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

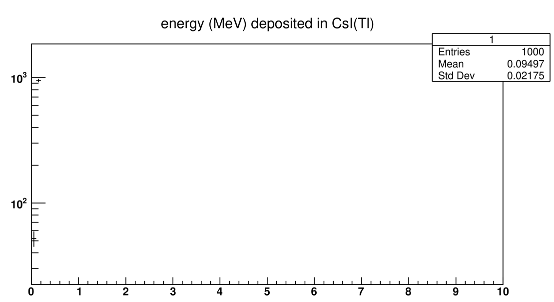
```
// cosntruct LYSO

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

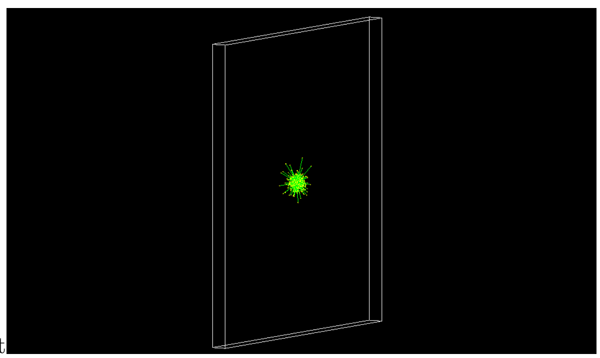
```
//
// Scintillator pannel 4cm x 4cm x 2mm
//

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)

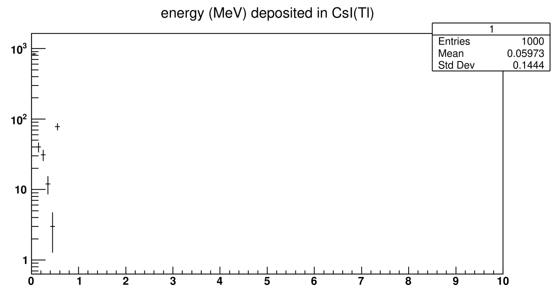


(a) Deposited energy in CsI(Tl) at 0.1 MeV incident energy

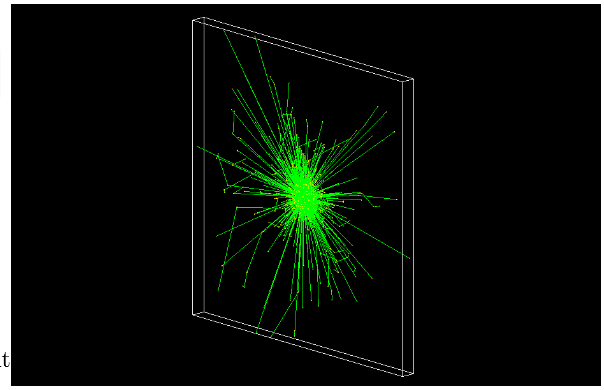


(b) Visualisation of the particle tracks

Figure 5: Results – CsI(Tl) – 0.1 MeV

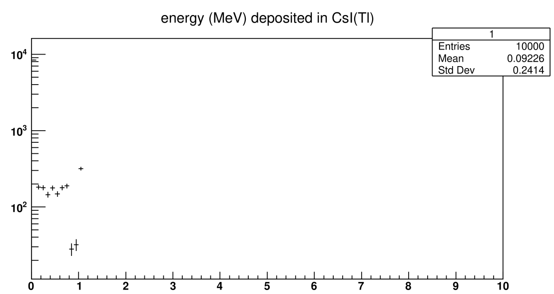


(a) Deposited energy in CsI(Tl) at 0.5 MeV incident energy

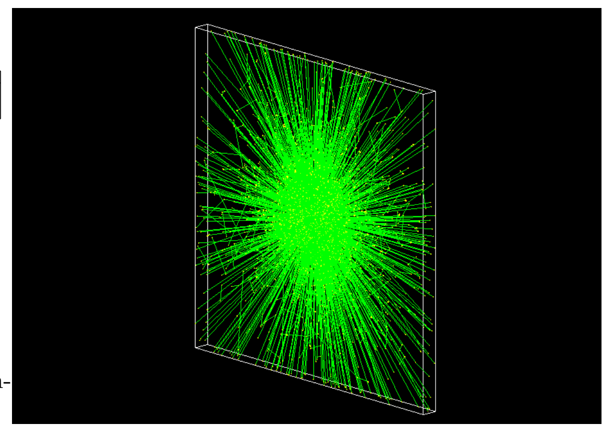


(b) Visualisation of the particle tracks

Figure 6: Results – CsI(Tl) – 0.5 MeV

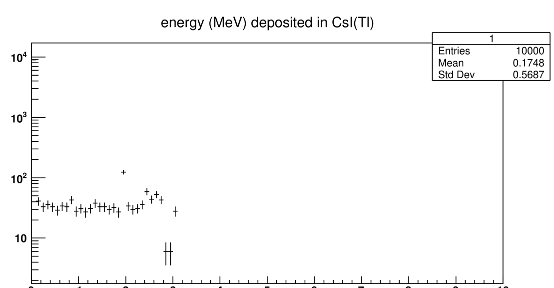


(a) Deposited energy in CsI(Tl) at 1 MeV incident energy

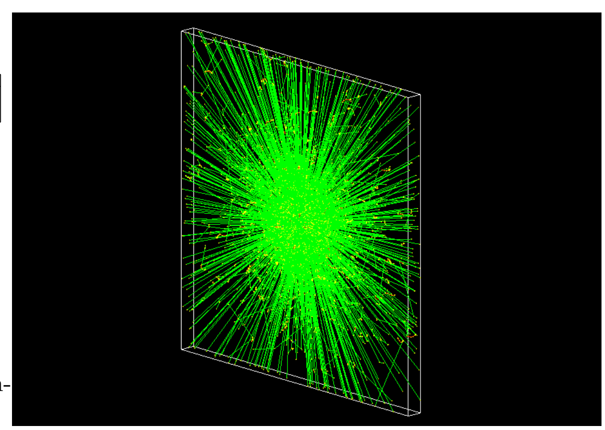


(b) Visualisation of the particle tracks

Figure 7: Results – CsI(Tl) – 1 MeV

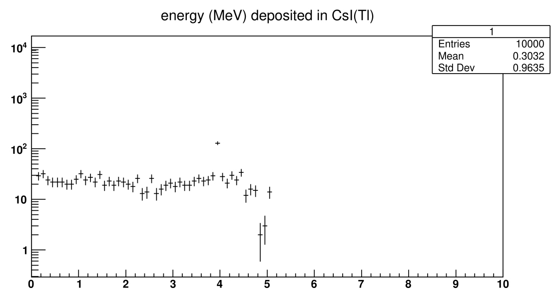


(a) Deposited energy in CsI(Tl) at 3 MeV incident energy

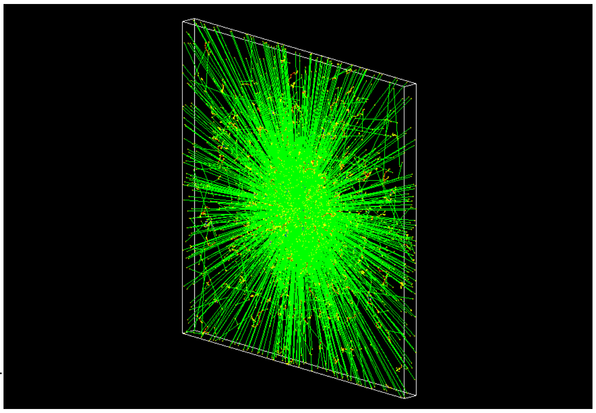


(b) Visualisation of the particle tracks

Figure 8: Results – CsI(Tl) – 3 MeV

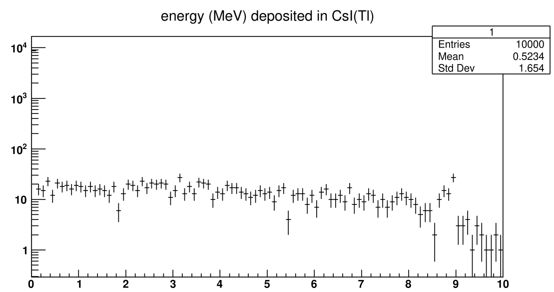


(a) Deposited energy in CsI(Tl) at 5 MeV incident energy

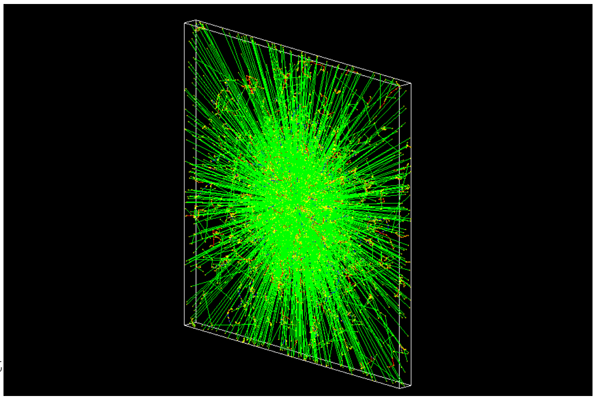


(b) Visualisation of the particle tracks

Figure 9: Results – CsI(Tl) – 5 MeV



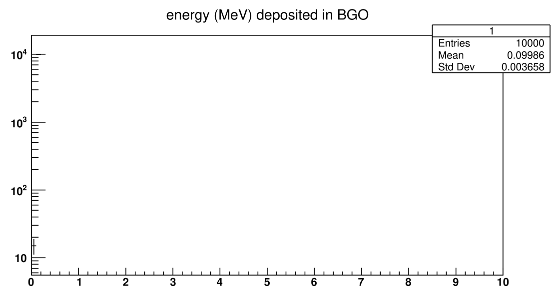
(a) Deposited energy in CsI(Tl) at 10 MeV incident energy



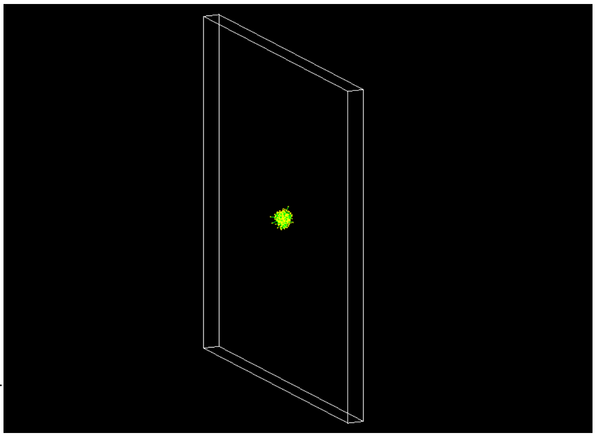
(b) Visualisation of the particle tracksy

