A Si based neutron detector for secondary radiation measurements in Proton Therapy applications

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Introduction

My PhD research focuses on two parts:

❖ The first Part

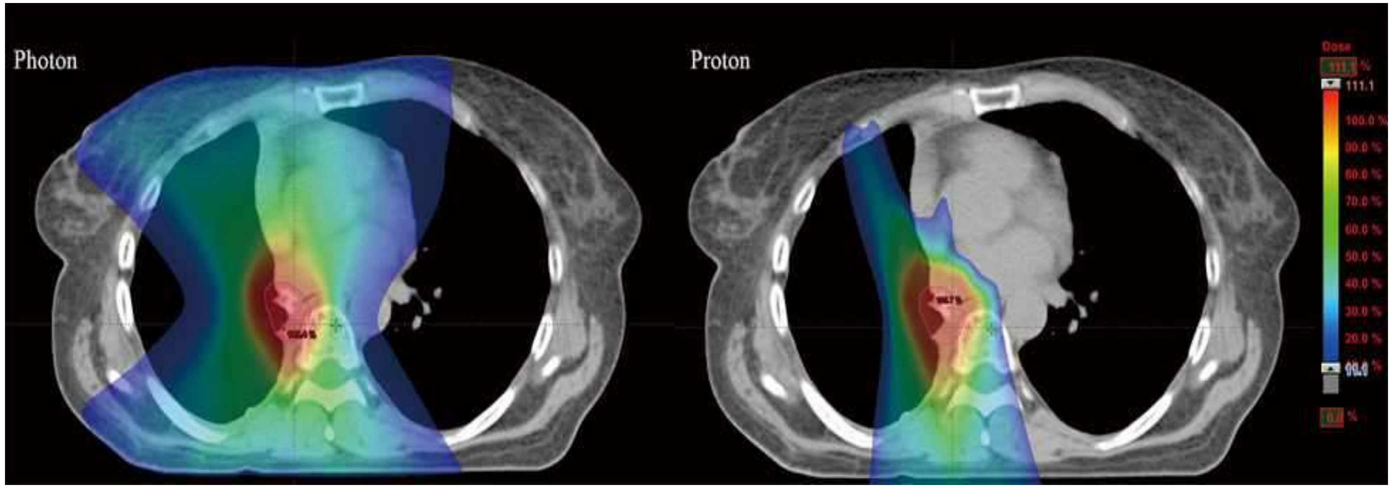
Geant4 Simulation study of Primary proton therapy beam and associated Secondary radiation.

❖ The Second Part

A study of developing a Si based thermal neutron detector.

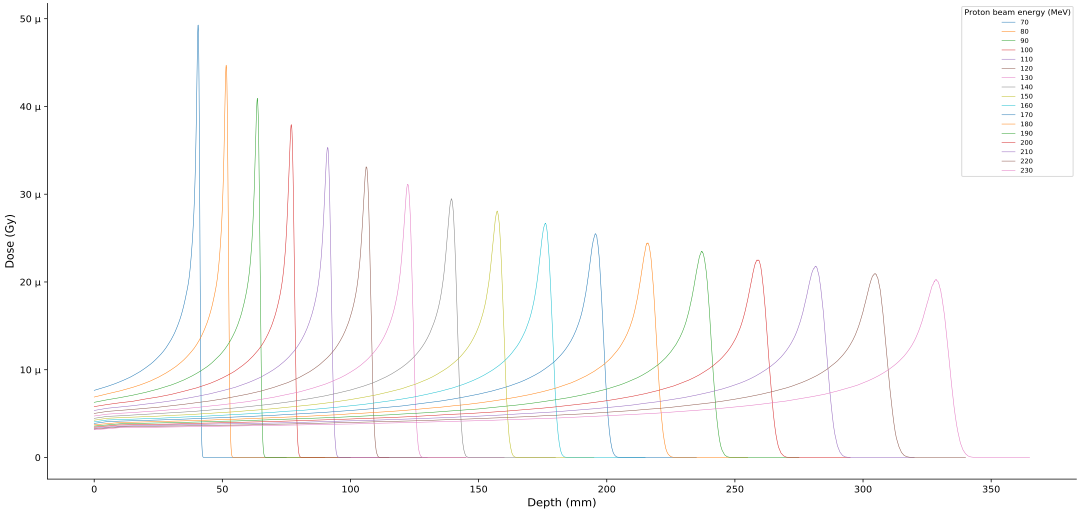
Proton therapy background

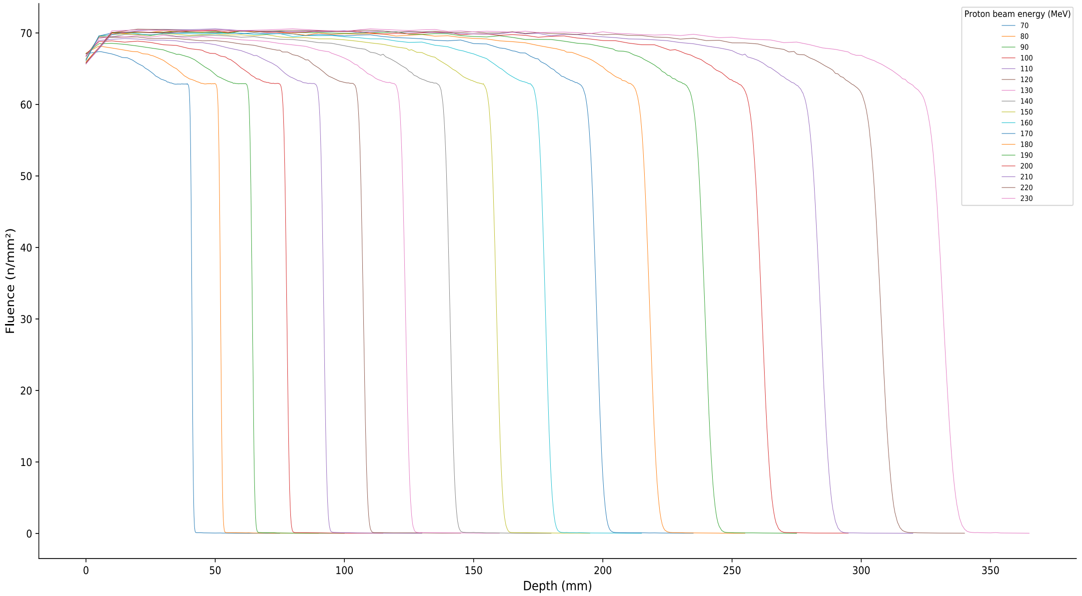
- Proton therapy delivers a precise, concentrated dose to the tumour, a low dose to the surrounding tissues, and minimal dose beyond the tumour.
- The treatment proton beam energies are within 70MeV up to 230MeV.
- Various secondary radiation is created during the treatment when protons interact with the tissues and the beam-line.
- Depends on the target material, beam delivery and the beam energy.



