.021 | 906684847.200 |
| | 2 | 90851 | 48275.586 | 0.531 | 88593.62 | 21254.840 | 1931023435.000 |
| 3 | 0.5 | 15348 | 9894.132 | 0.645 | 14129.429 | 25786.113 | 395765264.400 |
| | 1 | 29554 | 32379.815 | 1.096 | 28059.218 | 43824.613 | 1295192610.800 |
| | 2 | 57142 | 84555.136 | 1.48 | 55331.116 | 59189.483 | 3382205442.000 |
| 5 | 0.5 | 14493 | 9811.898 | 0.677 | 13395.965 | 27080.379 | 392475927.800 |
| | 1 | 28079 | 37552.324 | 1.337 | 26612.477 | 53495.244 | 1502092946.200 |
| | 2 | 54557 | 121099.03 | 2.22 | 52516.731 | 88787.162 | 4843961207.800 |
| 10 | 0.5 | 15439 | 9833.258 | 0.637 | 14395.677 | 25476.413 | 393330337.400 |
| | 1 | 30093 | 40718.942 | 1.353 | 28584.118 | 54124.138 | 1628757682.200 |
| | 2 | 58476 | 161542.563 | 2.763 | 56351.185 | 110501.787 | 6461702517.600 |

Table 4: Results obtained for $10^6$ incident photons in LYSO material. Yield(LYSO) = 40 photons/keV. The number of scintillations is calculated for the interacting particles. The column "scintil." represents scintillations per interacting particles, while the column "total scintil." refers to the entire beam.

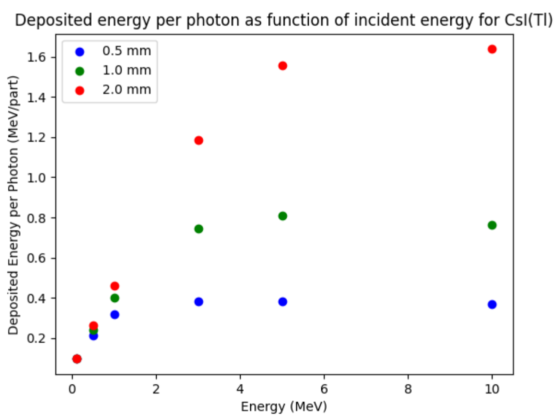



(a)

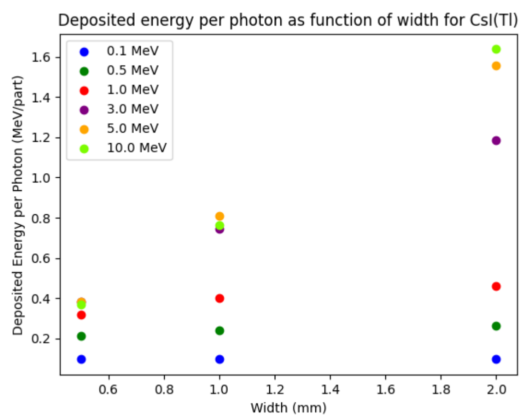



(b)

Figure 18: Deposited energy per photon – BGO

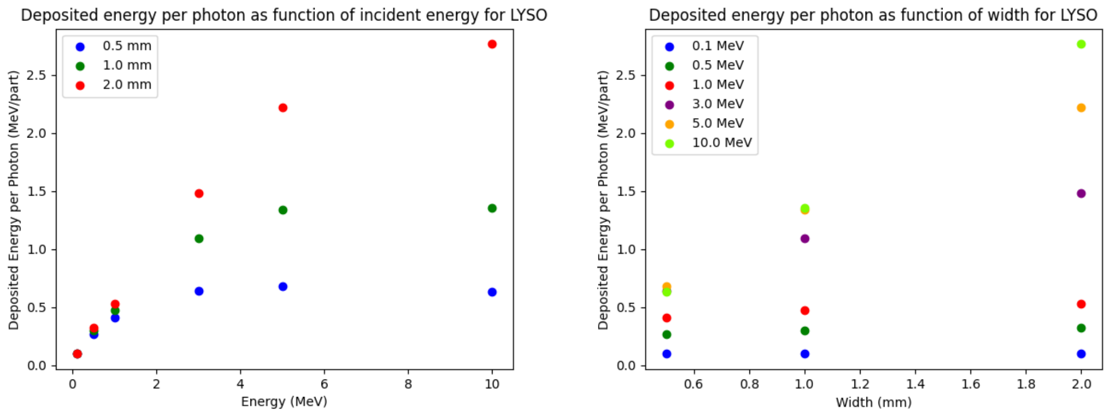



(a)