Figure 10: Results – CsI(Tl) – 10 MeV

2.1.2 BGO

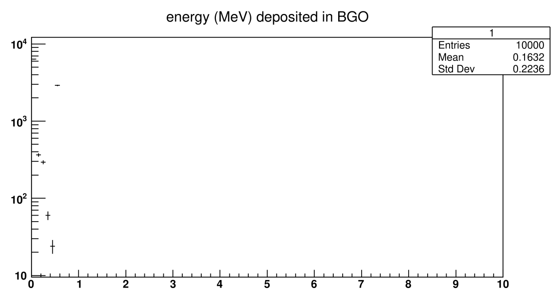


(a) Deposited energy in BGO at 0.1 MeV incident energy

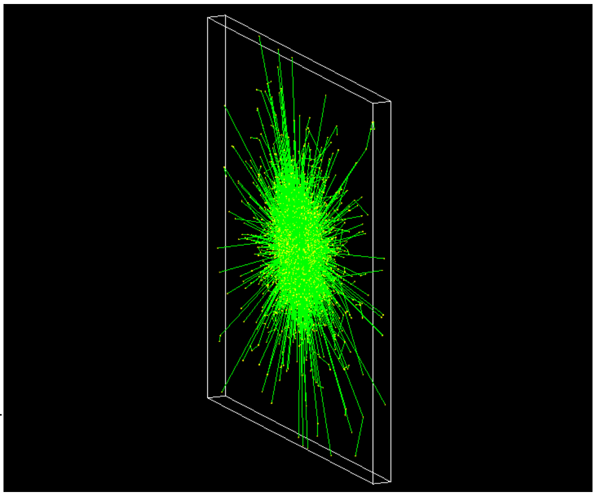


(b) Visualisation of the particle tracks

Figure 11: Results – BGO – 0.1 MeV

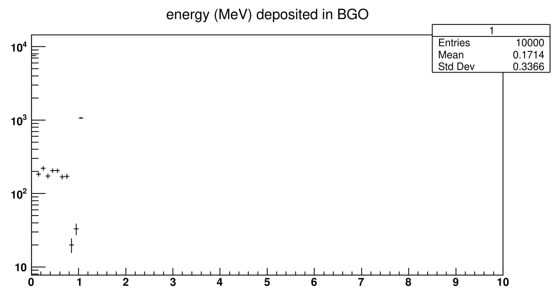


(a) Deposited energy in BGO at 0.5 MeV incident energy

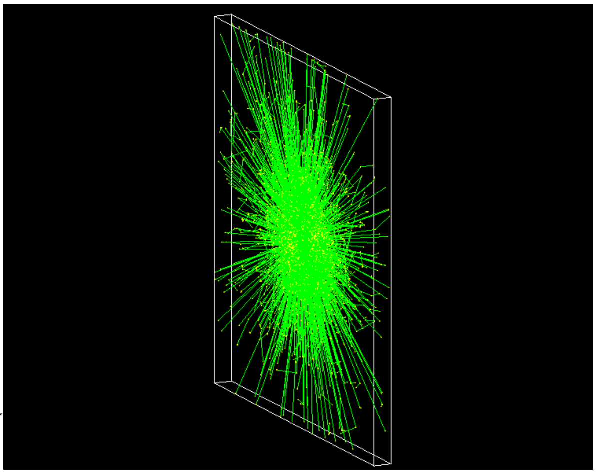


(b) Visualisation of the particle tracks

Figure 12: Results – BGO – 0.5 MeV

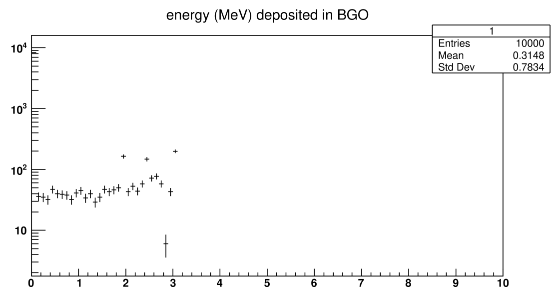


(a) Deposited energy in BGO at 1 MeV incident energy

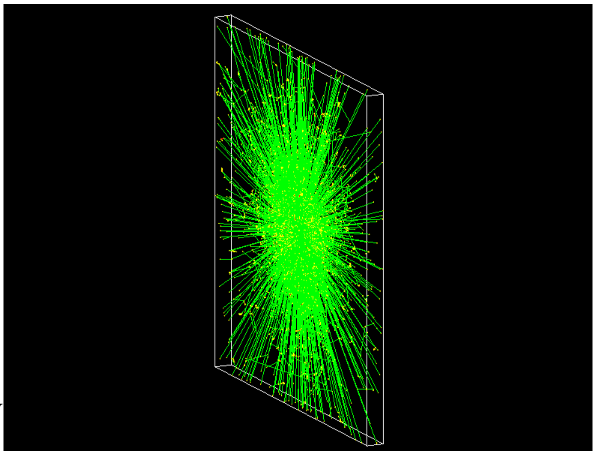


(b) Visualisation of the particle tracks

Figure 13: Results – BGO – 1 MeV

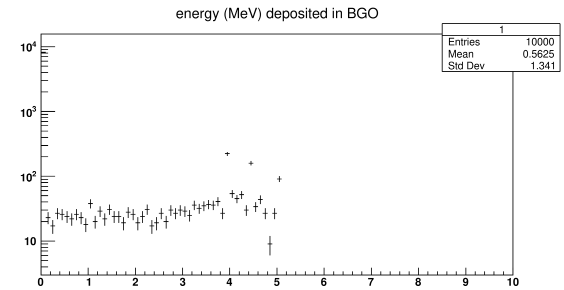


(a) Deposited energy in BGO at 3 MeV incident energy

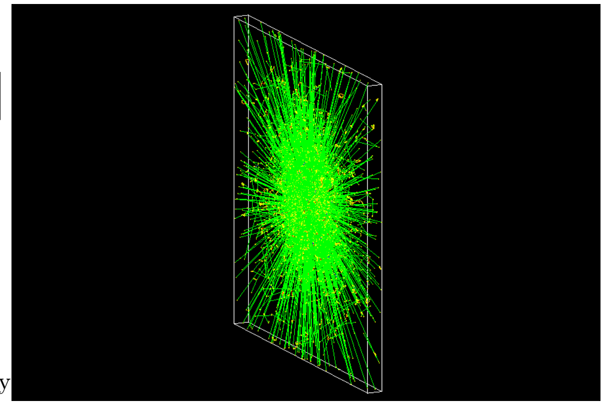


(b) Visualisation of the particle tracks

Figure 14: Results – BGO – 3 MeV

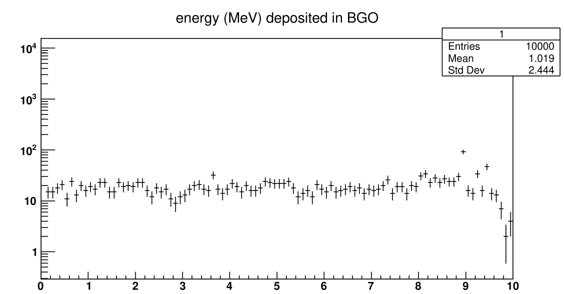


(a) Deposited energy in BGO at 5 MeV incident energy

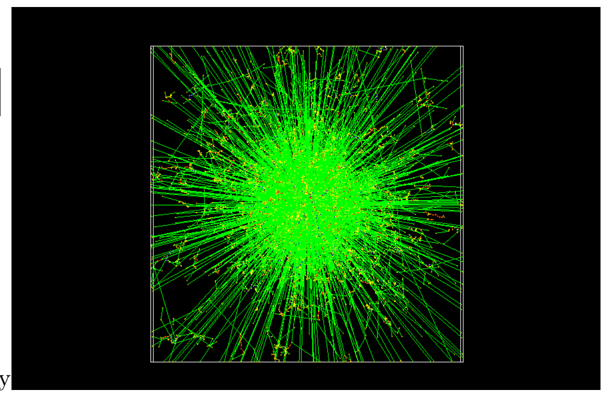


(b) Visualisation of the particle tracks

Figure 15: Results – BGO – 5 MeV



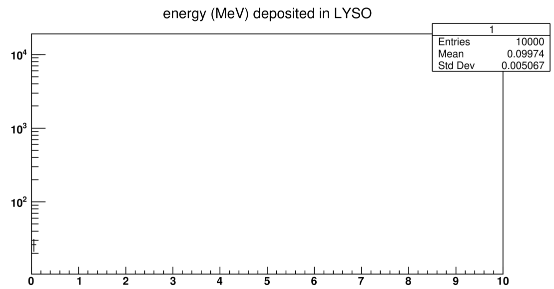
(a) Deposited energy in BGO at 10 MeV incident energy



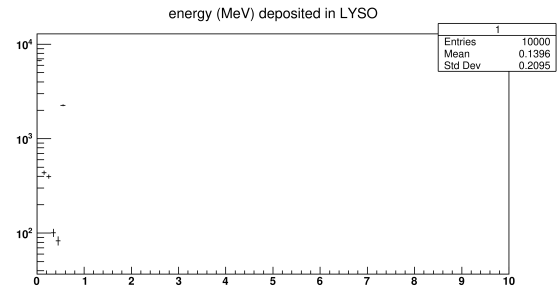
(b) Visualisation of the particle tracks