Dilmanian FA, Eley JG, Rusek A and Krishnan S (2015) Charged Particle Therapy with Mini-Segmented Beams.

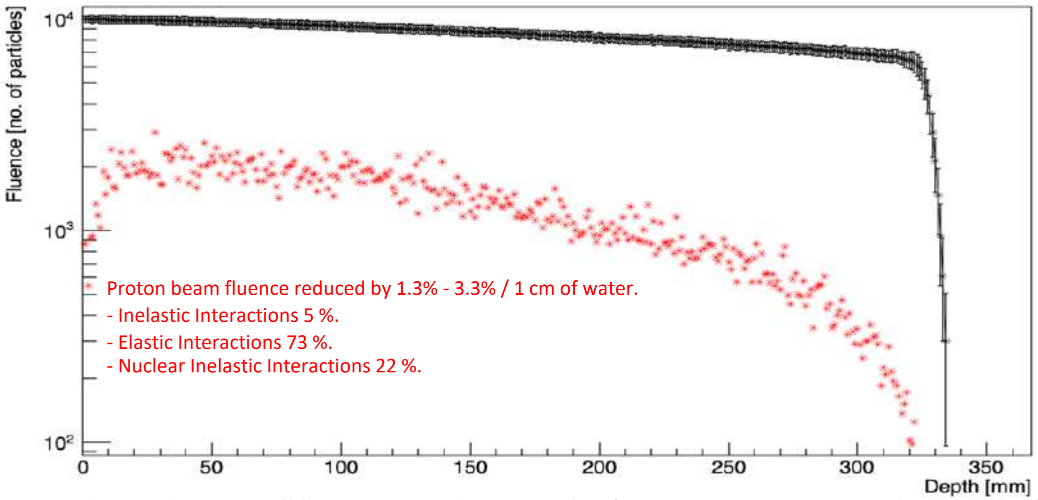
Proton therapy delivered less radiation to the heart, lungs and healthy tissues than conventional photon therapy



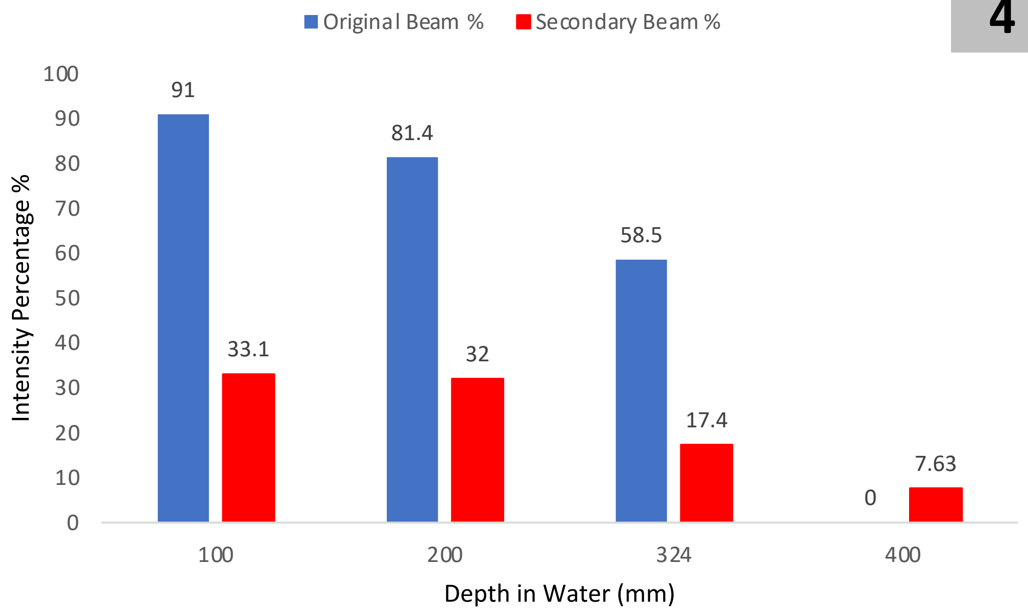


A proton beam behavior simulation modeling in water phantom with different proton energies for 70 to 230 MeV using TOPAS and GNU Parallel codes, (Above) the dose-depth (Bragg-Peak) curves and (Down) the fluence-depth curves.