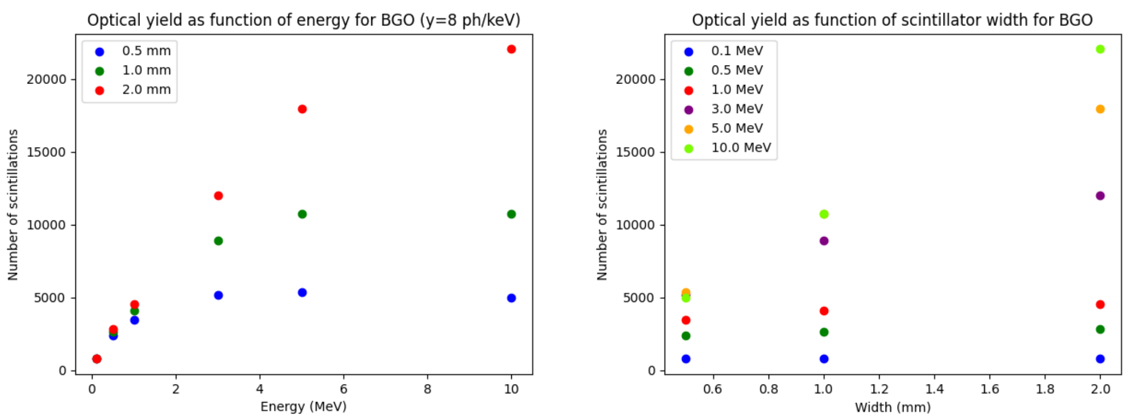

(b)

Figure 19: Deposited energy per photon – CsI(Tl)



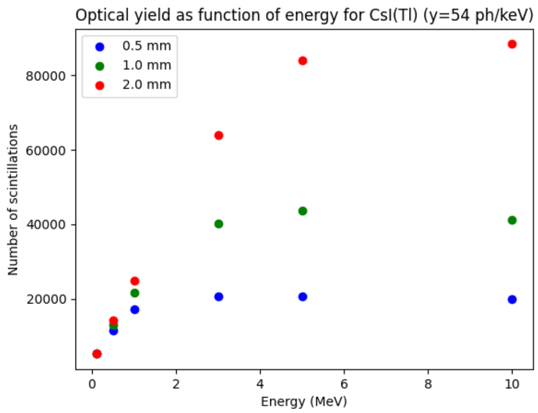

(a) (b)

Figure 20: Deposited energy per photon – LYSO

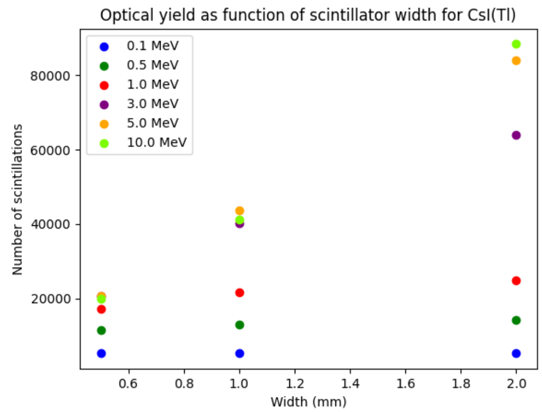



(a) (b)

Figure 21: Optical yield per photon - BGO

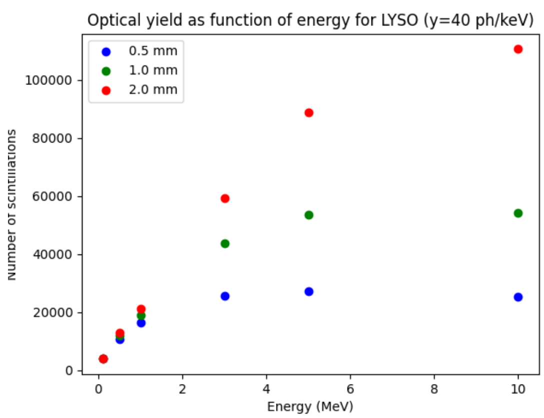



(a)