Figure 16: Results – BGO – 10 MeV

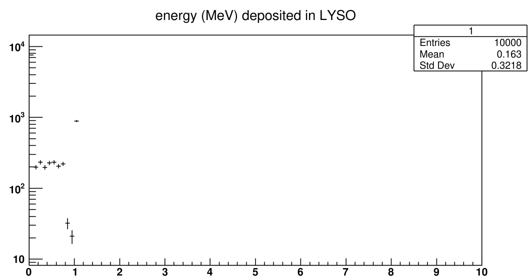
2.1.3 LYSO



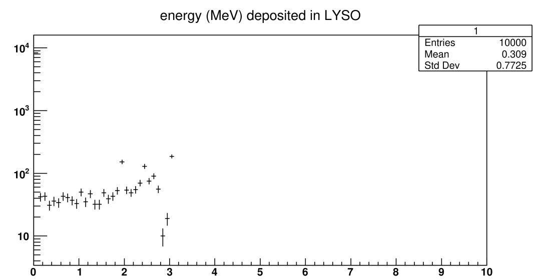
(a) LYSO - 0.1 MeV



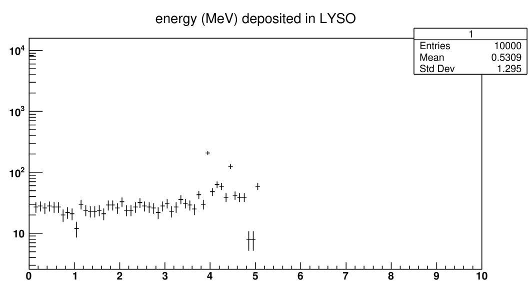
(b) LYSO - 0.5 MeV



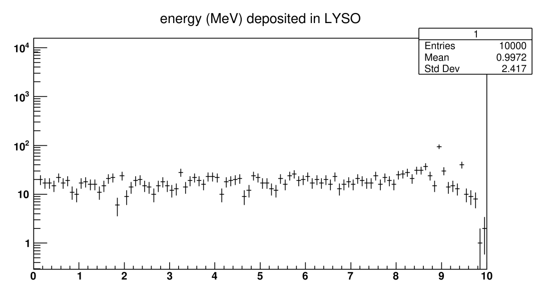
(c) LYSO - 1 MeV



(d) LYSO - 3 MeV



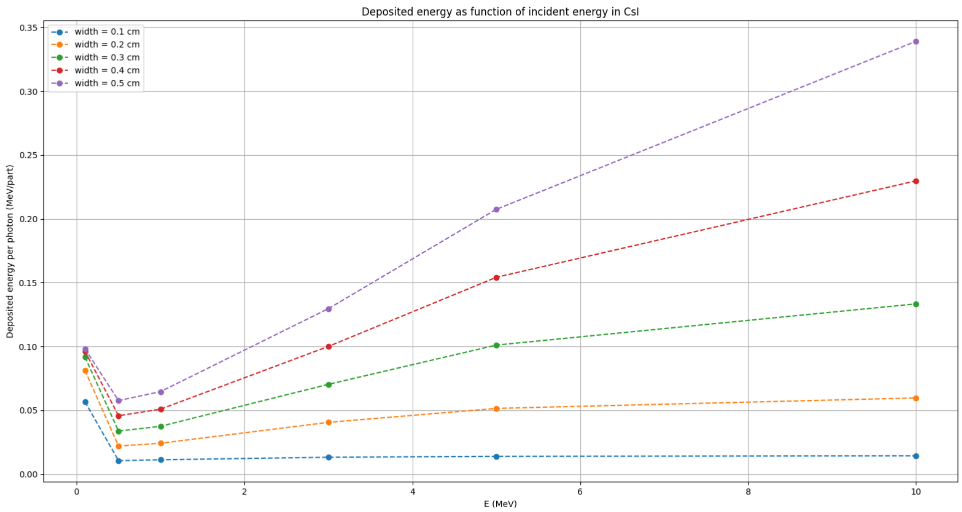
(e) LYSO - 5 MeV

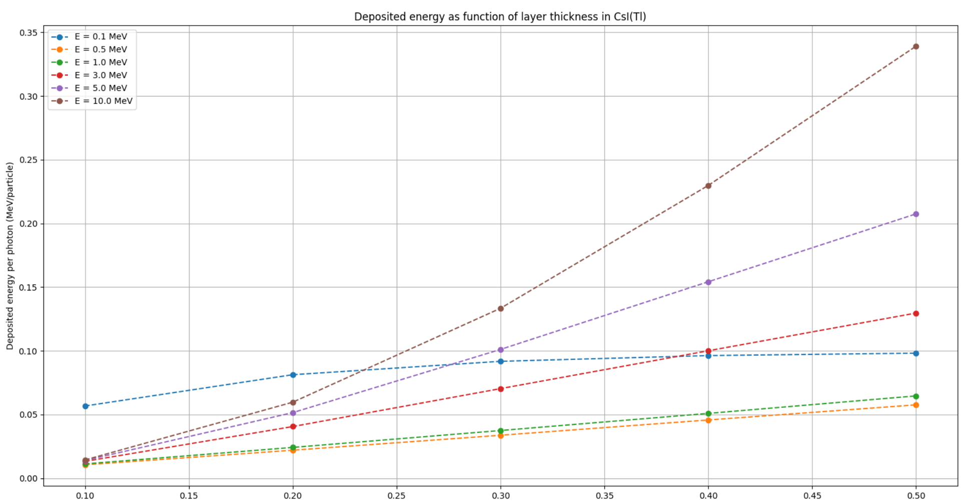


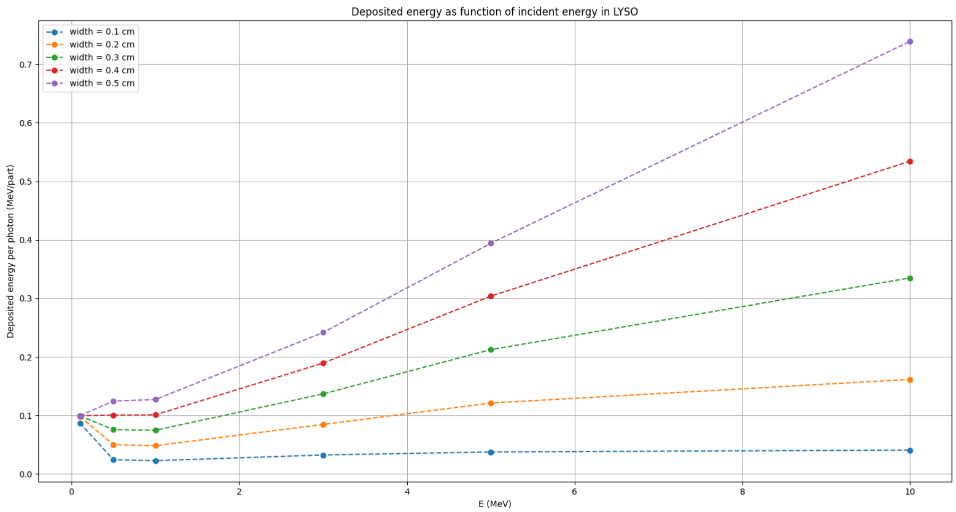
(f) LYSO - 10 MeV

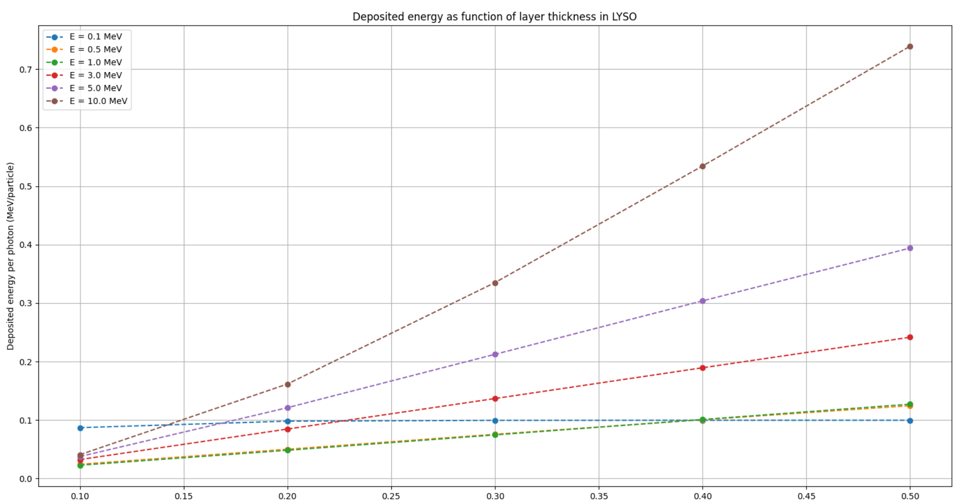
2.2 Task 2. Calculate the energy deposition (first)

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	ρ (g/cm^3)	yield (ph/keV)	E (MeV)	μ (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.

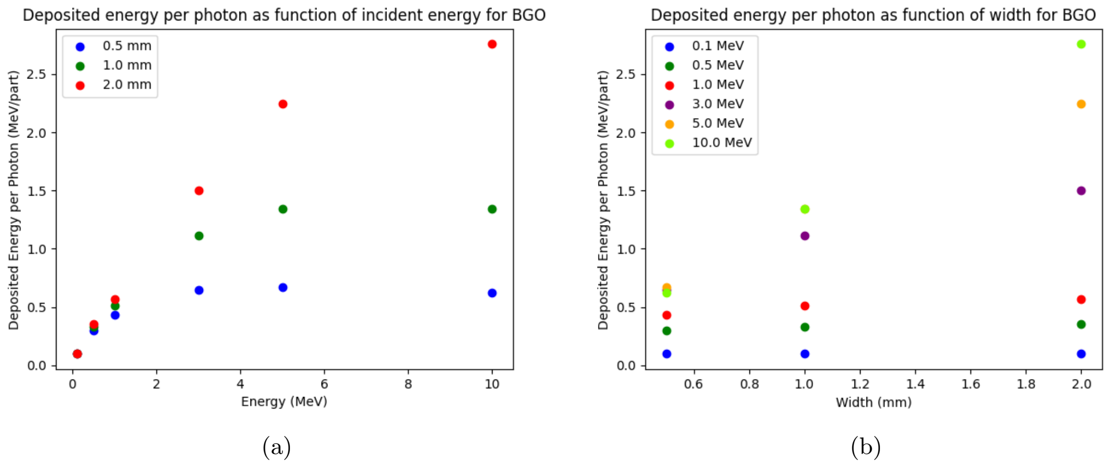


Figure 18: Deposited energy per photon – BGO

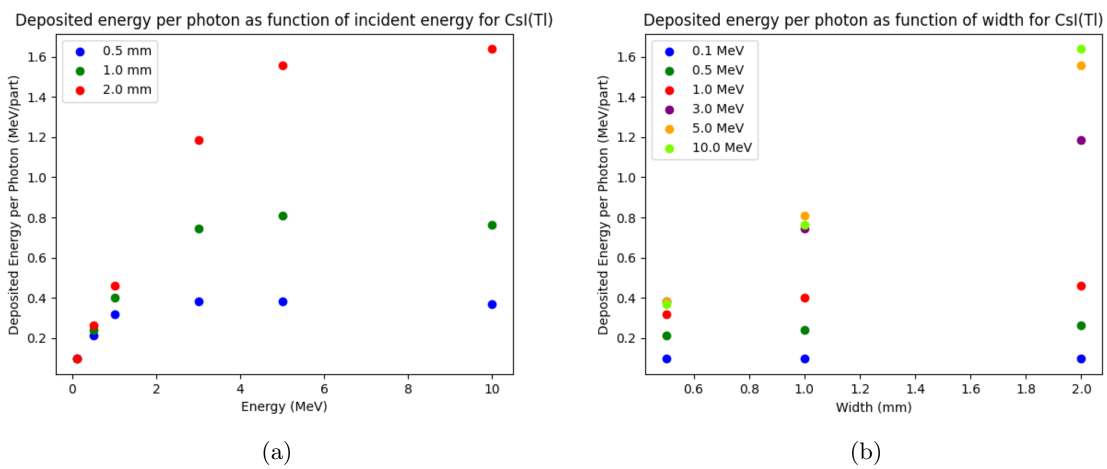
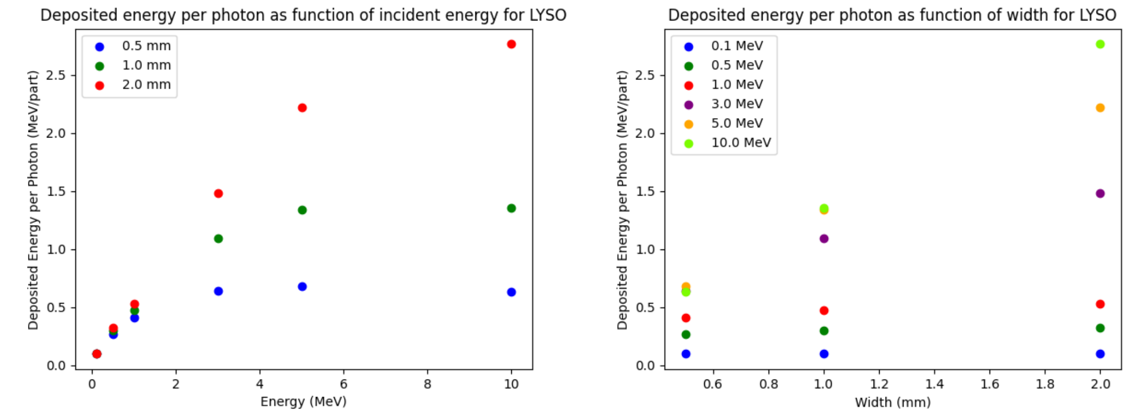
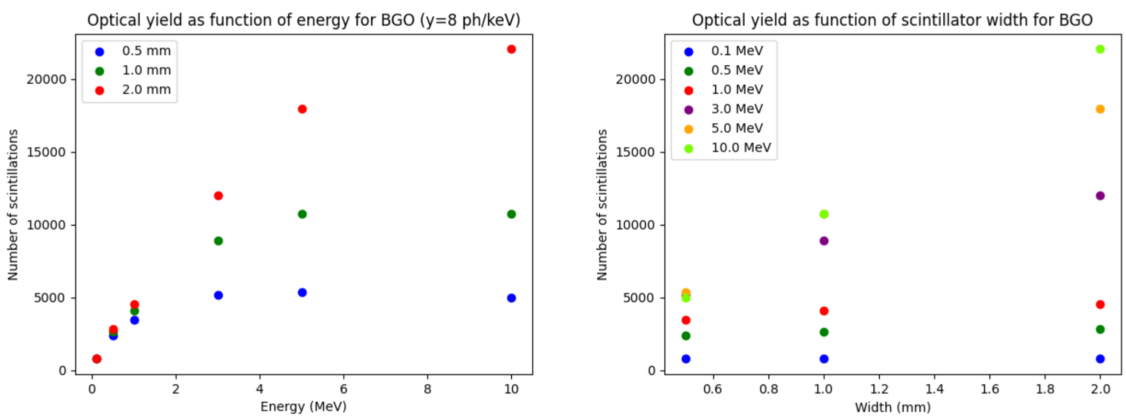


Figure 19: Deposited energy per photon – CsI(Tl)



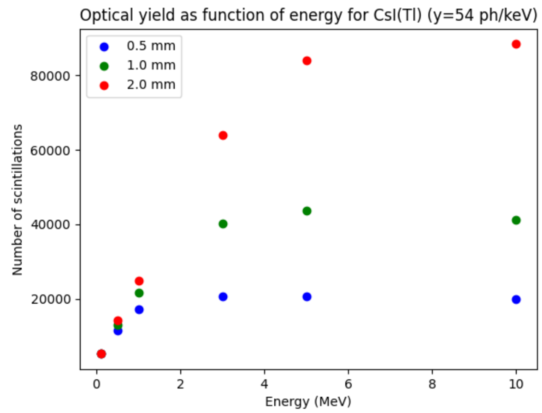
(a) (b)

Figure 20: Deposited energy per photon – LYSO

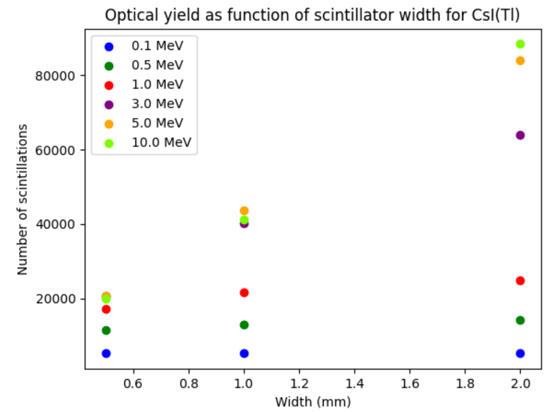


(a) (b)