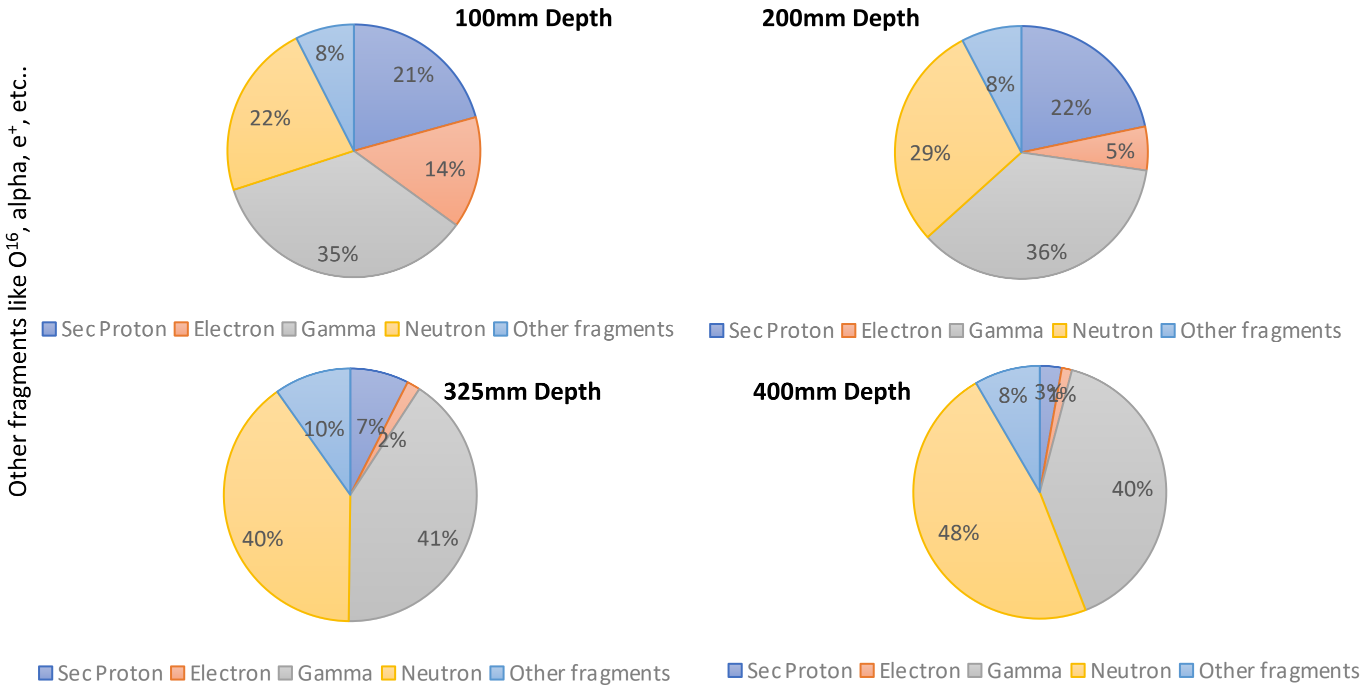
Secondary radiation associated with Proton therapy



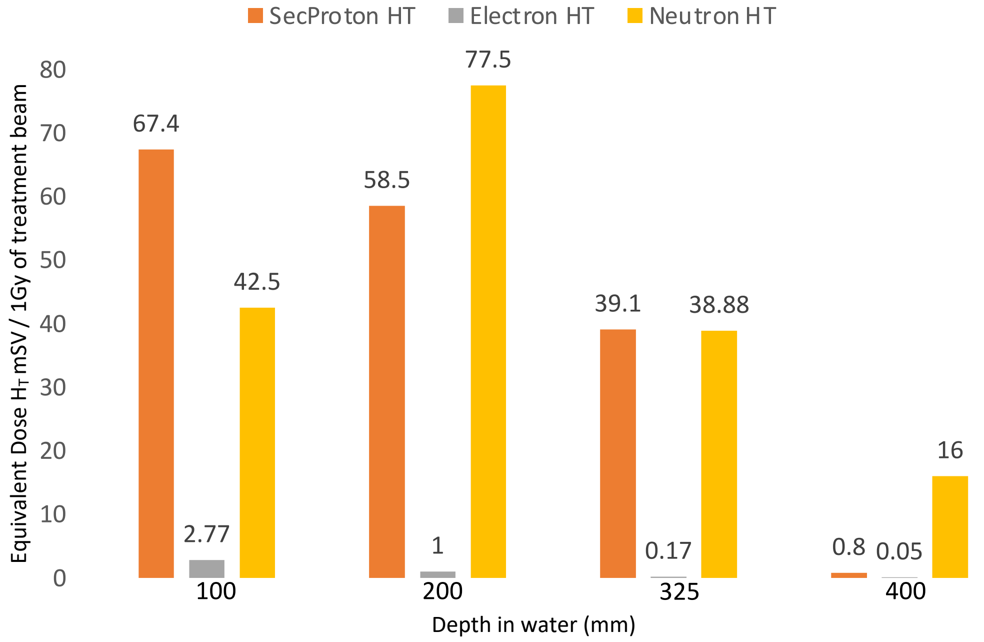
Secondary radiation will be generated as a result of protons interacting with water molecules via elastic scattering, inelastic scattering or nuclear interactions: a range of secondary particles will be created.



Primary and associated secondary ratio for Proton therapy



Range of produced secondary radiation during proton therapy within various depths.



Equivalent dose H_T mSV per 1Gy of treatment proton beam

The research motivation

The importance of neutron monitoring in hadron beam therapy:

- Neutrons are neutral particles travel long distance and depositing unwanted dose to the patient, treatment room, shielding and the facility.
- These unwanted radiation dose increase the risk of the radiological late effect and the potential of induction secondary cancer probability.
- Helium-3 proportional counters had remained the ideal choice in order to monitor the thermal neutrons with detection efficiency >60%.
- Rare availability and global shortage of Helium-3, a new generation of detector technologies will be highly needed such as neutron detectors based on semiconductor materials.
- A Si based neutron detector can be a promising alternative choice for neutron monitoring and imaging applications.

The He-3 proportional counter tube – University of Liverpool.

A Si based thermal neutron detector theory and design

- Coating a Si detector with high cross section converter materials for thermal neutron detection such as ${}^{6}_{3}Li$ will make the detector sensitive to thermal neutrons by capturing them inside the converter material.
- The resulting particles are Alpha and Triton which will be emitted in opposite directions from the converter material.

$${}^{6}_{3}Li + {}^{1}_{0}n \rightarrow {}^{3}_{1}H\ (2.73\ MeV) + {}^{4}_{2}\alpha\ (2.05\ MeV)$$

- These products could be measured through the Si sensors.