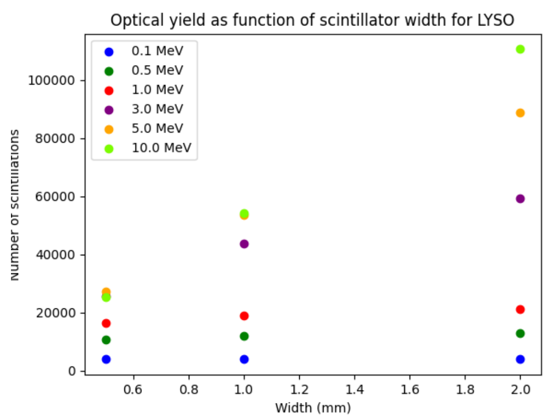



(b)

Figure 22: Optical yield per photon - CsI(Tl)




(a)




(b)

Figure 23: Optical yield per photon - LYSO

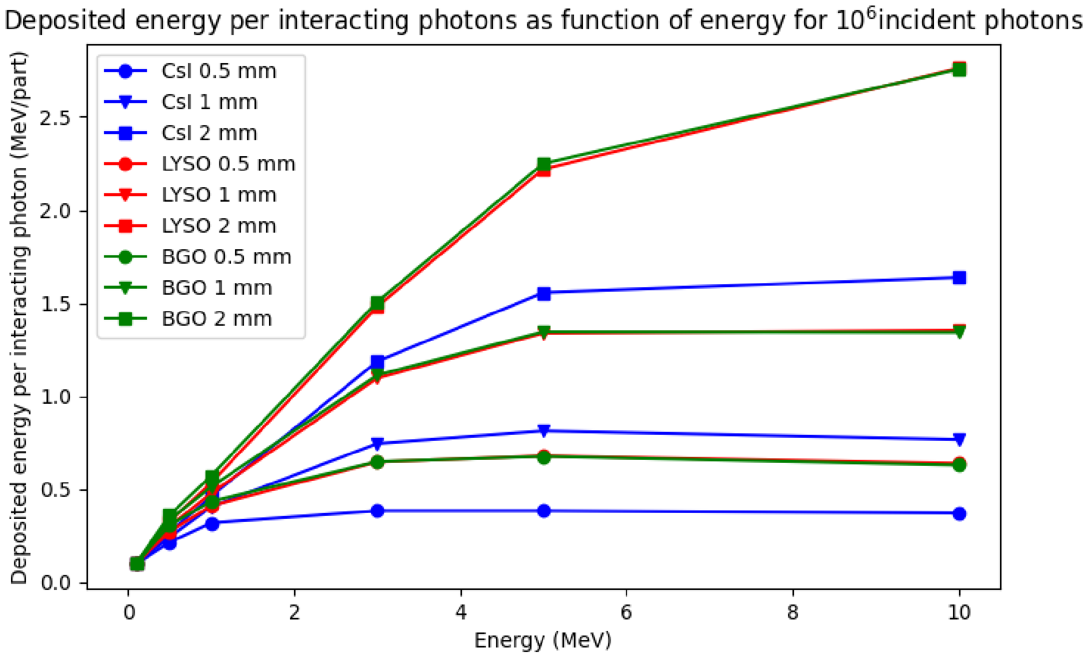



Figure 24: Deposited energy per photon for each scintillator material and detector thicnkess as function of incident photon energy. In these simulations, we used a beam of $10^6$ incident photons.