Figure 21: Optical yield per photon - BGO

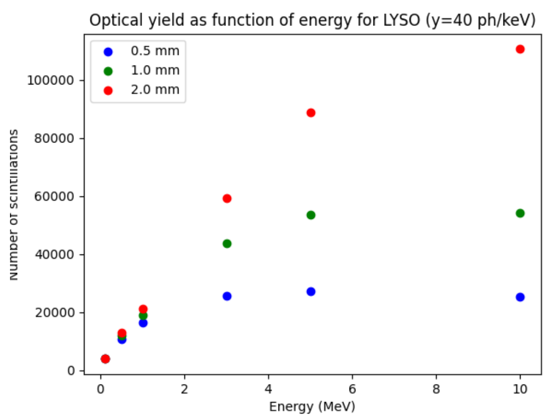


(a)

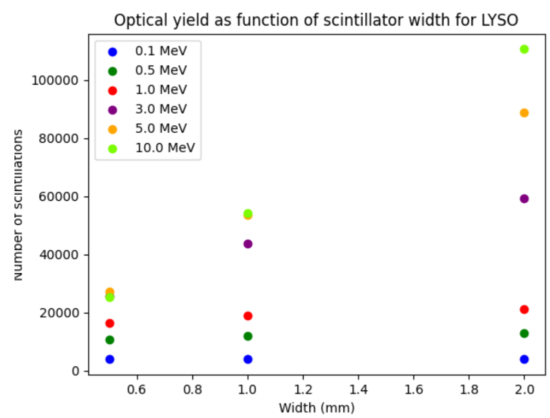


(b)

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



(a)



(b)

Figure 23: Optical yield per photon - LYSO

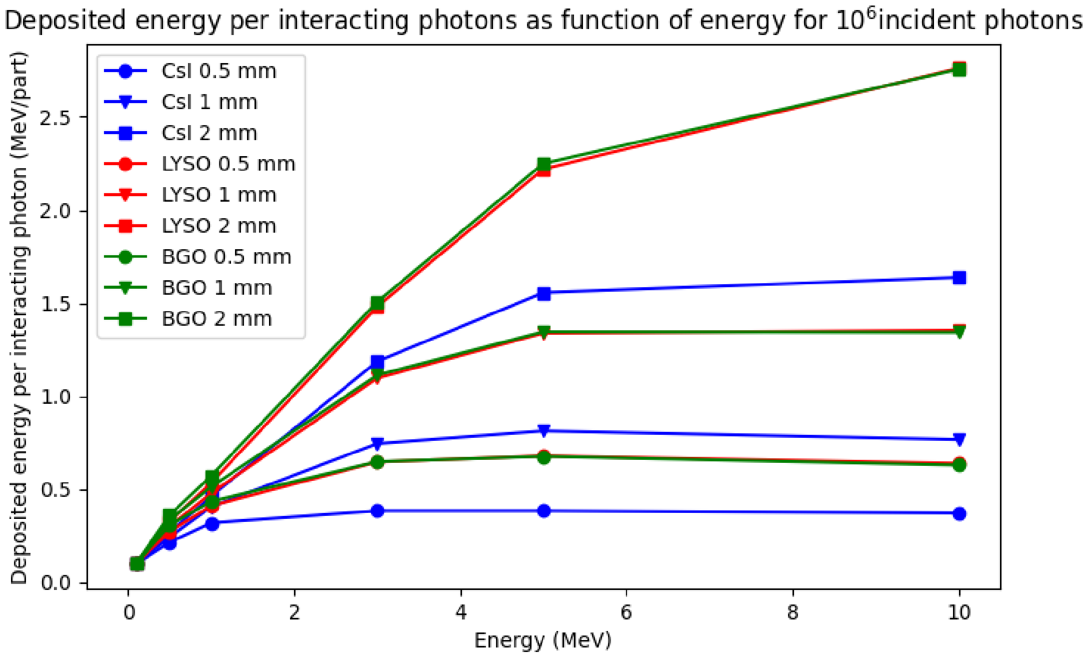


Figure 24: Deposited energy per photon for each scintillator material and detector thicnkess as function of incident photon energy. In these simulations, we used a beam of 10^6 incident photons.

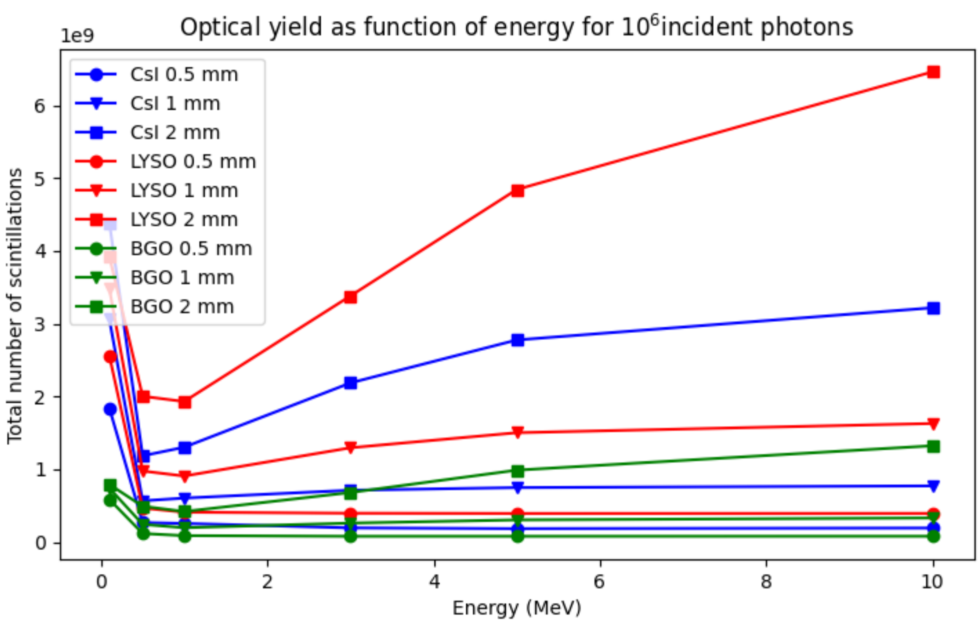


Figure 25: The total optical yield (total number of scintillations produced by the beam, not per incident photon) for each scintillator material and detector thicnkess as function of incident photon energy. In these simulations, we used a beam of 10^6 incident photons.

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.

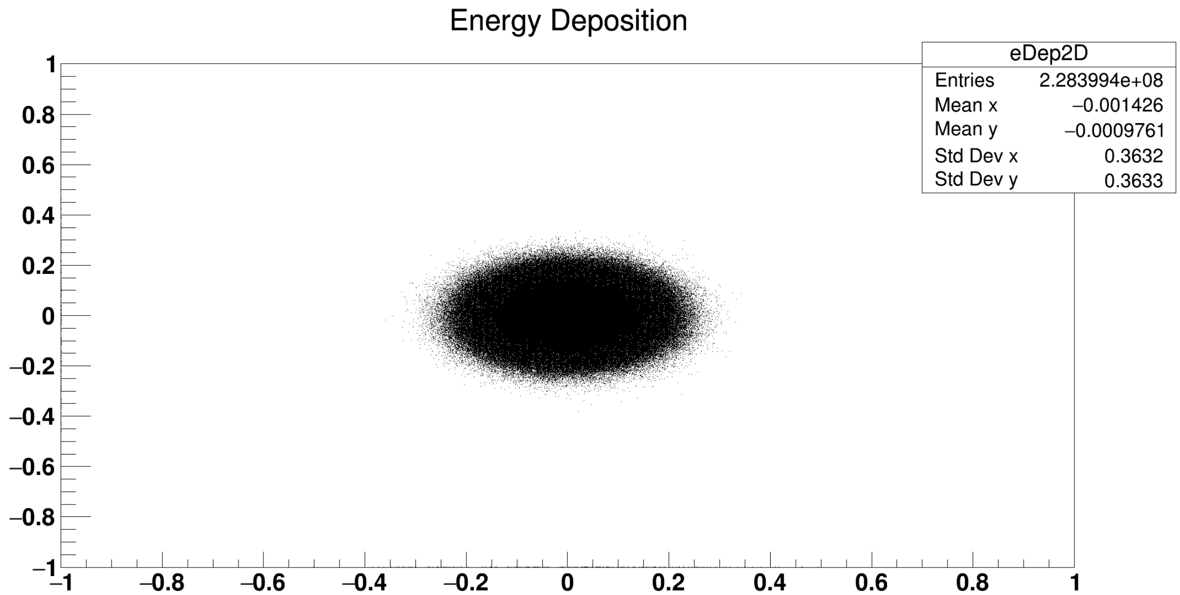


Figure 26: 2D energy deposition for a beam of 10^7 photons of 10 MeV in a 2mm thick CsI scintillator.

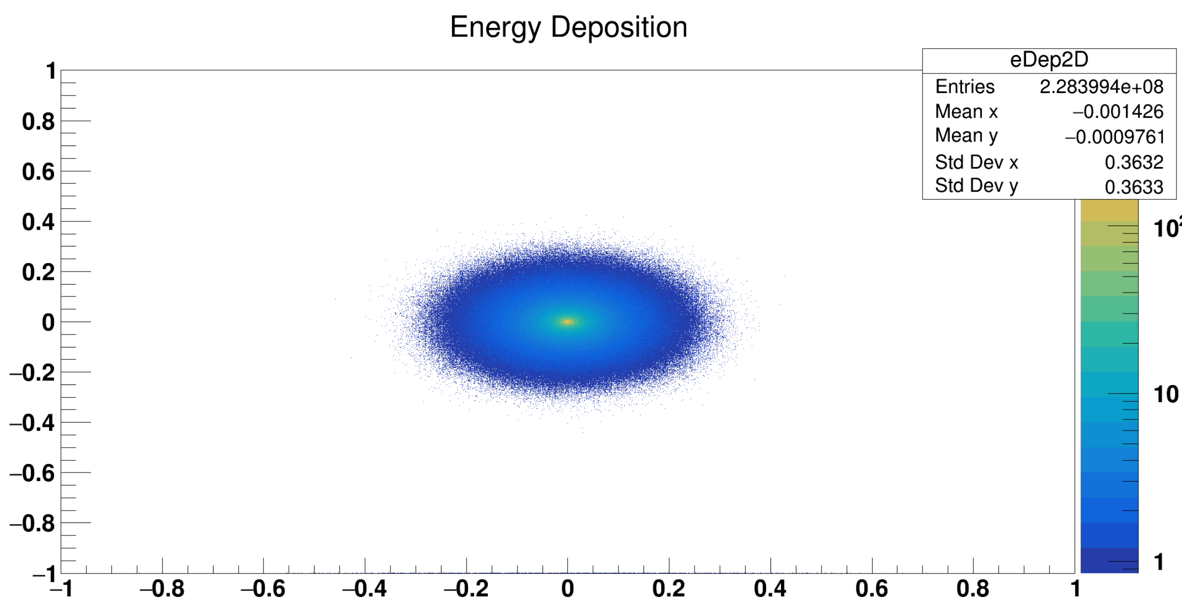


Figure 27: Log scale view of the energy deposition.

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.

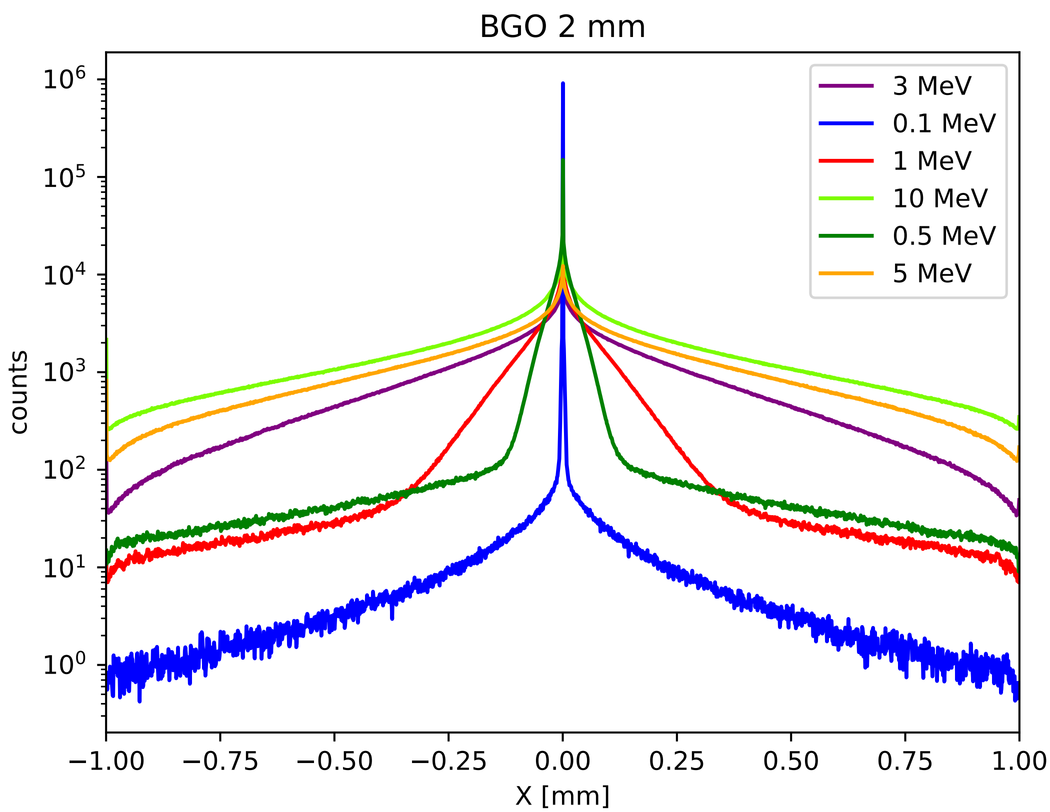


Figure 28: X projection of the 2D energy deposition histogram for BGO scintillator at 2mm detector thickness.