❖**Increasing the neutron converter thickness leads to:**

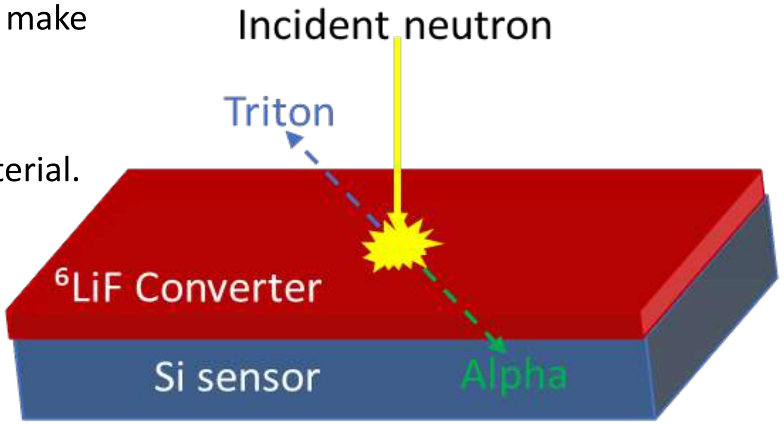
➢***Increased*** *neutron capture probability.*

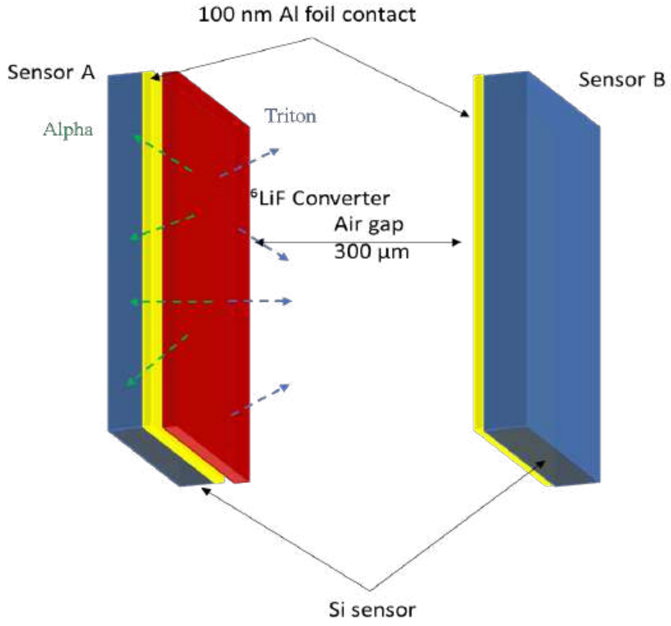
➢***Decreased*** *number of reaction products that reach the Si sensors.*

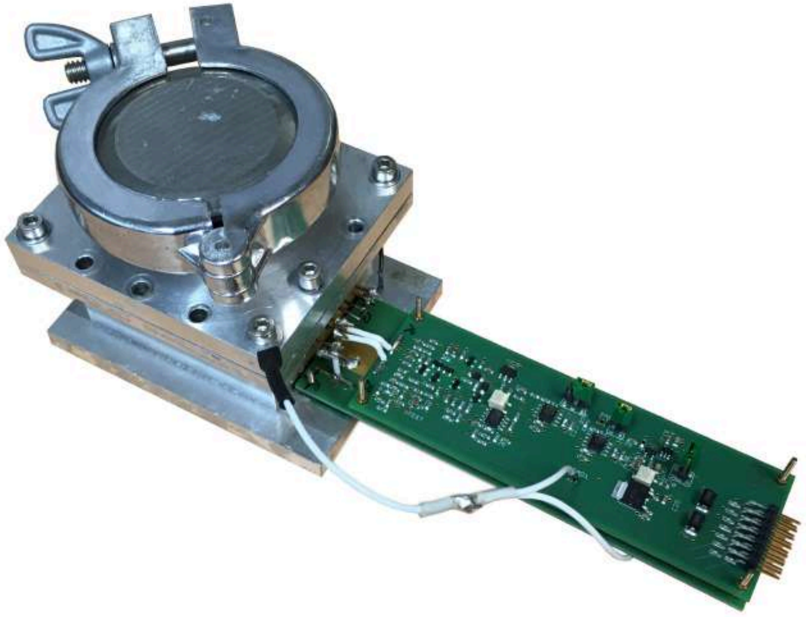
➢***Decreased*** *energy peak resolution.*

➢***A reduction*** *in detector efficiency.*

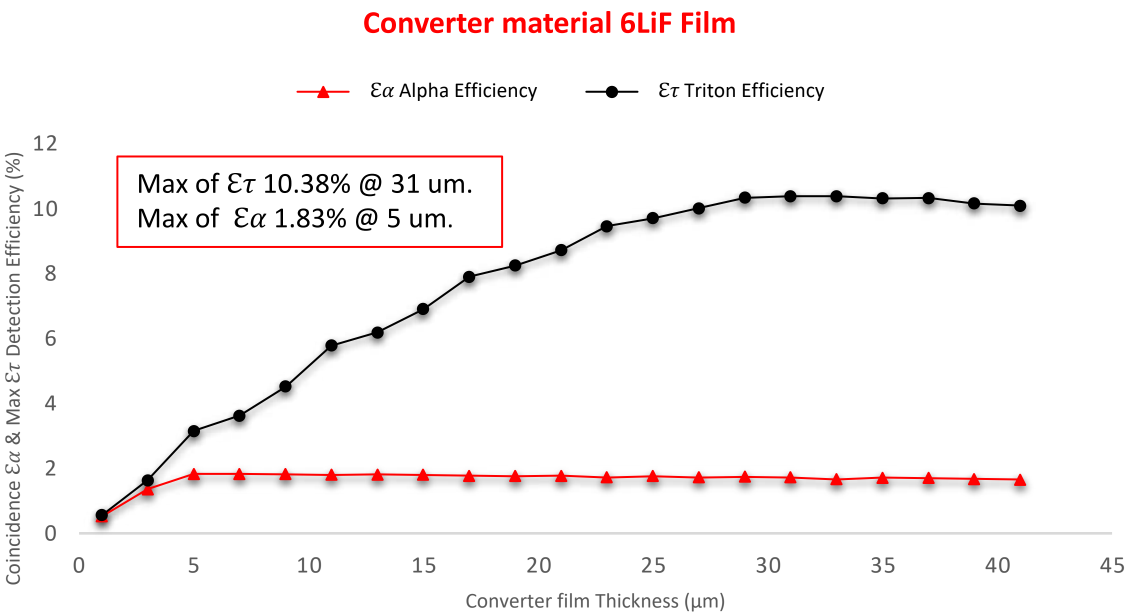
There is a need to find the optimal converter material thickness!

