Optimized Hadronic Calorimeter Designs for Low-Energy Hadrons

Cemre Kurt

Criteria for an Optimized Hadronic Calorimeter

For low energy hadrons:

- A high fraction of incident particles should be detected.
- The detector should record multiple hits per event.
- A high fraction of events should contain at least two adjacent hits.

For moderately high energy hadrons:

- A high fraction of incident particles should be detected.
- The detector should be sufficiently deep to contain most of the secondary particles.
- The detector should maximize the number of recorded hits.

General:

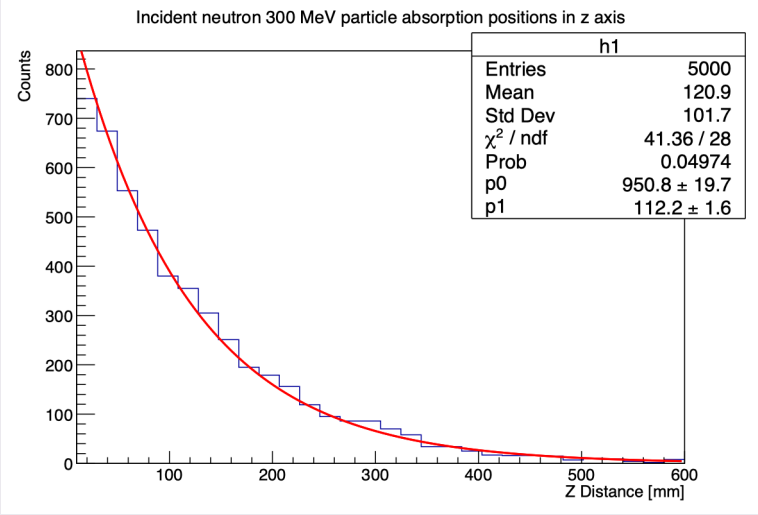
- The energy of individual hits should exceed a threshold determined by the active-layer noise level.

Primary Particle Disappearance Depths Inside Thick Iron Absorber

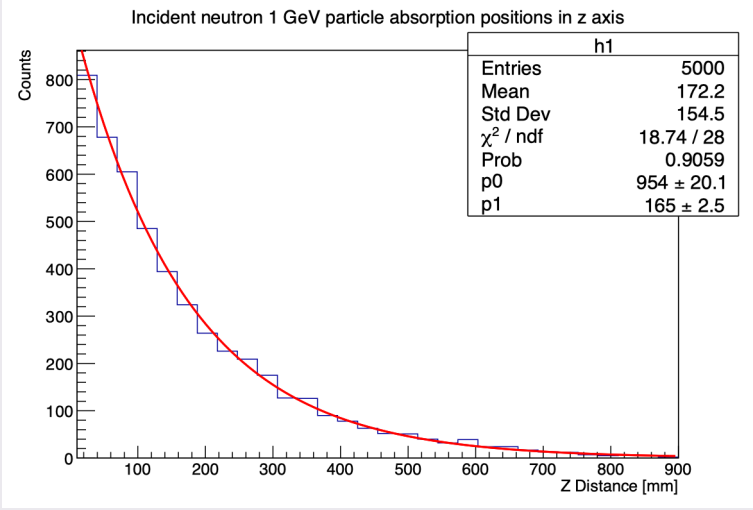
Simulated Particles: Charged and Neutral Hadrons
Energy Range: 100 MeV to 2 GeV

Behavior of a Neutral Hadron :