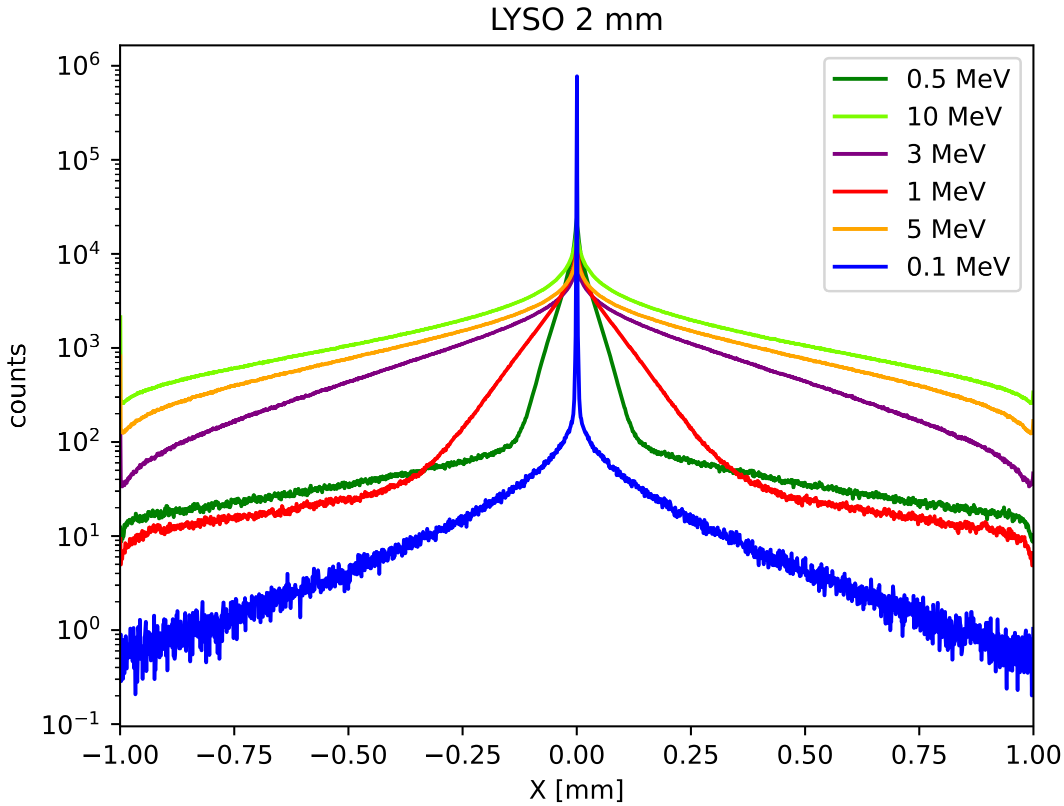


Figure 29: X projection of the 2D energy deposition histogram for LYSO scintillator at 2mm detector thickness.

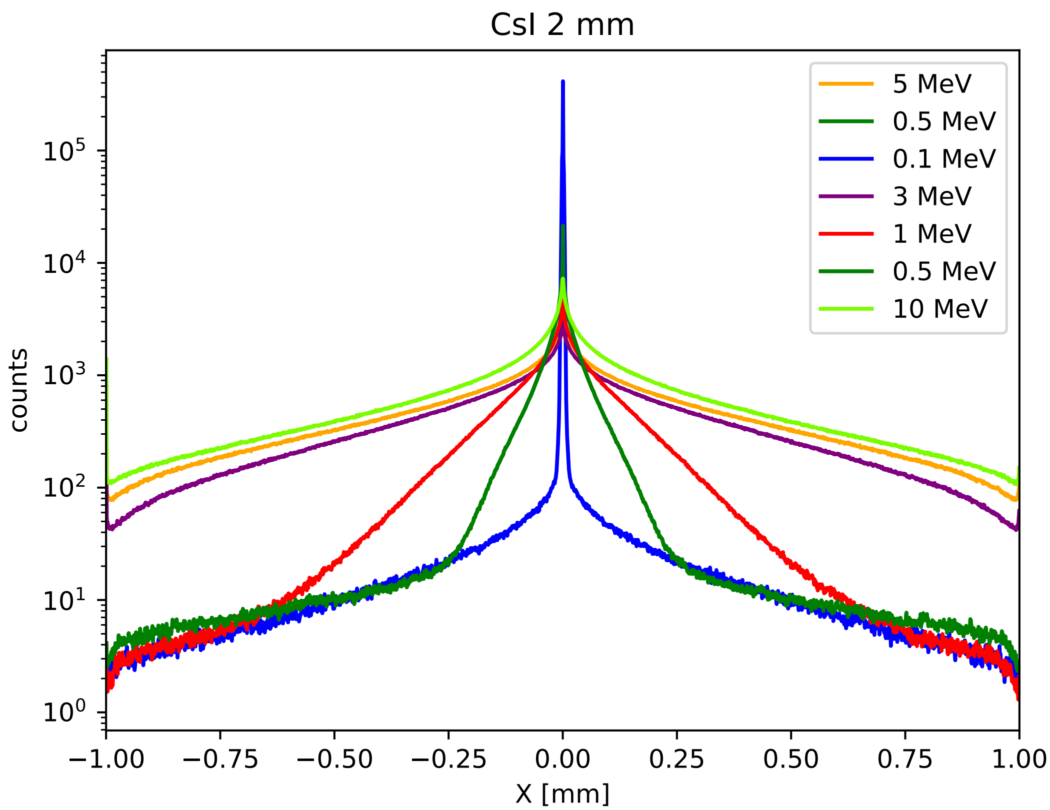


Figure 30: X projection of the 2D energy deposition histogram for CsI(Tl) scintillator at 2mm detector thickness.

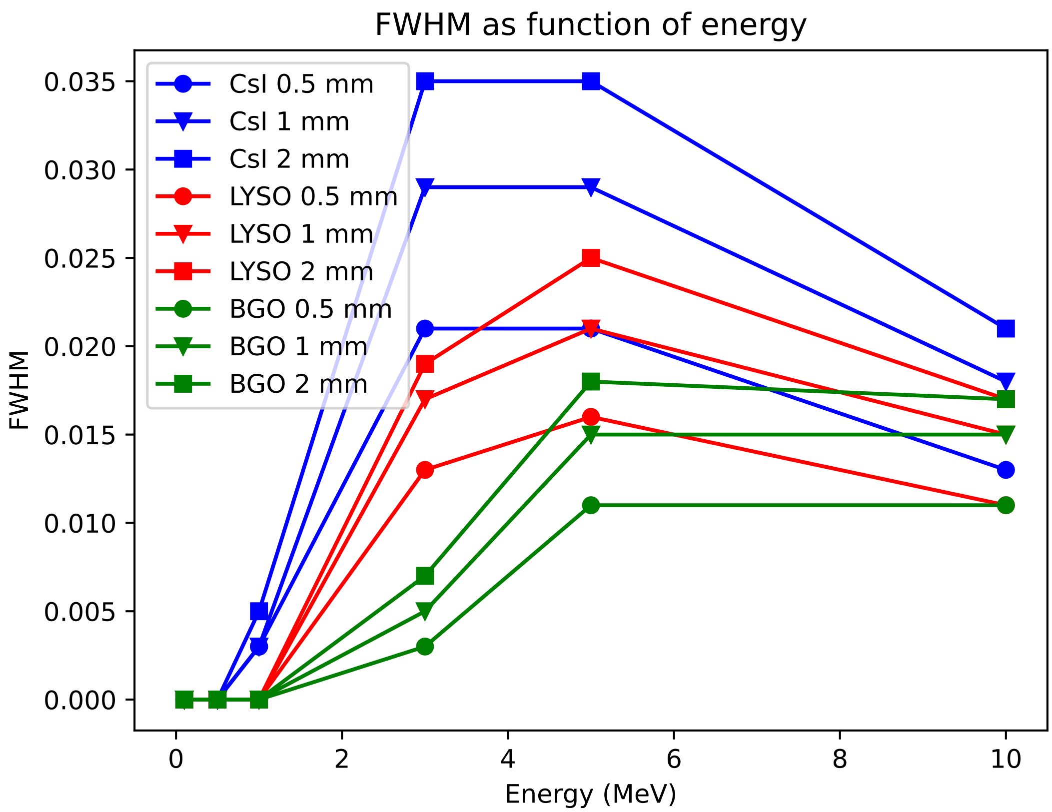


Figure 31: Full width at half maximum for all scintillators and all energies.

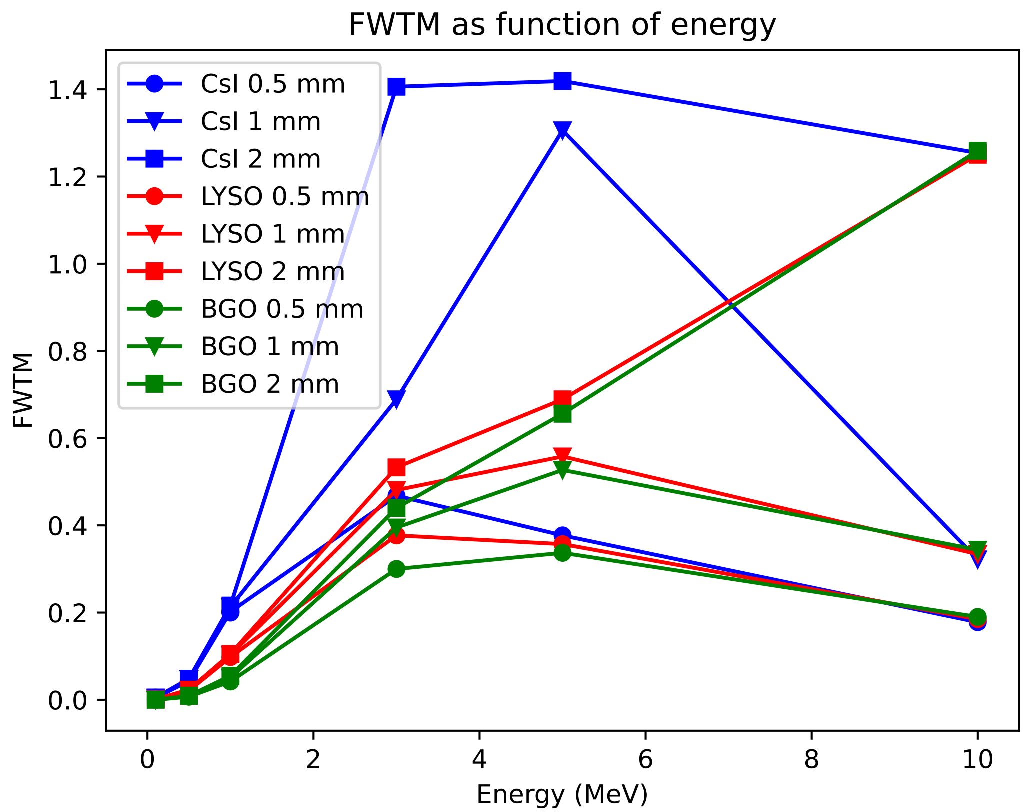


Figure 32: Full width at tenth maximum for all scintillators and all energies.

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).

Simulatins are done for the data located on the server in the folder
`/home/raluca/tasks_geant4/scintillator_task/data_sim`.

To be continued with super gaussian fit.