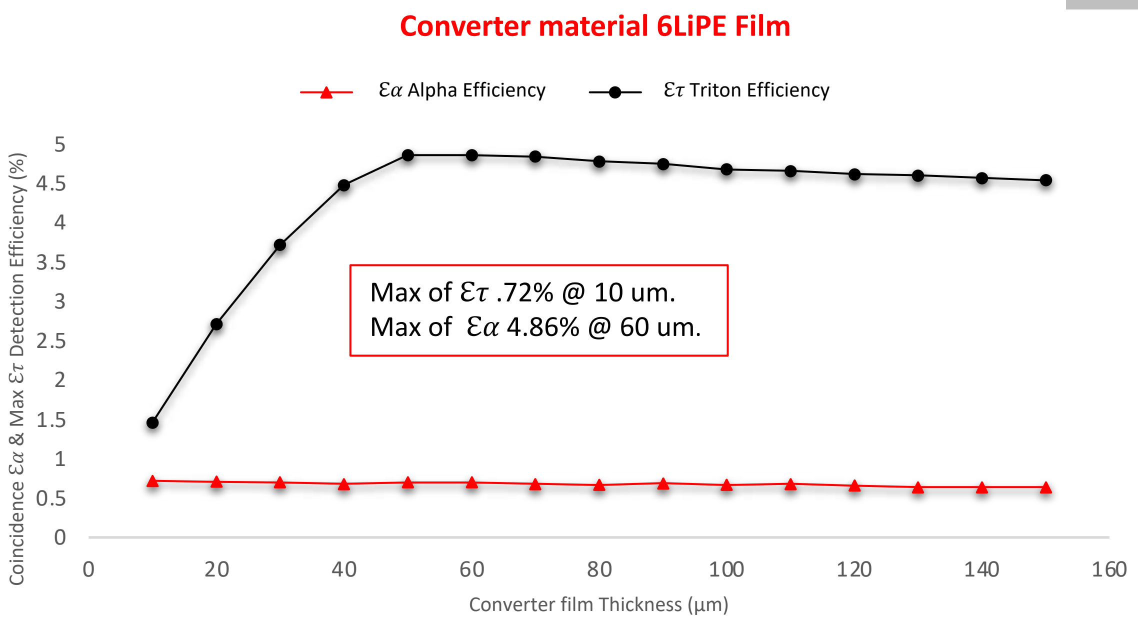


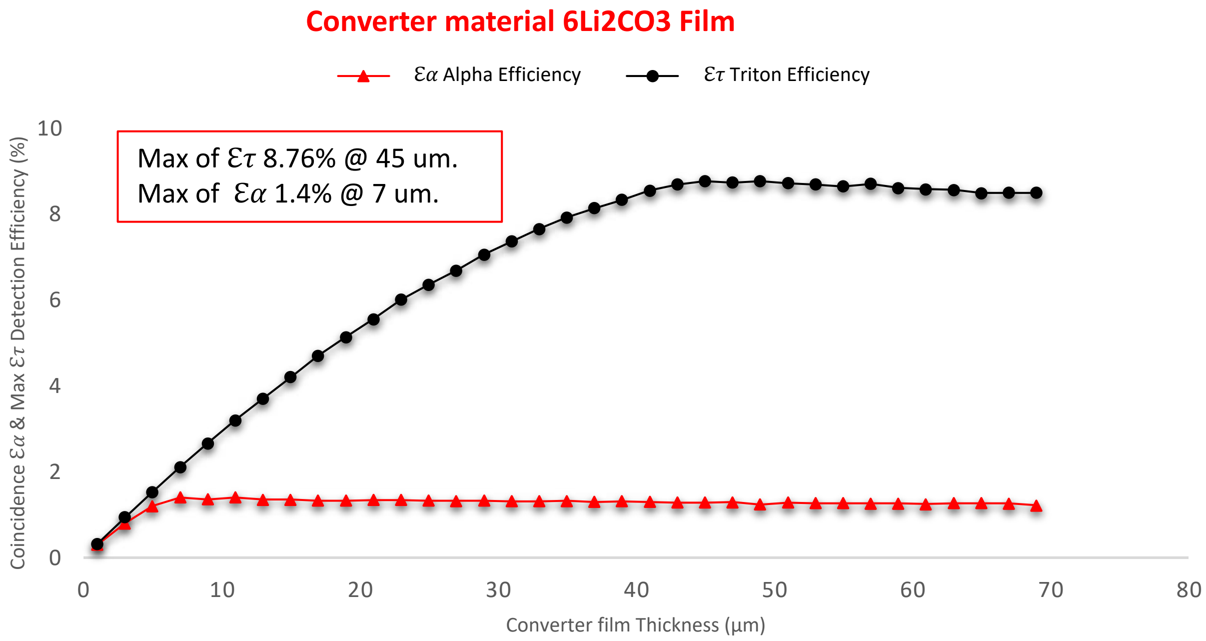


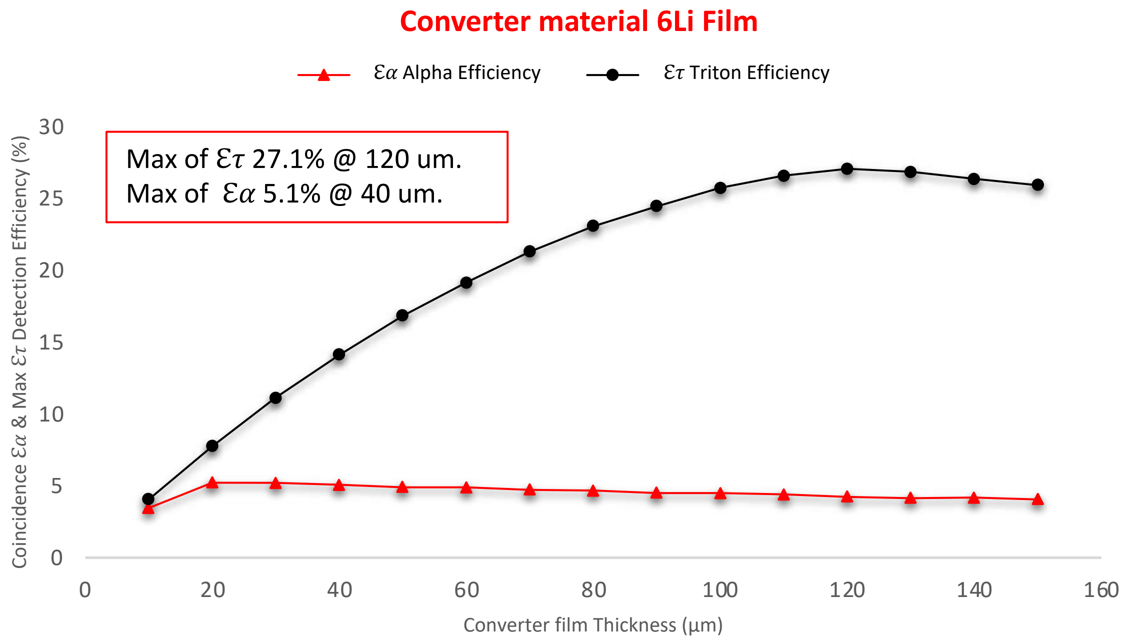


A Si based thermal neutron detector Geant4 modelling of different converter/thickness materials