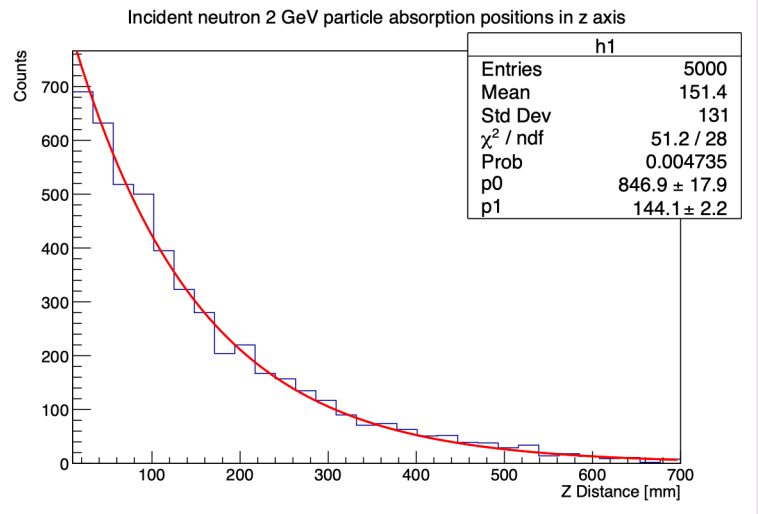
300 MeV neutron



1 GeV neutron

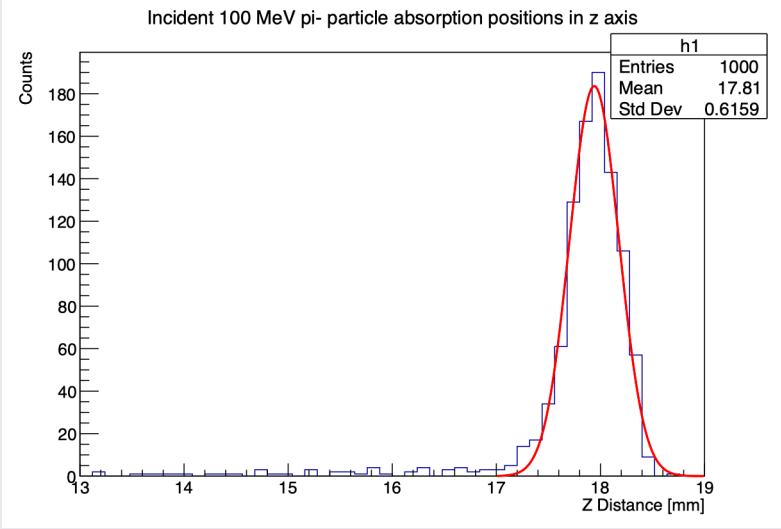


2 GeV neutron



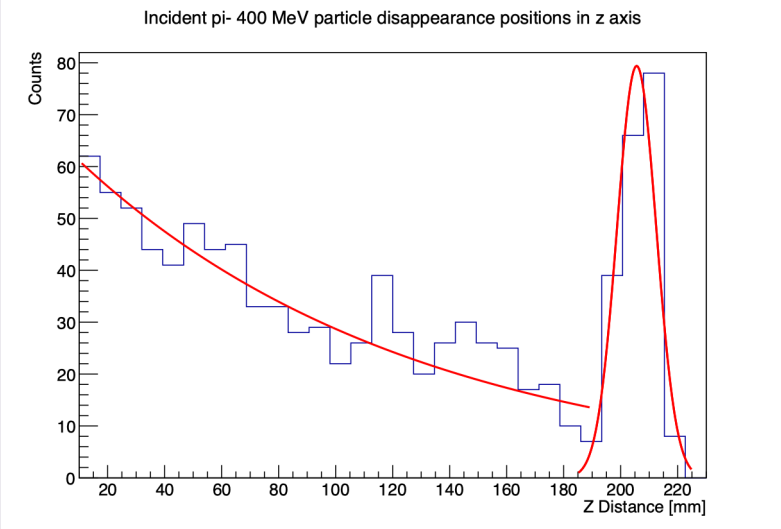
Behavior of a Charged Hadron:

100 MeV pi-



Ionization energy loss dominates

500 MeV pi



Both nuclear absorption and ionization energy loss occurs

1 GeV pi-

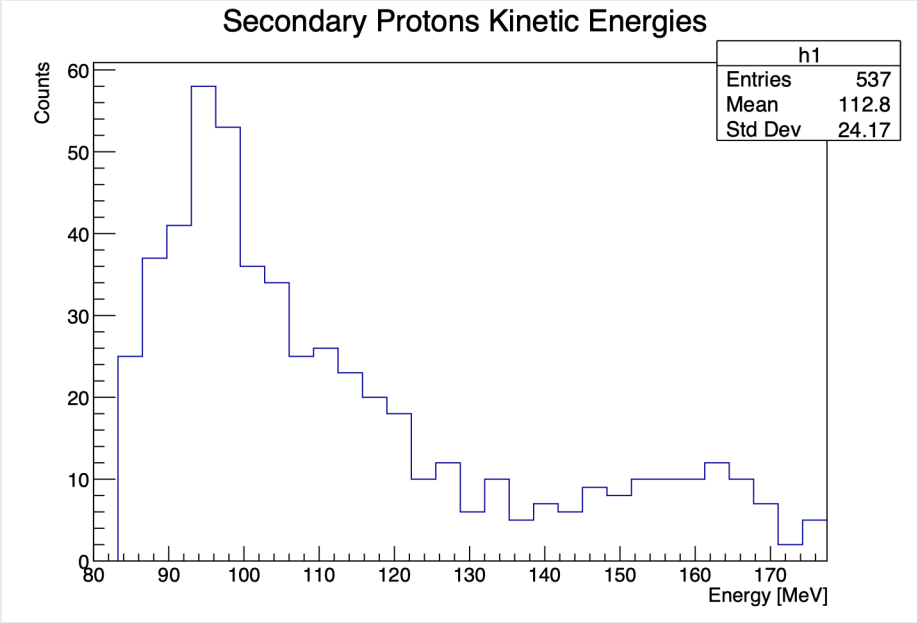
Nuclear absorption dominated

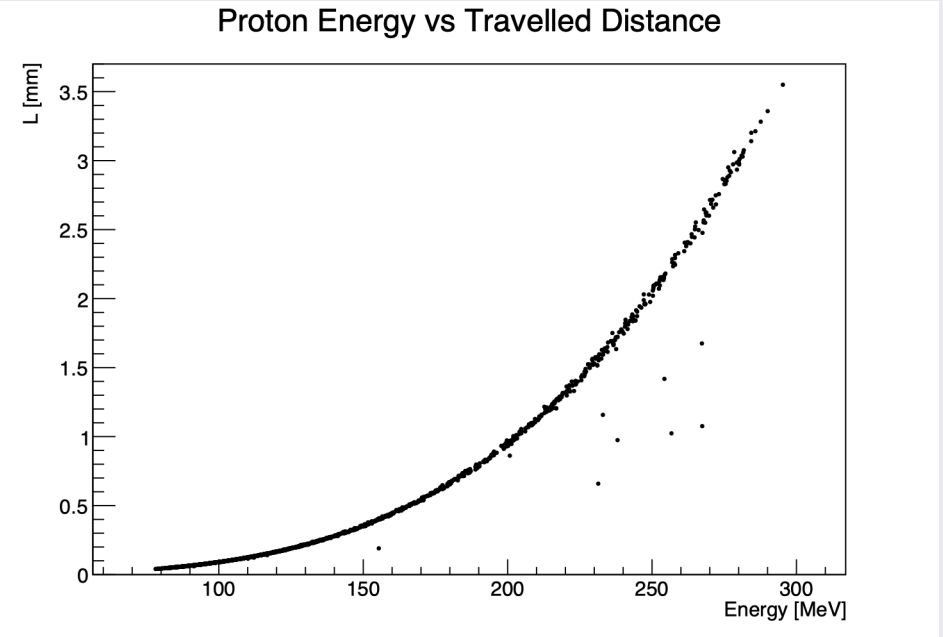
Low Energy Neutron (300 MeV) Secondary Particles