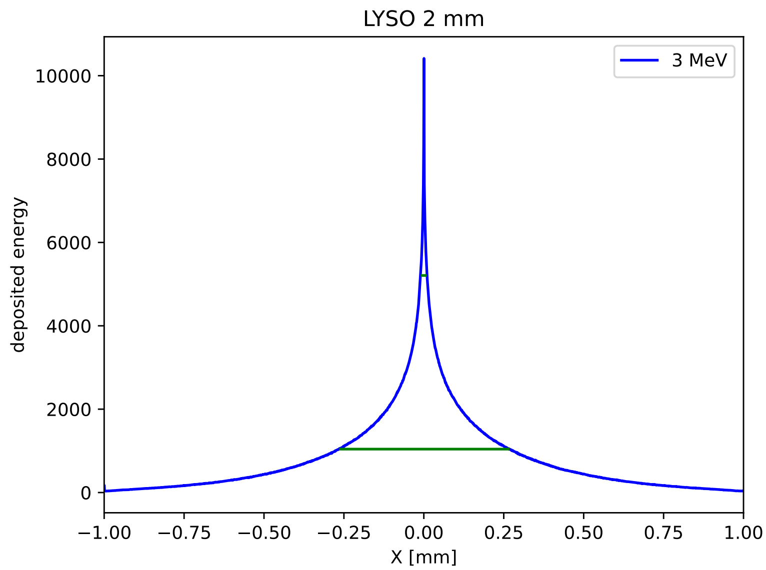


Figure 33: Full width at tenth maximum for LYSO at 3 MeV energy.

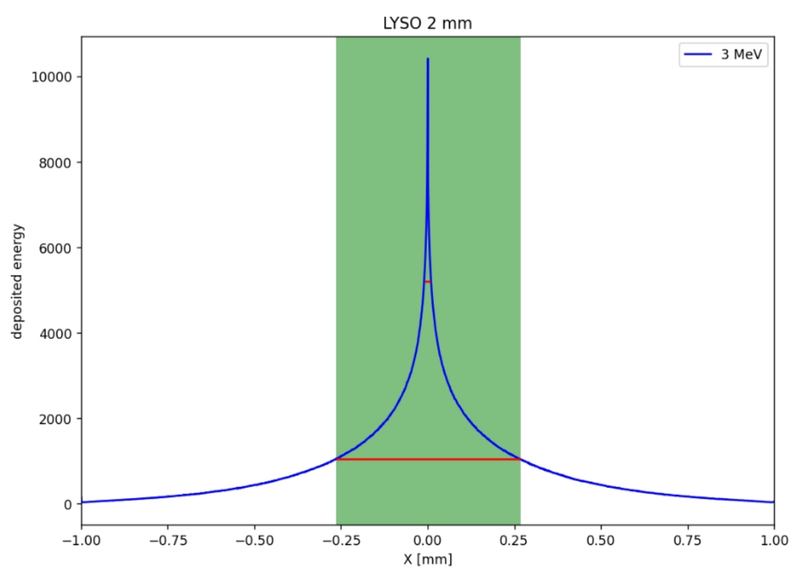


Figure 34: The green area represents the area where the deposited energy is calculated.

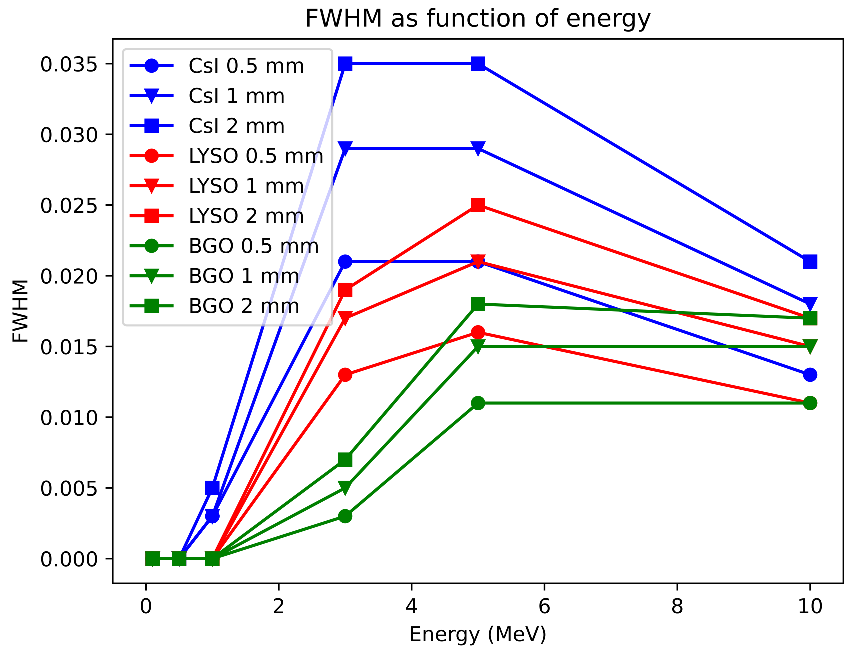


Figure 35: Full width at half maximum for all cases.

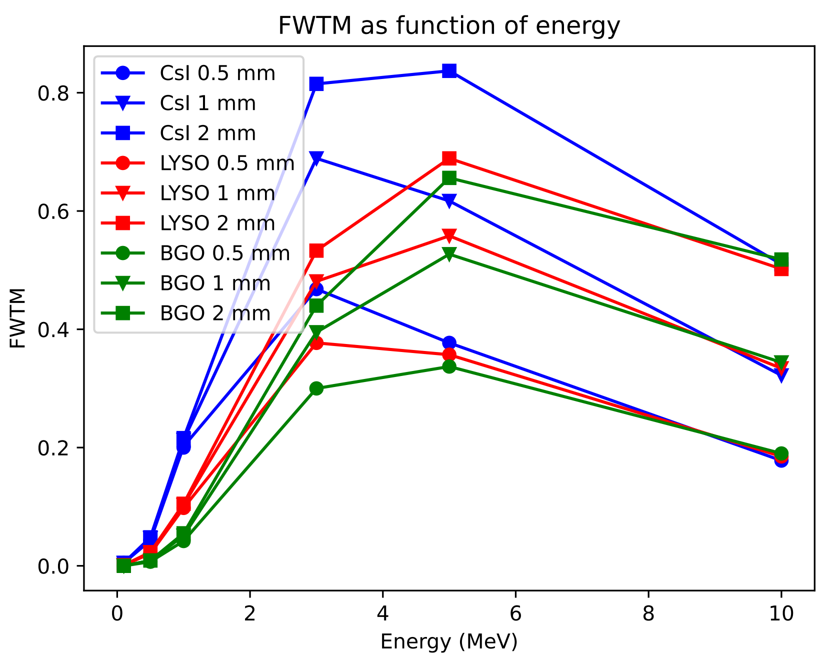


Figure 36: Full width at tenth maximum for all cases.

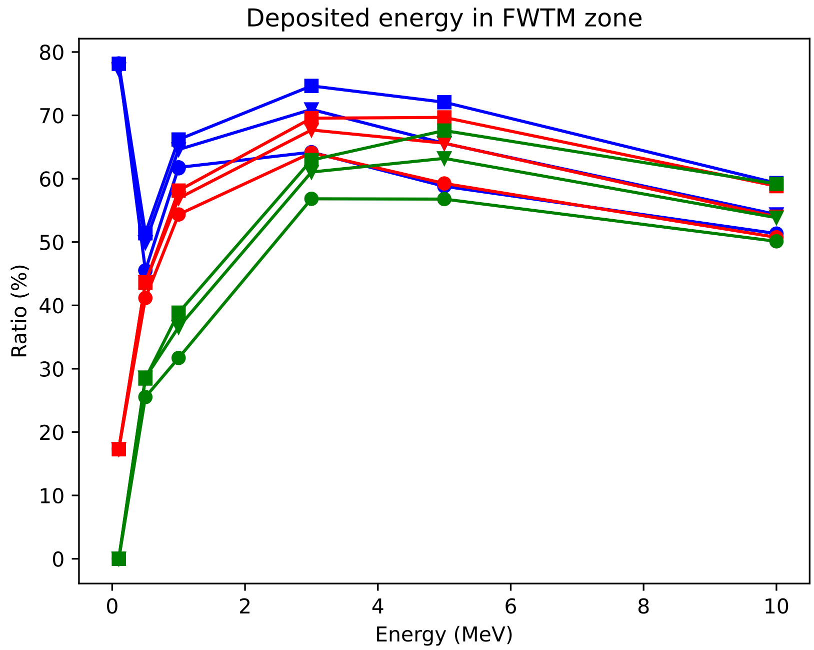


Figure 37: The ratio between the deposited energy in FWTM zone and the total deposited energy.

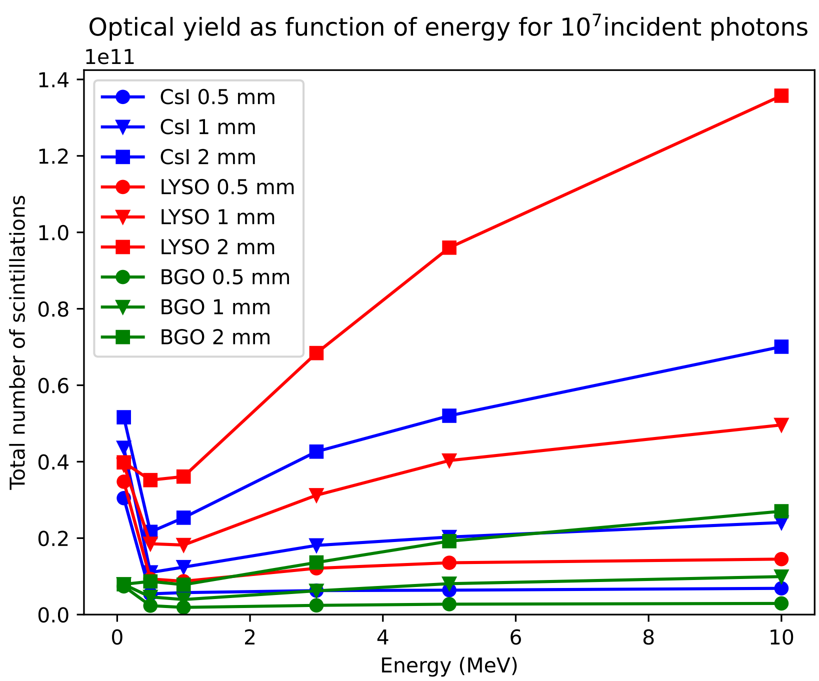


Figure 38: The total number of scintillations produced for each energy and detector thickness. The incident beam contains 10^7 photons.

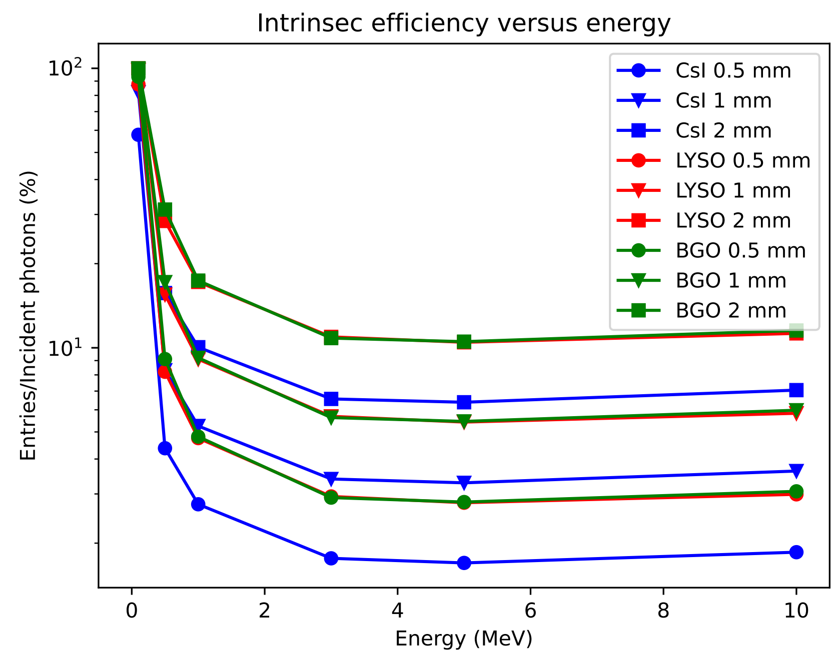


Figure 39: The intrinsic efficiency

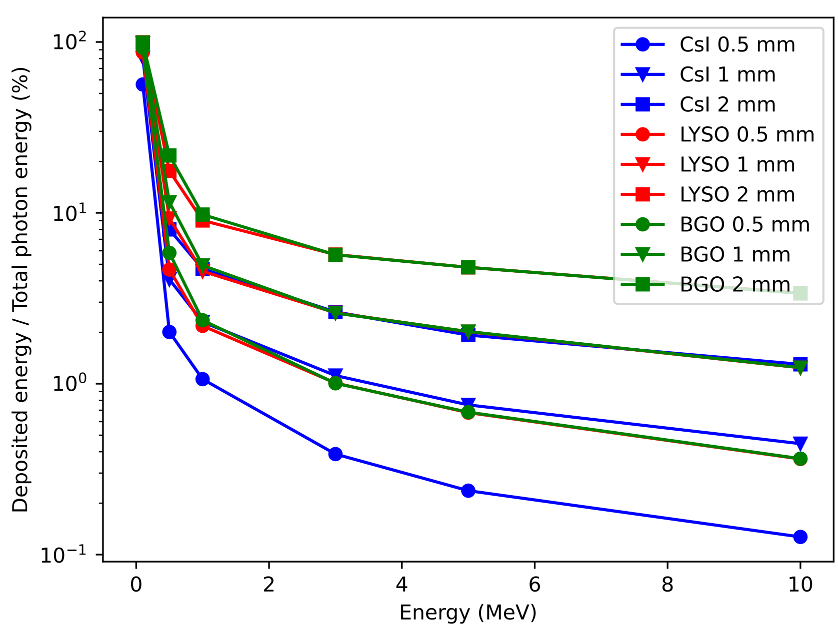


Figure 40: The deposited energy.