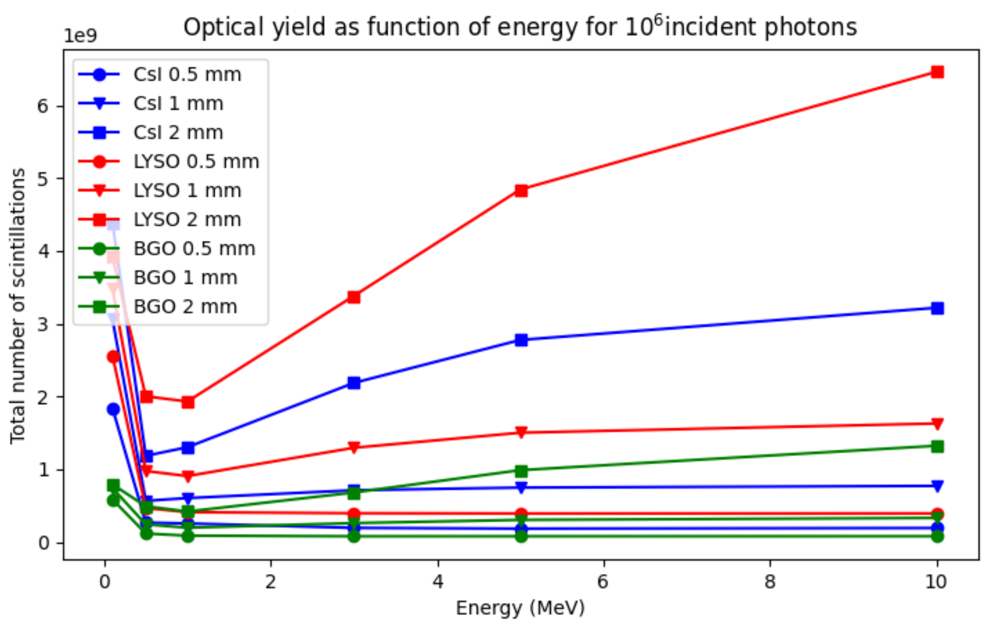



Figure 25: The total optical yield (total number of scintillations produced by the beam, not per incident photon) for each scintillator material and detector thicnkess as function of incident photon energy. In these simulations, we used a beam of $10^6$ incident photons.

## 2.4 Task 4. Surface energy deposition

Simulations were performed for the following materials: CsI(Tl), BGO, LYSO. The thicknesses of the scintillator were 0.5, 1 and 2 mm. The energies used for the incident photons were 0.1, 0.5, 1, 3, 5 and 10 MeV. The simulations were performed for $10^7$ incident photons. The results are presented in the following figures.

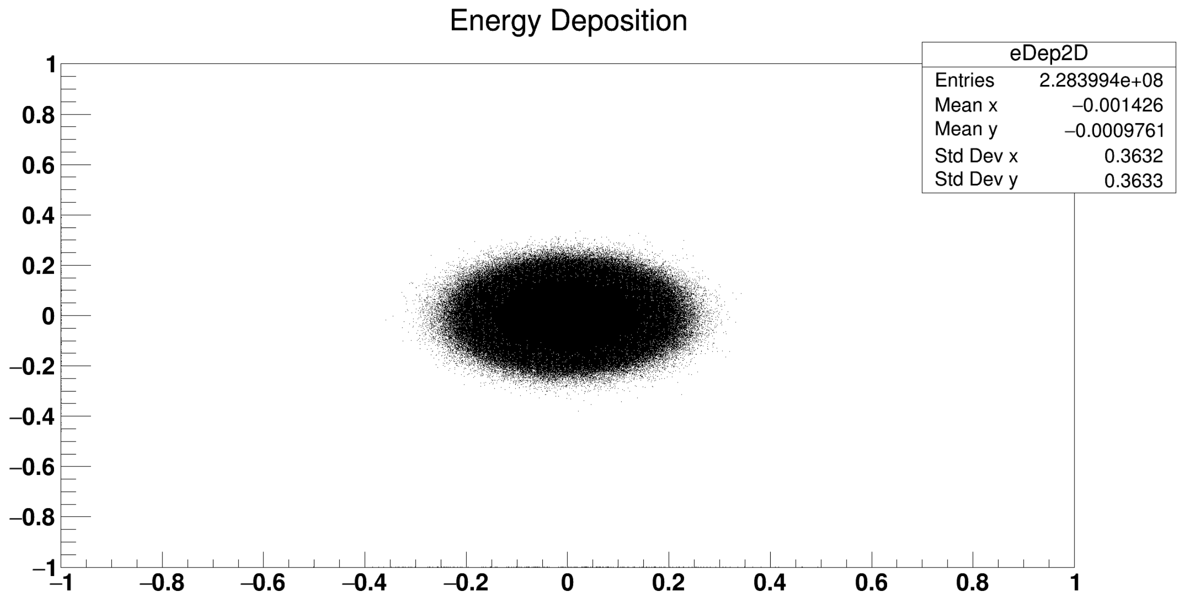



Figure 26: 2D energy deposition for a beam of $10^7$ photons of 10 MeV in a 2mm thick CsI scintillator.