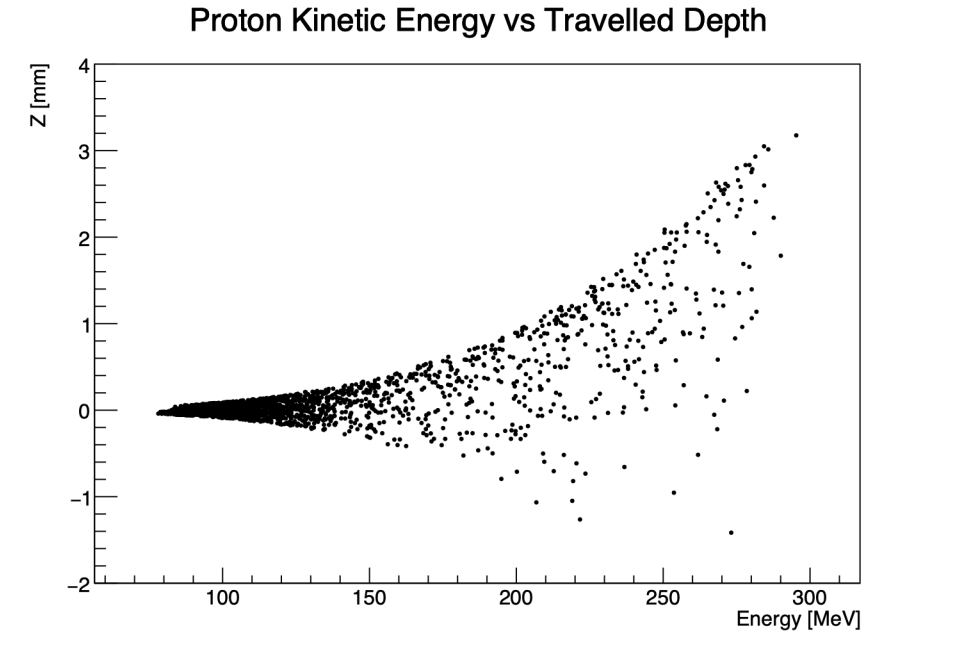
Secondary particles produced inside the detector:

```
neutron 300 MeV
Protons :   2732
Neutrons :   21583
Photons :   30454
Electrons :   25773
Nuclear Fragments :   2032
```

Secondary proton energies and how much they travelled before their disappearance:





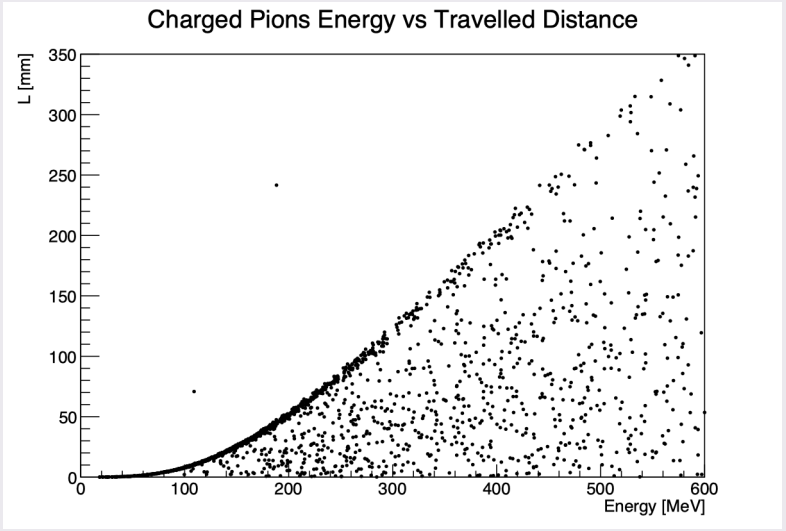


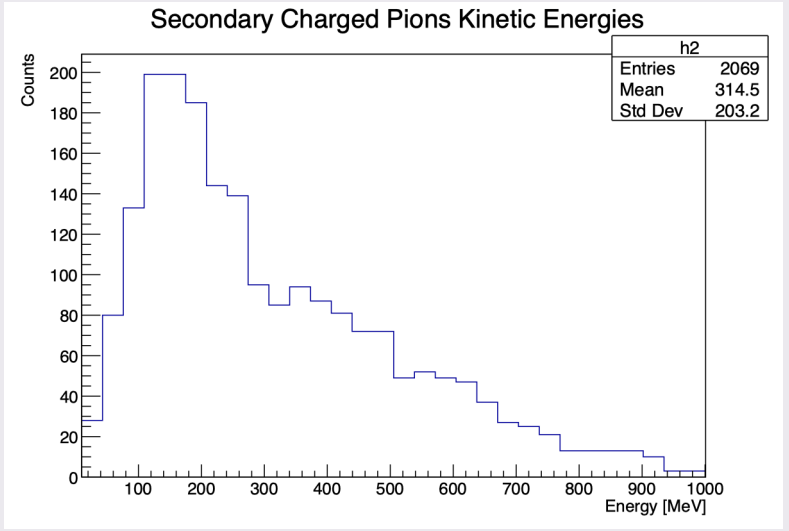
High Energy Neutron (2 GeV) Secondary Particles