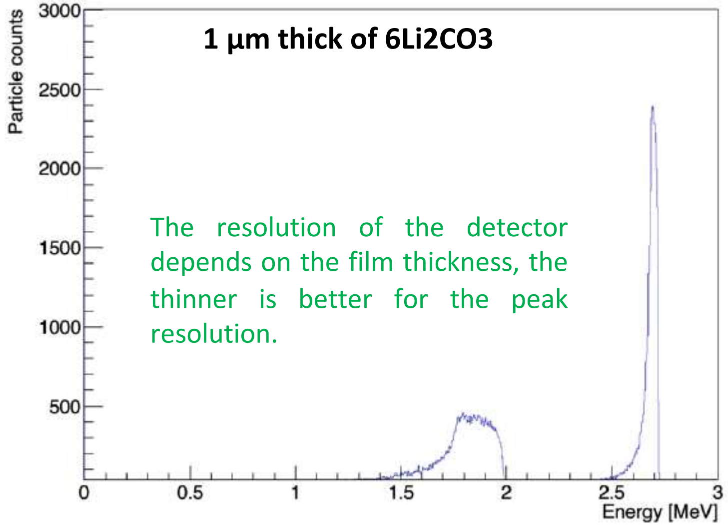


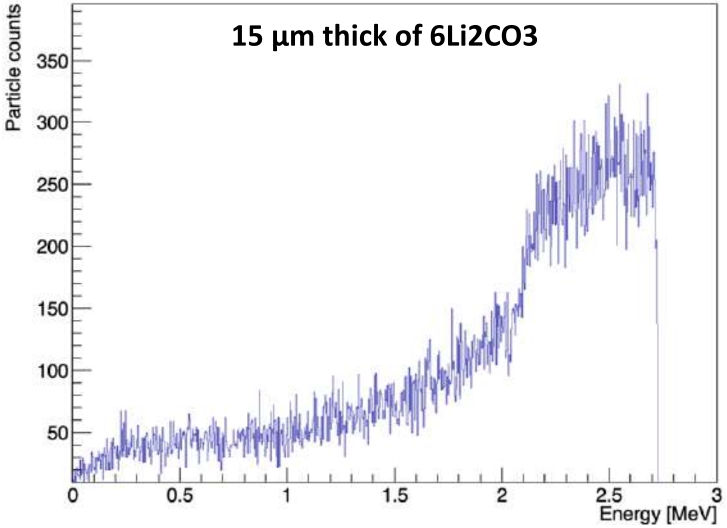


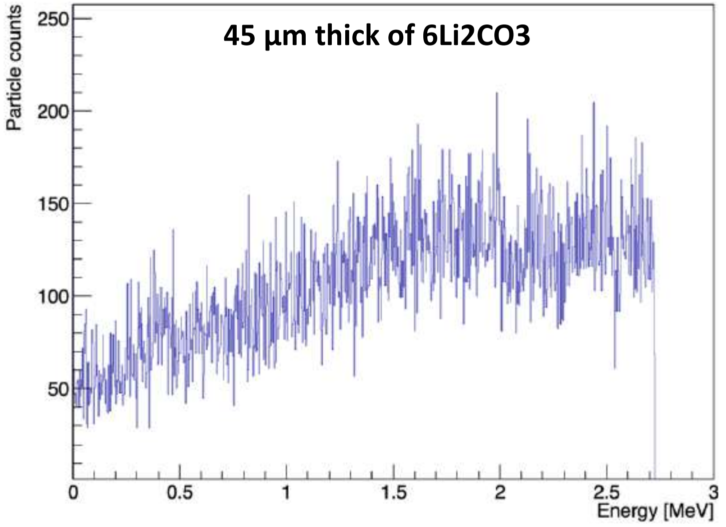


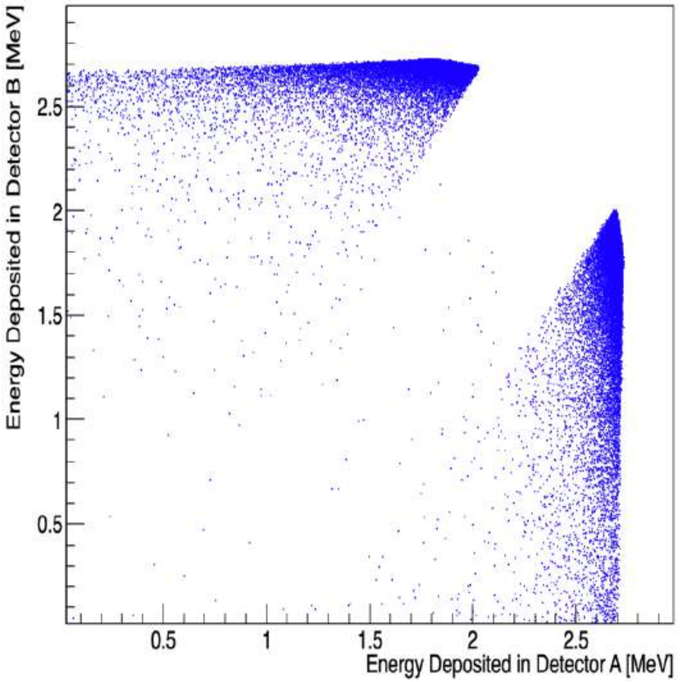
A Si based thermal neutron detector Geant4 modelling results

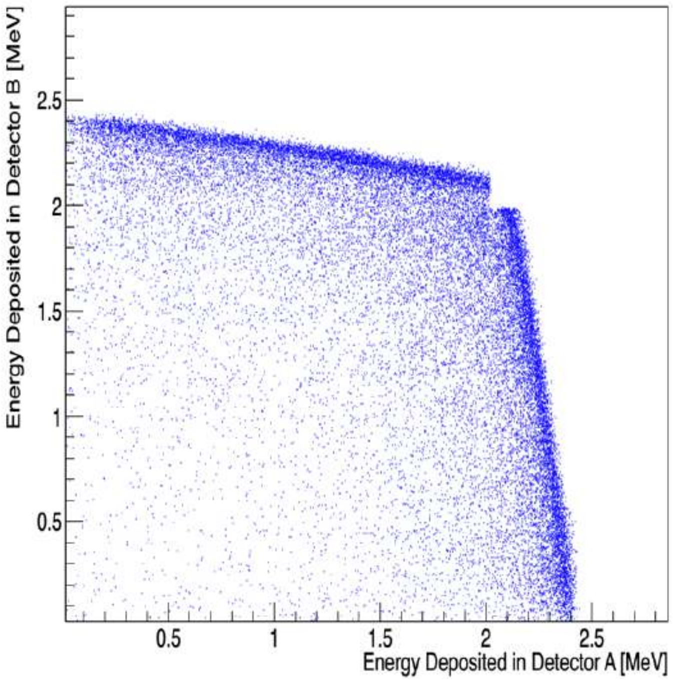
The effect of converter layer thickness on the intensity of the produced radiation products and energy resolution