2.6 Task 6. Energy deposited in FWTM region - improved. Intrinsec efficiency (March)

For each computed FWHM and FWTM, the deposited energy was computed. The binning is from 1 to GetNbins + 1 (the correct formula).

Also, we noticed that the chosen thickness was wrong in the previous chapter. Previously, 0.5, 1 and 2 mm were actually 1, 2 and 4. We discovered this also after checking the number of entries analitically with the formula $I(x) = I_0 e^{-\mu x}$.

Here will be shown the correct results.

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

Besides FW at 10th max, we also studied 20th max and 30th max. We want to find the region with $\approx 90\%$ of the deposited energy.

Simulatins are done for the data located on the server in the folder `/home/raluca/tasks_geant4/scintillator_task/sim_edep_ten`.

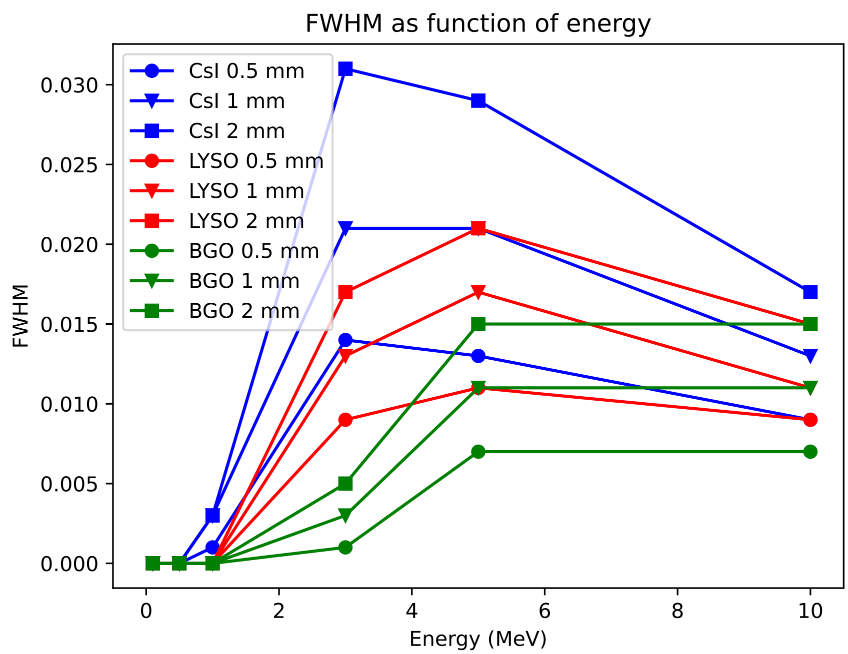


Figure 41: The Full width at half maximum for all cases.

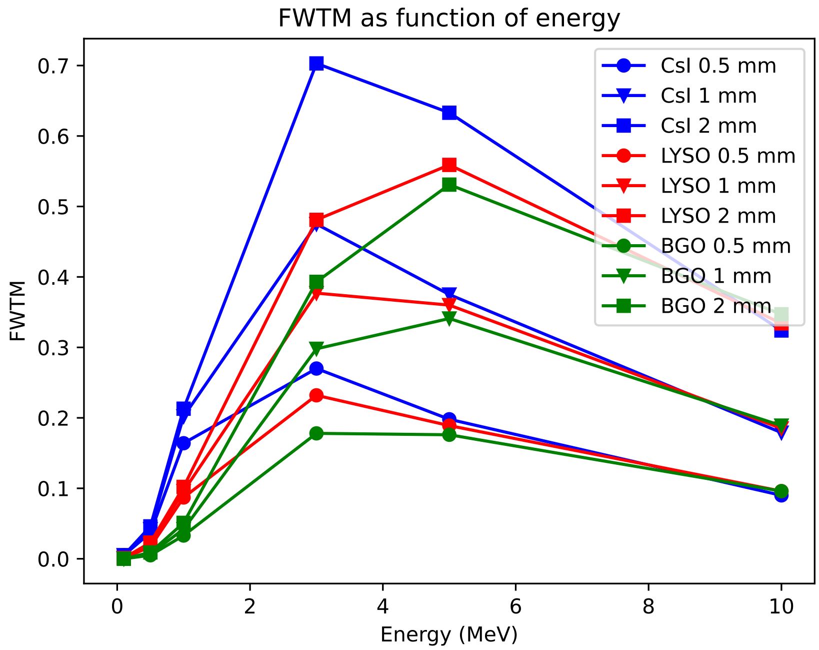


Figure 42: The Full width at tenth maximum for all cases.

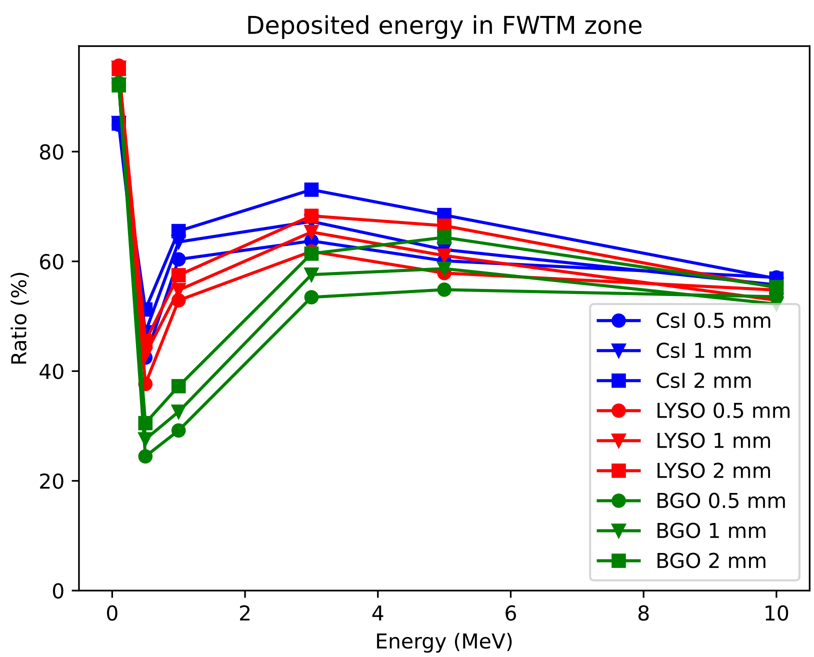


Figure 43: The ratio between the deposited energy in FWTM zone and the total deposited energy.

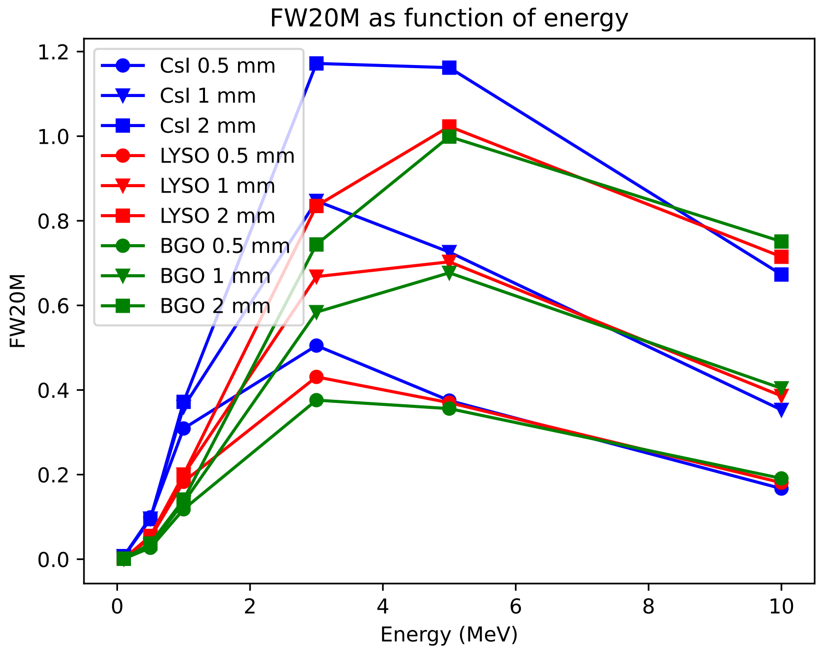


Figure 44: The Full width at twentieth maximum for all cases.

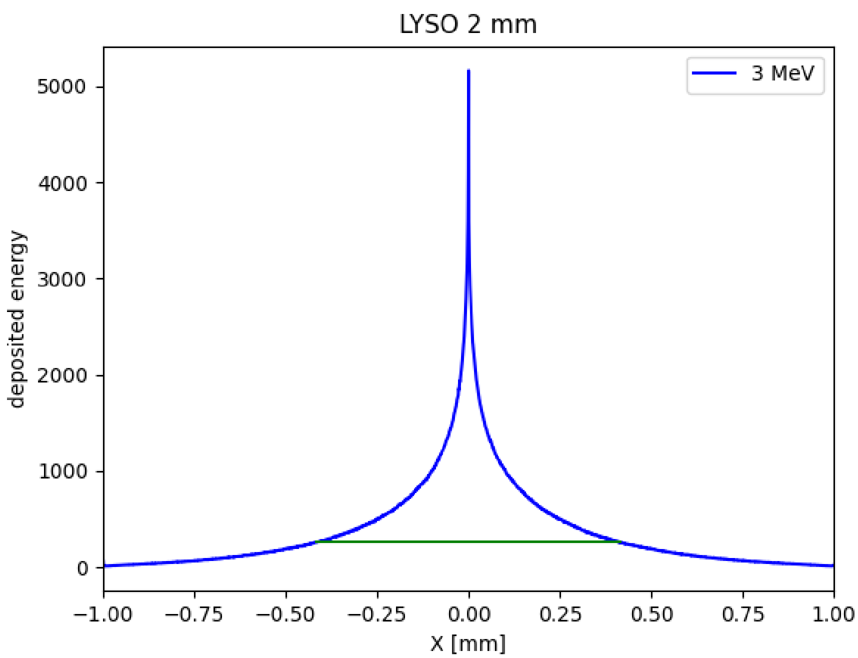


Figure 45: The Full width at twentieth maximum for LYSO, 3 MeV, 2mm.