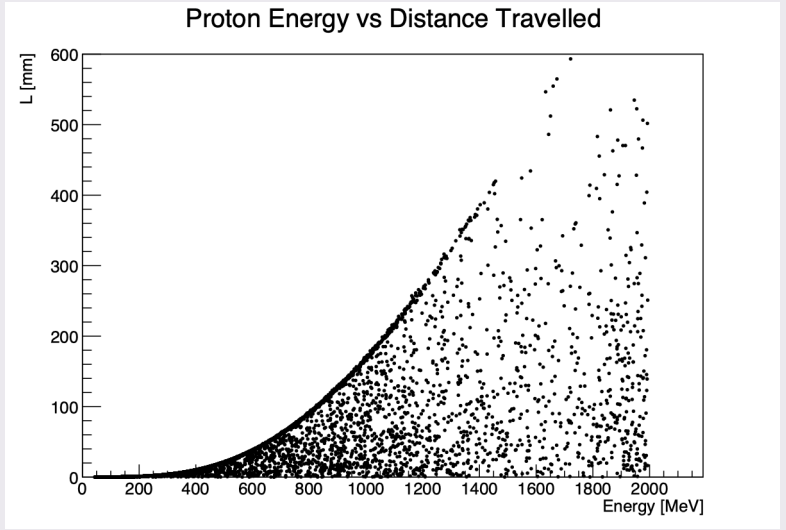
Secondary particles produced inside the detector:

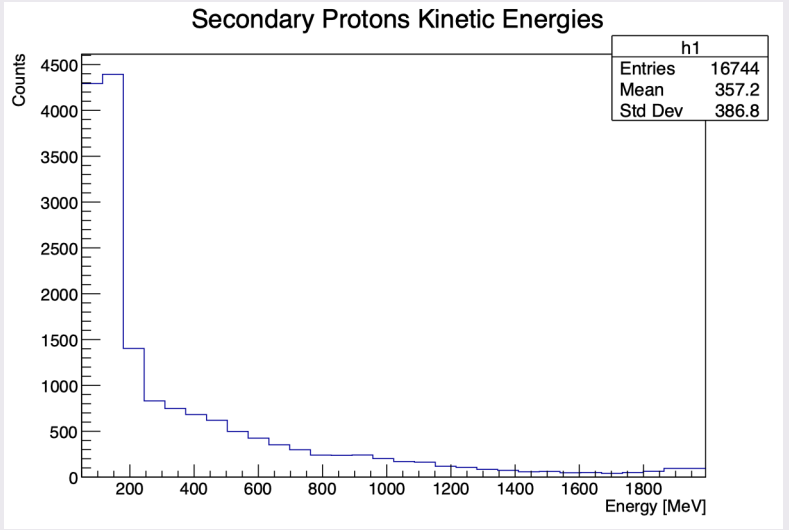
```
neutron 2 GeV
Protons :   63764
Neutrons :   187610
Charged Pions :   3576
Neutral Pions :   1640
Photons :   370577
Electrons :   365318
Nuclear Fragments :   30196
```

Secondary proton and pion energies and how much they travelled before their disappearance:









HCAL Design

Calorimeter Properties:

- Absorber layer material : Iron
- Active layer: 2 cm Scintillator layer with 0.25 MeV energy threshold value

Design Idea:

- Divide the calorimeter into three regions (or four if necessary) with different absorber thicknesses.
- Design the first two layers to maximize the detection efficiency for lowest energy particles.
- Design the third layer to collect the remaining energy deposited by higher-energy particles.

Simulation Strategy:

- Determine the total absorber thickness required for each region.
- Simulate the first region using different absorber-layer thicknesses and select the best-performing configurations.
- Simulate the first two regions together and select the best configurations for different ranges of total layer counts.
- Simulate all three regions together and select the best configurations for different ranges of total layer counts.

About Simulation:

- Number of the events per simulation: 3000

What should be the thickness of the first two regions?