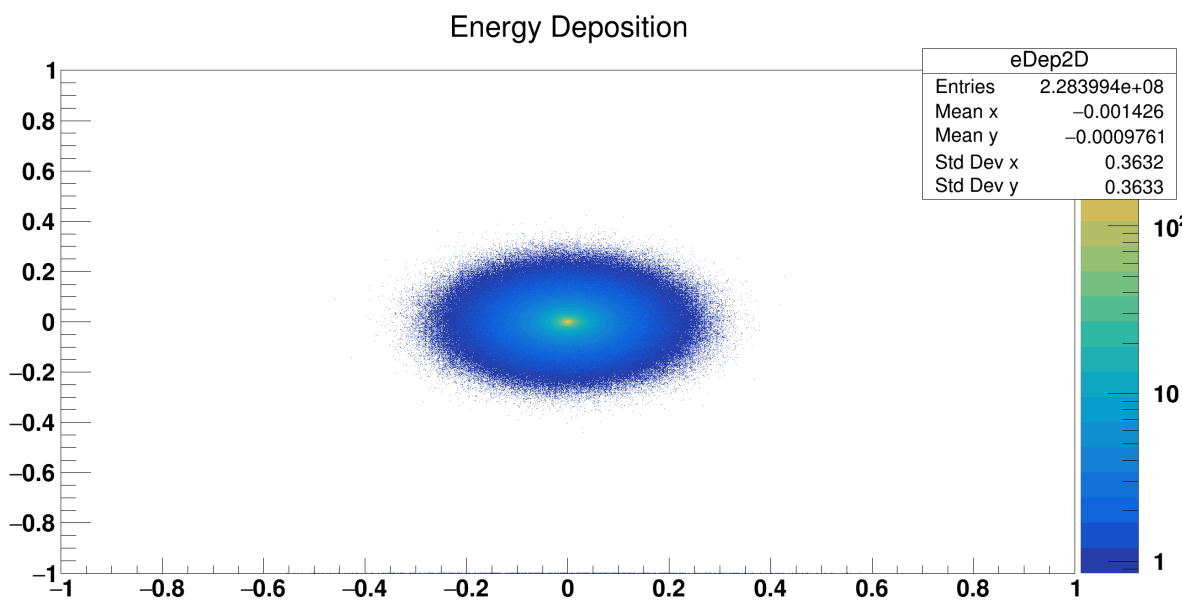



Figure 27: Log scale view of the energy deposition.

What I added new to the code:

- I included a `config.json` file where the parameters of interest can be modified (so far, beam energy, detector thickness and material)
- in the root file, there can be found 3 histograms: 1D energy deposition histogram, 2D surface energy deposition histogram and another histogram from which we can identify the energy of the beam and number of particles
- in `SteppingAction.cc`, modified `G4ThreeVector position = aStep->GetPostStepPoint()->GetPosition();` in order to obtain a better projection shape that can be fitted with a function

The first 3 figures show the X projection of the 2D energy deposition histogram for each scintillator material and detector thickness. From these projections, the FWHM and FWTM was computed analitically and plotted in the last 2 figures. The next step is to compare this values with the ones obtained from fitting.