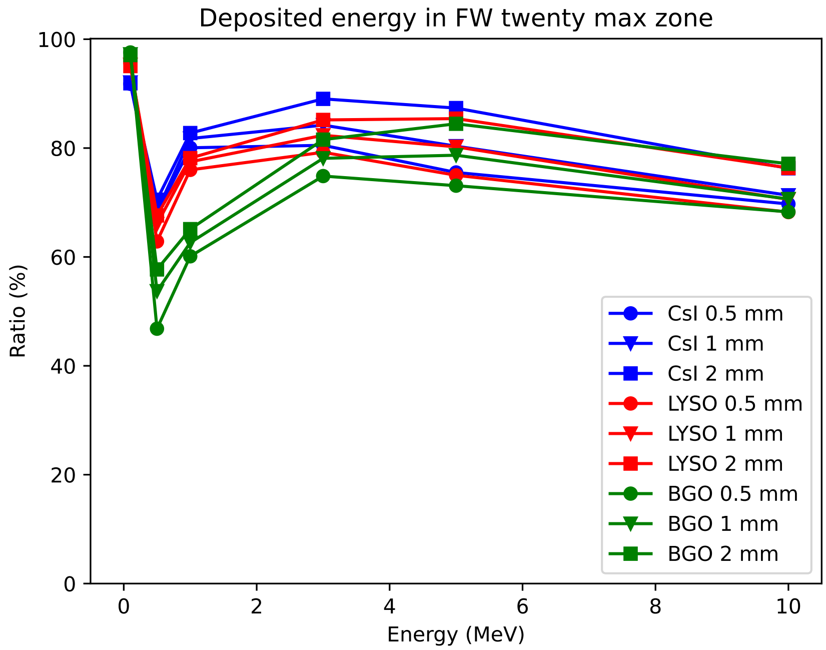


Figure 46: The ratio between the deposited energy in FW20M zone and the total deposited energy.

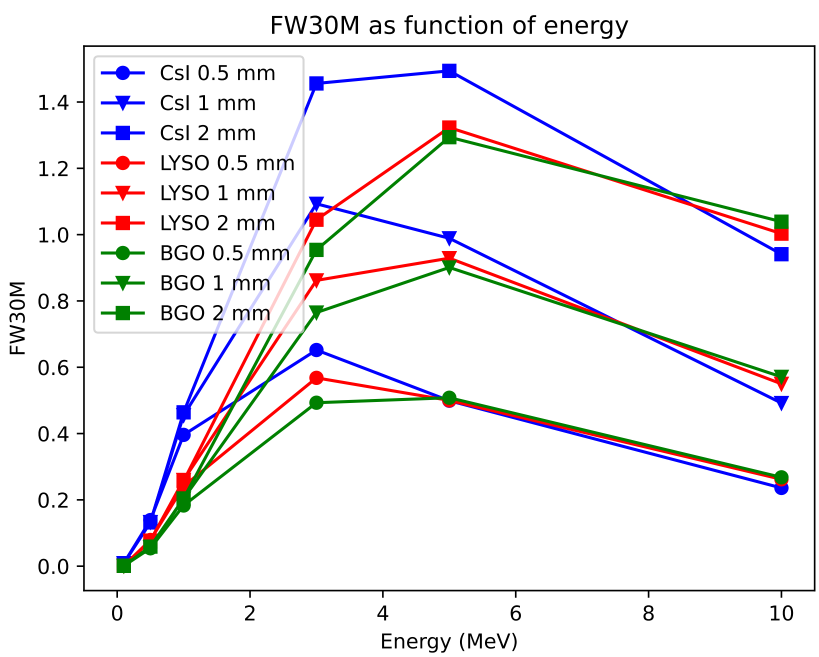


Figure 47: The Full width at thirtieth maximum for all cases.

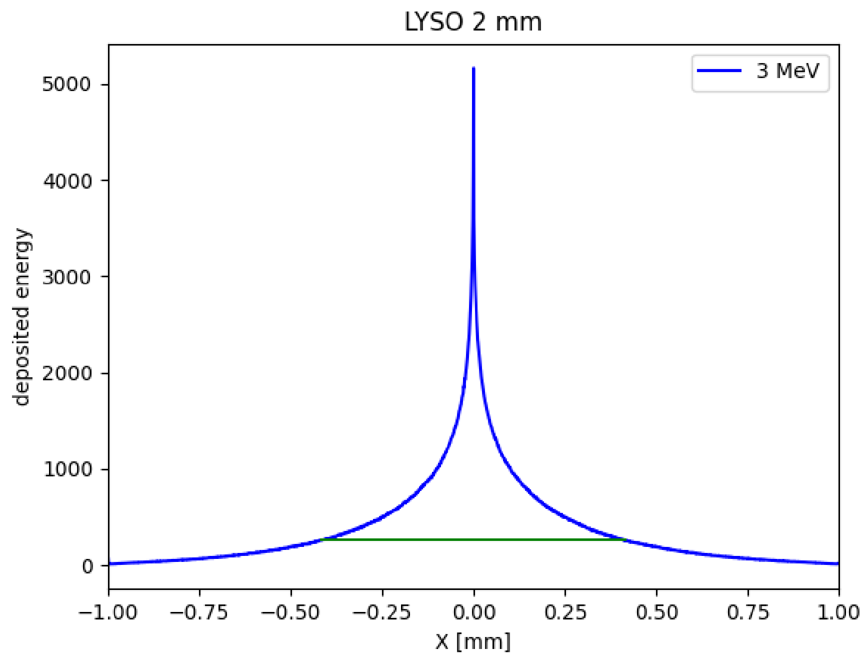


Figure 48: The Full width at thirtieth maximum for LYSO, 3 MeV, 2mm.

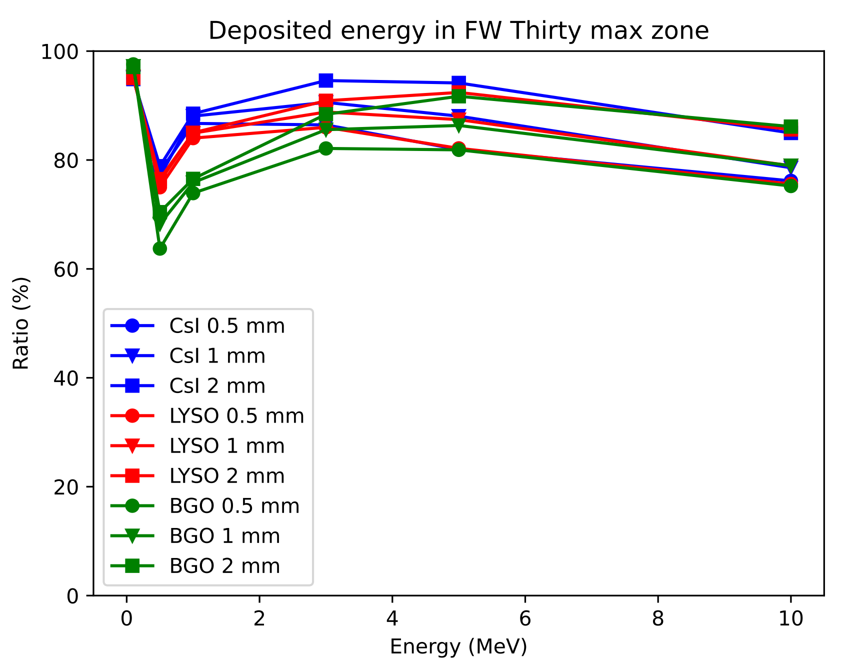


Figure 49: The ratio between the deposited energy in FW30M zone and the total deposited energy.

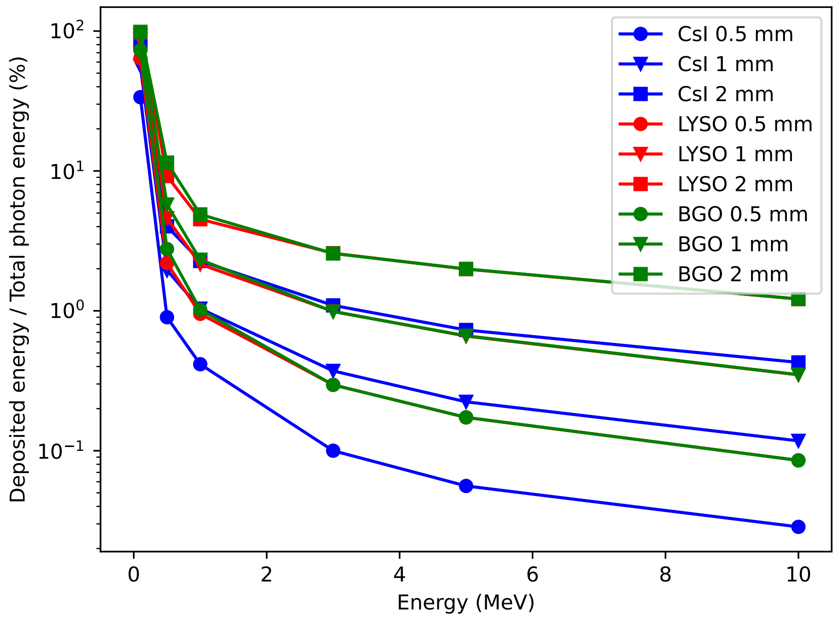


Figure 50: The ratio between the deposited energy and the total energy of the beam (the number of photons multiplied by the incident energy).

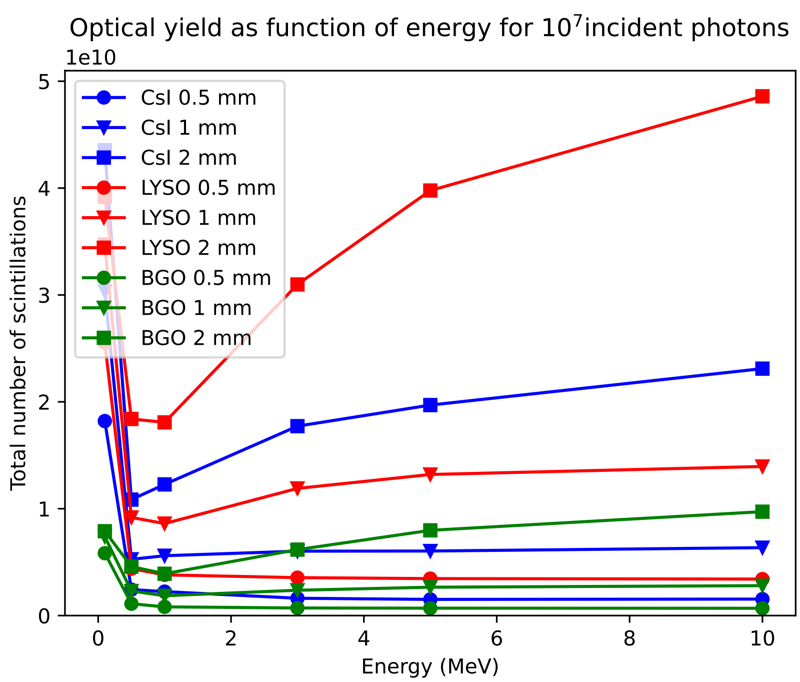


Figure 51: The total number of scintillations produced for each energy and detector thickness. The incident beam contains 10^7 photons.

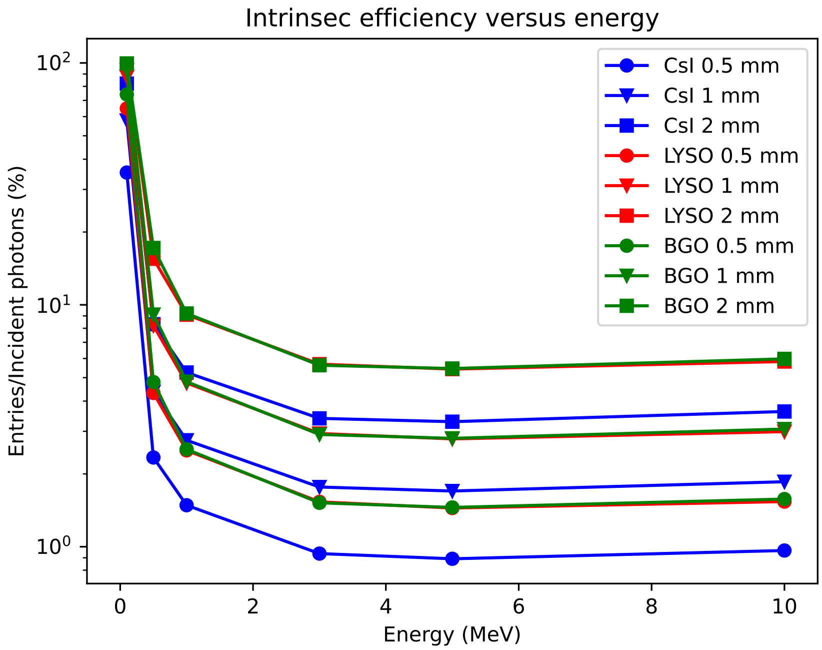


Figure 52: The intrinsic efficiency (the number of entries divided by the total number of incident photons).