Absorption length of high energy neutrons: $\lambda \approx 160$ mm

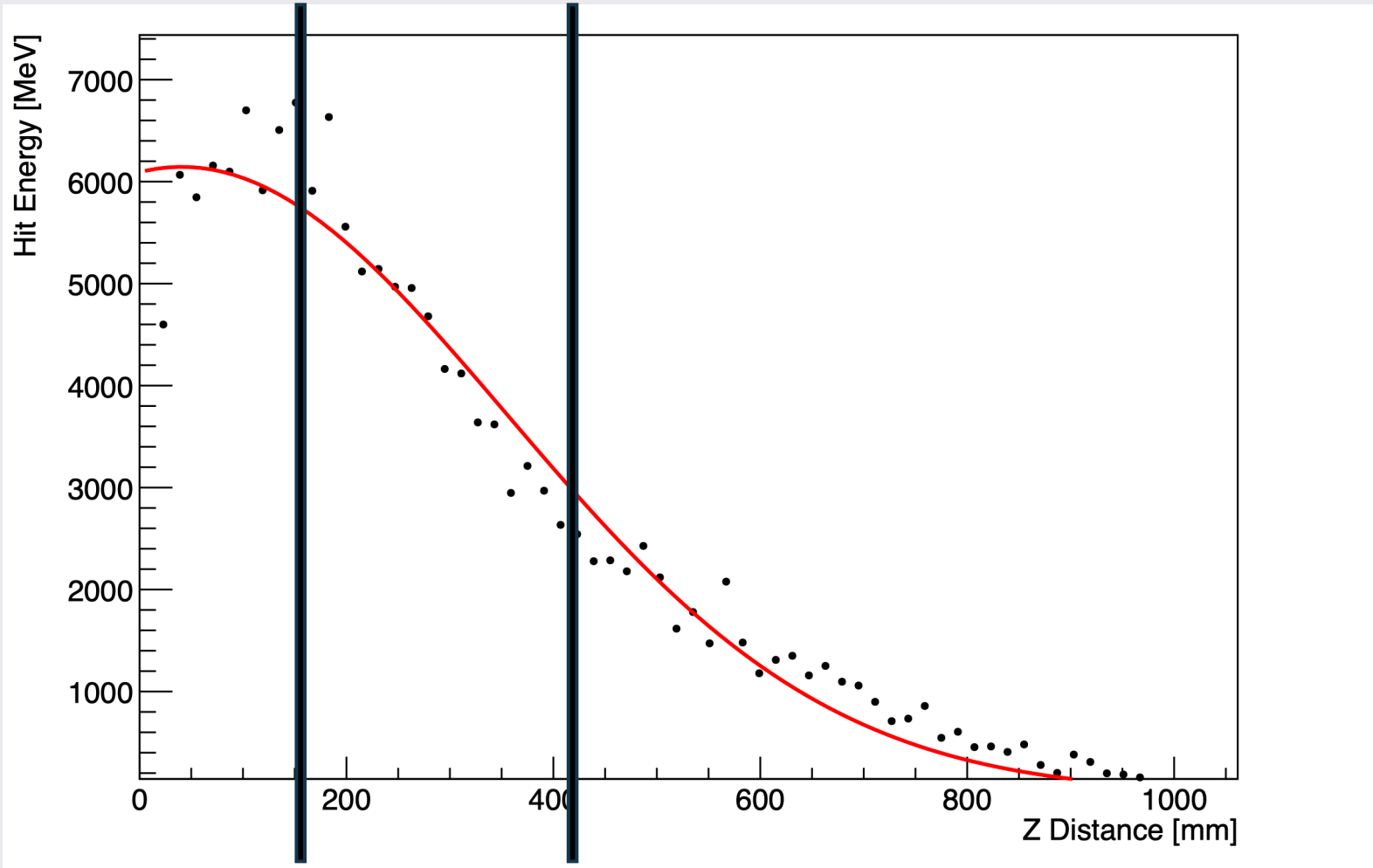
Minimum required total absorber thickness needed for %99,8 absorption: 6-7λ $\approx$ 1000 mm