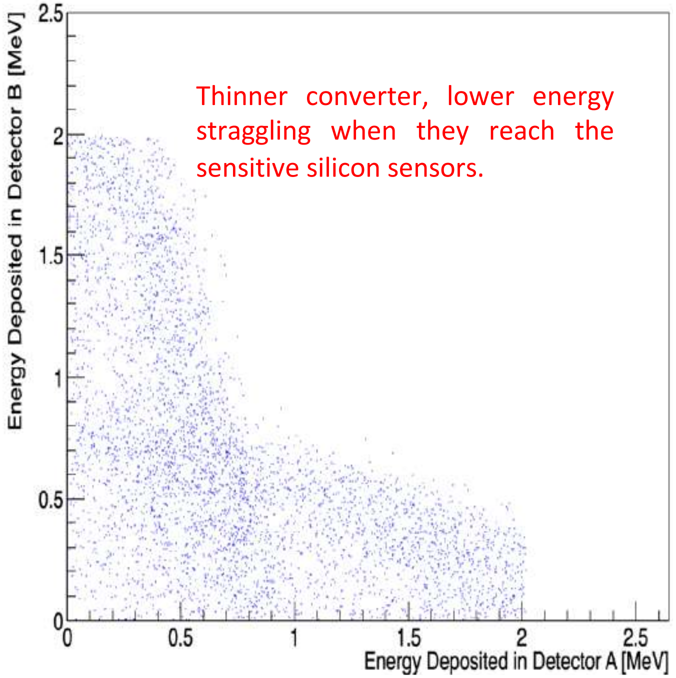










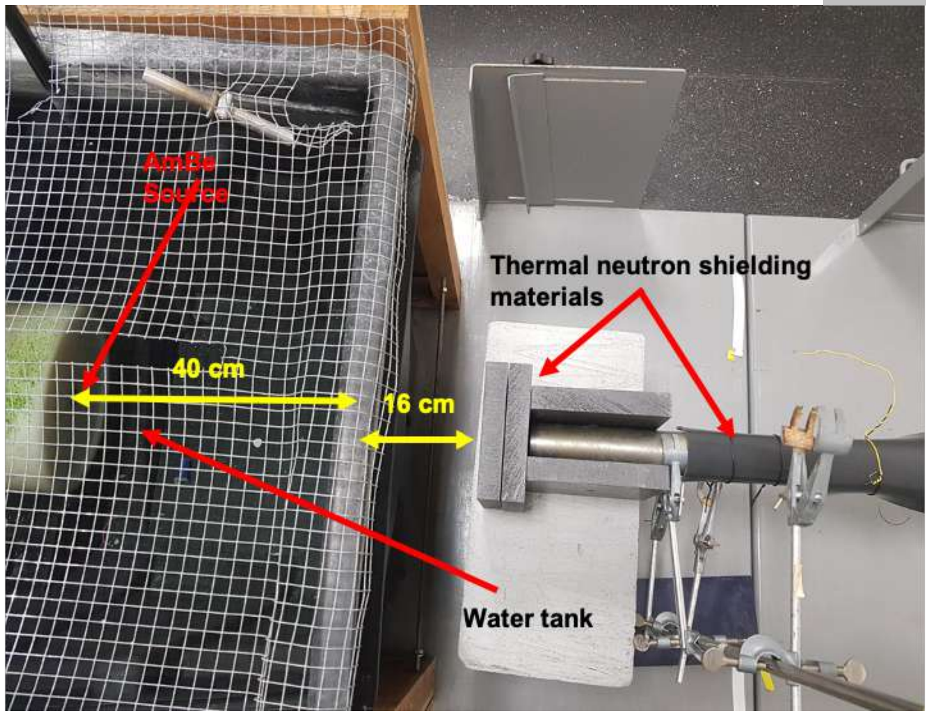


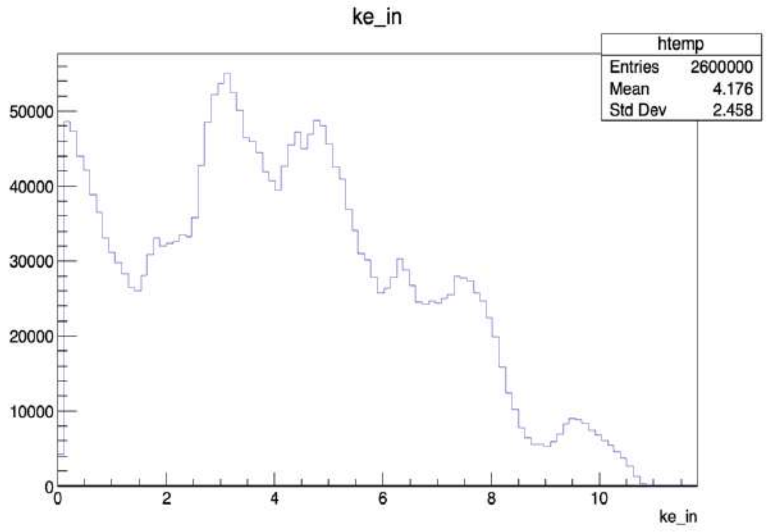
He3 proportional detector, modelling & experimental results

Specifications of the He3 proportional tube used in the experiment

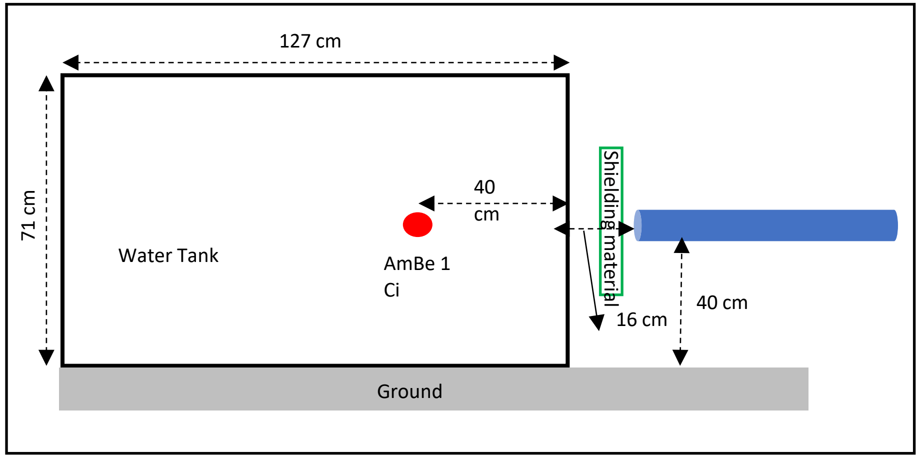