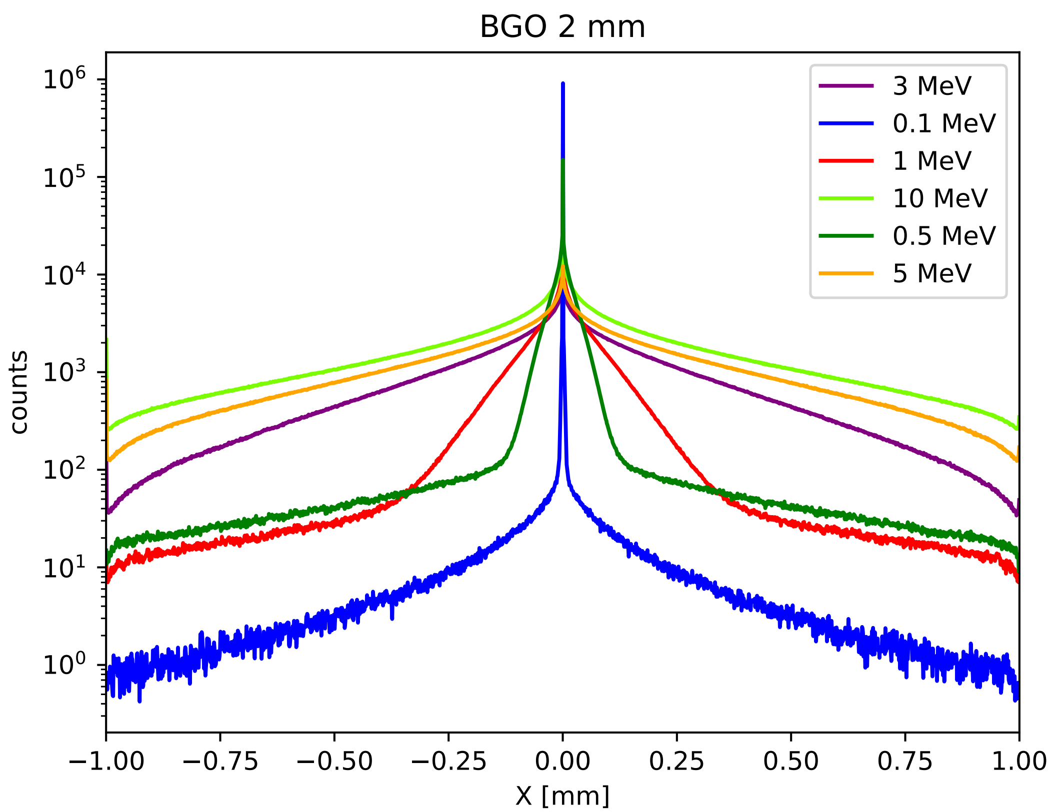



Figure 28: X projection of the 2D energy deposition histogram for BGO scintillator at 2mm detector thickness.

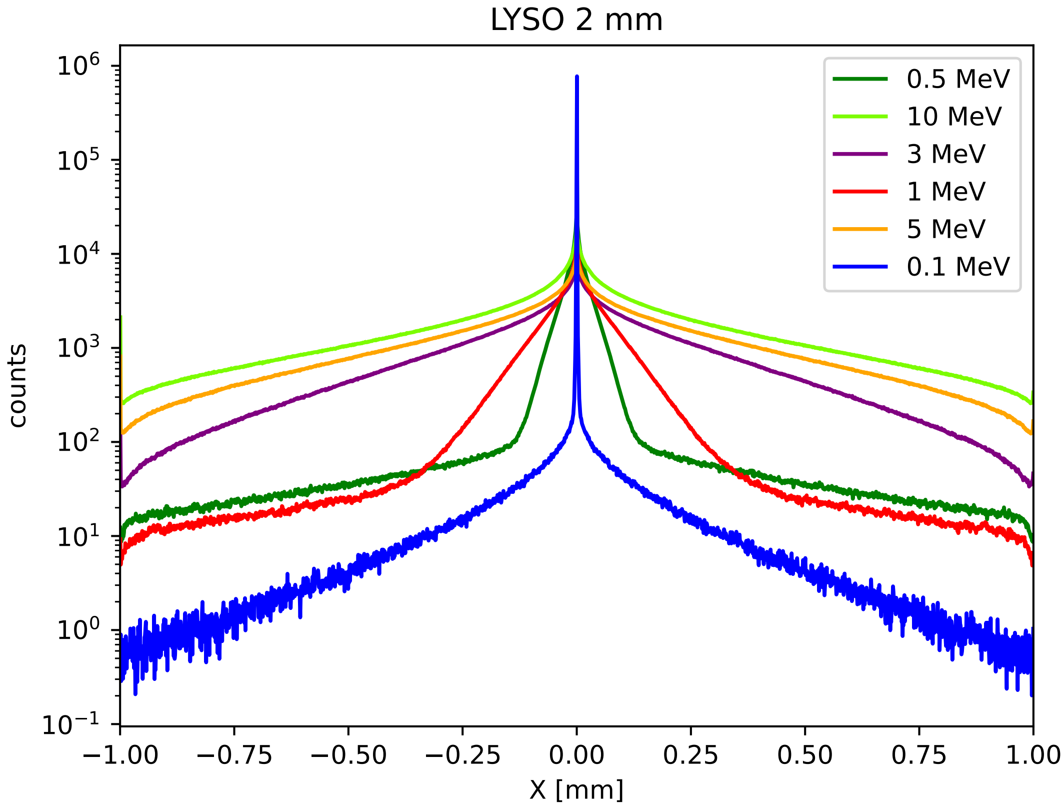



Figure 29: X projection of the 2D energy deposition histogram for LYSO scintillator at 2mm detector thickness.