Absorption length of 300 MeV: $\lambda \approx 112$ mm

$$N(x) = N_0 e^{-x/\lambda}$$

	First Region Thickness	Second Region Thickness	Rest of the neutrons will be absorbed in third region	Third Region Thickness
% 75 of the low energy neutrons will be absorbed: ln(4) x 112 mm $\approx$ 160 mm	60 mm	100 mm	→	900 mm
% 90 of the low energy neutrons will be absorbed: ln(10) x 112 mm $\approx$ 260 mm	100 mm	160 mm	→	800 mm
% 95 of the low energy neutrons will be absorbed: ln(20) x 112 mm $\approx$ 360 mm	120 mm	240 mm	→	720 mm

120-240-720
HCAL
Separation



%95 of the low energy hadrons will be absorbed and detected

Rest of the low and high energy hadrons will be absorbed and detected

First Region Simulations:

First Region Thickness	Best-Performing Configurations
60 mm →	(3 mm, 20 layer), (4 mm, 15 layer)
100 mm →	(3 mm, 33 layer), (4 mm, 25 layer), (5 mm, 20 layer)
120 mm →	(4 mm, 30 layer), (5 mm, 24 layer), (6 mm, 20 layer)

```
neutron 300 MeV 20 mm active (5, 0, 0, 0) mm absorbers (24, 0, 0, 0) layers

Number of Events With No Absorption: 326
Number of Missed Events With Absorption: 16
Number of Events With One Hit: 141
Number of Events With More Than One But No Consecutive Hits: 39
```

→ Good Configuration

```
neutron 300 MeV 20 mm active (8, 0, 0, 0) mm absorbers (15, 0, 0, 0) layers

Number of Events With No Absorption: 524
Number of Missed Events With Absorption: 44
Number of Events With One Hit: 199
Number of Events With More Than One But No Consecutive Hits: 36
```

→ Bad Configuration

First Two Regions Simulations:

Layer Interval	Best-Performing Configurations
50-60 →	(3, 8) mm with (33, 10) layers
40-50 →	(4, 10) mm with (25, 16) layers + (5, 10) mm with (24, 20) layers
30-40 →	(3, 10) mm with (20, 10) layers + (4, 16) mm with (25, 10) layers + (5, 20) mm with (24, 12) layers
20-30 →	(4, 10) mm with (15, 10) layers

```
neutron 300 MeV 20 mm active (4, 8, 0, 0) mm absorbers (25, 20, 0, 0) layers -> 45
Number of Events With No Absorption: 40
Number of Missed Events With Absorption: 16
Number of Events With One Hit: 105
Number of Events With More Than One But No Consecutive Hits: 38
```

→ Bad Configuration

```
neutron 300 MeV 20 mm active (4, 10, 0, 0) mm absorbers (25, 16, 0, 0) layers -> 41
Number of Events With No Absorption: 44
Number of Missed Events With Absorption: 10
Number of Events With One Hit: 93
Number of Events With More Than One But No Consecutive Hits: 51
```

→ Good Configuration

All Three Regions Simulations:

Layer Interval: 55 – 65

Best Configuration:
(4, 10, 30) mm with (15, 10, 30) layers

```
Simulation: neutron 300 MeV 20 mm active (4, 10, 30, 0) mm absorbers (15, 10, 30, 0) layers --> 55 Layer
Number of Events With No Absorption: 9
Number of Missed Events With Absorption: 15
Number of Events With One Hit: 81
Number of Events With More Than One But No Consecutive Hits: 41


Simulation: neutron 1 GeV 20 mm active (4, 10, 30, 0) mm absorbers (15, 10, 30, 0) layers
Successful Events Mean Hits:  20.991661107404937 +- 8.013601873744795
Number of Events With No Absorption: 2
Number of Missed Events With Absorption: 0
Number of Missed Secondary Neutrons: 850
Number of Missed Secondary Protons: 4
Number of Events With One Hit: 0


Simulation: neutron 2 GeV 20 mm active (4, 10, 30, 0) mm absorbers (15, 10, 30, 0) layers
Successful Events Mean Hits:  47.68289429809936 +- 13.858975128783653
Number of Events With No Absorption: 0
Number of Missed Events With Absorption: 1
Number of Missed Secondary Neutrons: 1976
Number of Missed Secondary Protons: 20
Number of Events With One Hit: 0
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```
Simulation: neutron 300 MeV 20 mm active (5, 10, 30, 0) mm absorbers (24, 20, 20, 0) layers --> 64 layer
Successful Events Mean Hits:  6.275686673448627 +- 2.940549954475301
Number of Events With No Absorption: 14
Number of Missed Events With Absorption: 37
Number of Events With One Hit: 96
Number of Events With More Than One But No Consecutive Hits: 37


Simulation: neutron 1 GeV 20 mm active (5, 10, 30, 0) mm absorbers (24, 20, 20, 0) layers
Successful Events Mean Hits:  23.717529215358933 +- 8.920622076694075
Number of Events With No Absorption: 5
Number of Missed Events With Absorption: 0
Number of Missed Secondary Neutrons: 1037
Number of Missed Secondary Protons: 4
Number of Events With More Than One But No Consecutive Hits: 0


Simulation: neutron 2 GeV 20 mm active (5, 10, 30, 0) mm absorbers (24, 20, 20, 0) layers
Successful Events Mean Hits:  57.39572906239573 +- 15.015019909227526
Number of Events With No Absorption: 3
Number of Missed Events With Absorption: 0
Number of Missed Secondary Neutrons: 2393
Number of Missed Secondary Protons: 30
Number of Events With More Than One But No Consecutive Hits: 0
```

→ Bad Configuration

Layer Interval: 45 – 55

Best Configuration:
(3, 10, 60) mm with (20, 10, 15) layers

```
Simulation: neutron 300 MeV 20 mm active (3, 10, 60, 0) mm absorbers (20, 10, 15, 0) layers --> 45 Layer
Number of Events With No Absorption: 18
Number of Missed Events With Absorption: 9
Number of Events With One Hit: 79
Number of Events With More Than One But No Consecutive Hits: 50


Simulation: neutron 1000 MeV 20 mm active (3, 10, 60, 0) mm absorbers (20, 10, 15, 0) layers
Successful Events Mean Hits:  20.360814419225633 +- 8.906731704373499
Number of Events With No Absorption: 2
Number of Missed Events With Absorption: 2
Number of Missed Secondary Neutrons: 730
Number of Missed Secondary Protons: 2
Number of Events With One Hit: 0
Number of Events With More Than One But No Consecutive Hits: 1


Simulation: neutron 2000 MeV 20 mm active (3, 10, 60, 0) mm absorbers (20, 10, 15, 0) layers
Successful Events Mean Hits:  46.92097365788596 +- 17.352410813092366
Number of Events With No Absorption: 1
Number of Missed Events With Absorption: 0
Number of Missed Secondary Neutrons: 1893
Number of Missed Secondary Protons: 26
Number of Events With One Hit: 0
Number of Events With More Than One But No Consecutive Hits: 0
```

```
Simulation: neutron 300 MeV 20 mm active (5, 20, 80, 0) mm absorbers (24, 12, 9, 0) layers --> 45 layer
Successful Events Mean Hits:  6.086166273981824 +- 2.8937376616581014
Number of Events With No Absorption: 13
Number of Missed Events With Absorption: 16
Number of Events With One Hit: 109
Number of Events With More Than One But No Consecutive Hits: 40


Simulation: neutron 1 GeV 20 mm active (5, 20, 80, 0) mm absorbers (24, 12, 9, 0) layers
Successful Events Mean Hits:  21.260535117056858 +- 8.447267066407152
Number of Events With No Absorption: 8
Number of Missed Events With Absorption: 2
Number of Missed Secondary Neutrons: 1095
Number of Missed Secondary Protons: 7
Number of Events With One Hit: 2
Number of Events With More Than One But No Consecutive Hits: 1


Simulation: neutron 2 GeV 20 mm active (5, 20, 80, 0) mm absorbers (24, 12, 9, 0) layers
Successful Events Mean Hits:  49.3091577540107 +- 15.65277518969927
Number of Events With No Absorption: 8
Number of Missed Events With Absorption: 0
Number of Missed Secondary Neutrons: 2718
Number of Missed Secondary Protons: 43
Number of Events With One Hit: 0
Number of Events With More Than One But No Consecutive Hits: 0
```

→ Bad Configuration