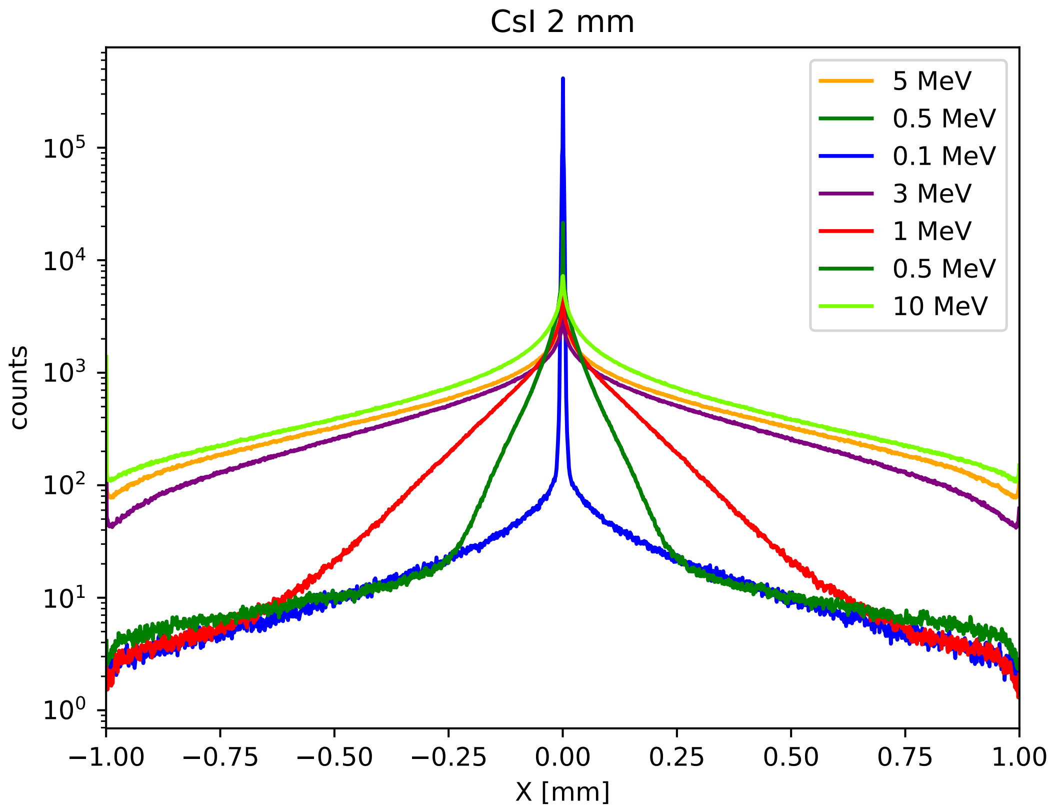



Figure 30: X projection of the 2D energy deposition histogram for CsI(Tl) scintillator at 2mm detector thickness.

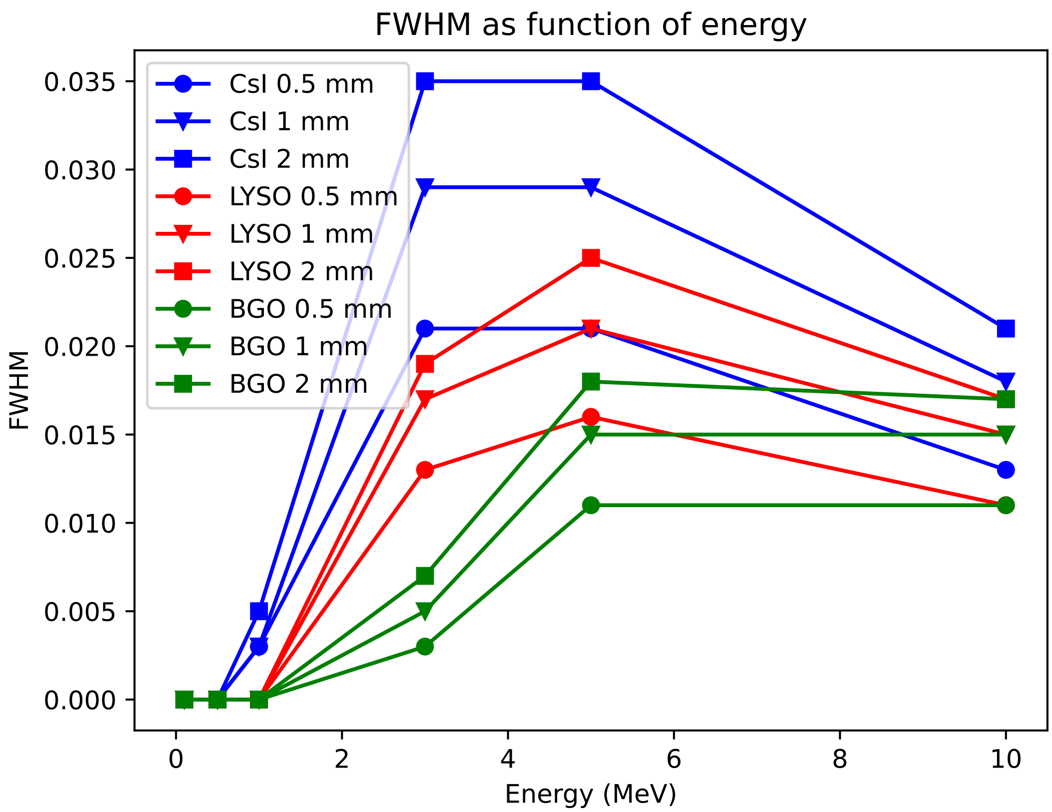



Figure 31: Full width at half maximum for all scintillators and all energies.

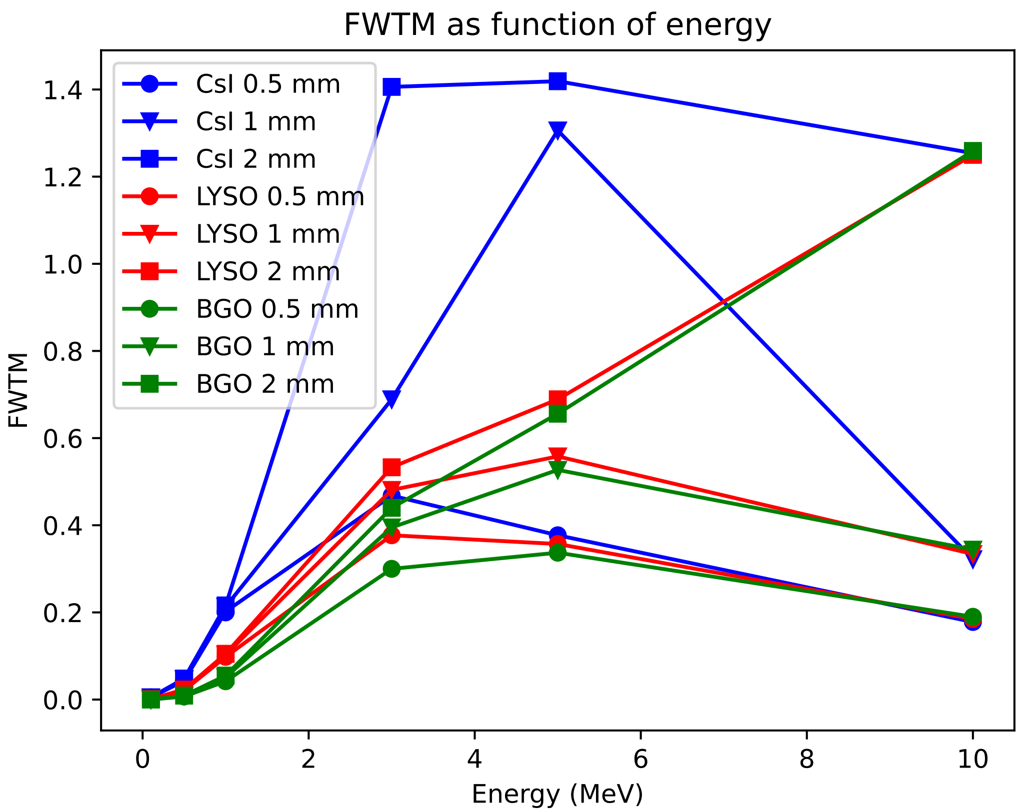



Figure 32: Full width at tenth maximum for all scintillators and all energies.

Notes 25 ianuarie:

- de repetat simularile CsI 2 mm si 1 mm
- grafic, cum arata proiectia in fct de distanta si ca fwtm e exact ce da script-ul
- la 10 MeV verifica valoarea obtinuta
- CsI 3 MeV 5 MeV - ceva nu este in regula
- de verificat ca script-ul face ce trebuie

Intre timp, am identificat de ce FWTM nu era calculat bine – la marginea proiectiei 1D a histogramei 2D, se adunau niste count-uri care ajungeau la un maxim mai mare decat FWTM, iar programul se oprea cu marker-ul din stanga la acesta zona, nu la fwtm al distributiei. In sectiunea urmatoare sunt afisate graficele bune.

### 2.5 Task 5. Energy deposited in FWTM region (february and beginning of March)

For each computed FWHM and FWTM, the deposited energy was computed.

Find the markers which define FWTM and FWHM and integrate between them, then compare with the total deposited energy.

The purpose is to see how much energy is deposited in the region of interest and how much is left out (the noise).

To be continued with super gaussian fit.