Detector Tube	Diameter Overall (cm)	length (cm)	Active Fill length (cm)	Fill gas	Pressure	Operating Voltage	Detector Efficiency
He3 Detector	5	91.4	90	He3	2 atm	1100 Volts	60%

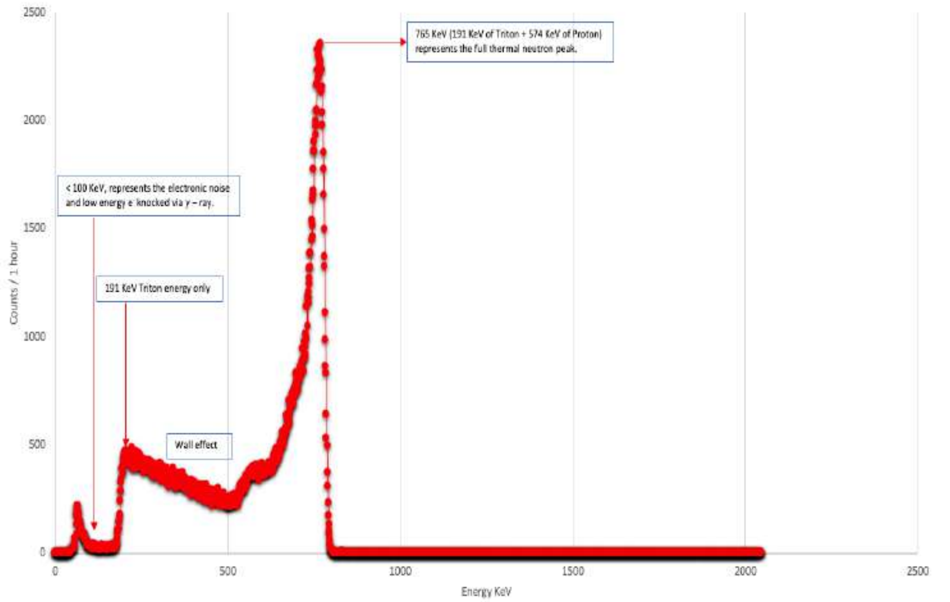
Simulation Result	**11.8 cps/cm^2**
Experimental Results	**9.13 cps/cm^2**
Experimental Results with efficiency corrections	**15.2 cps/cm^2**





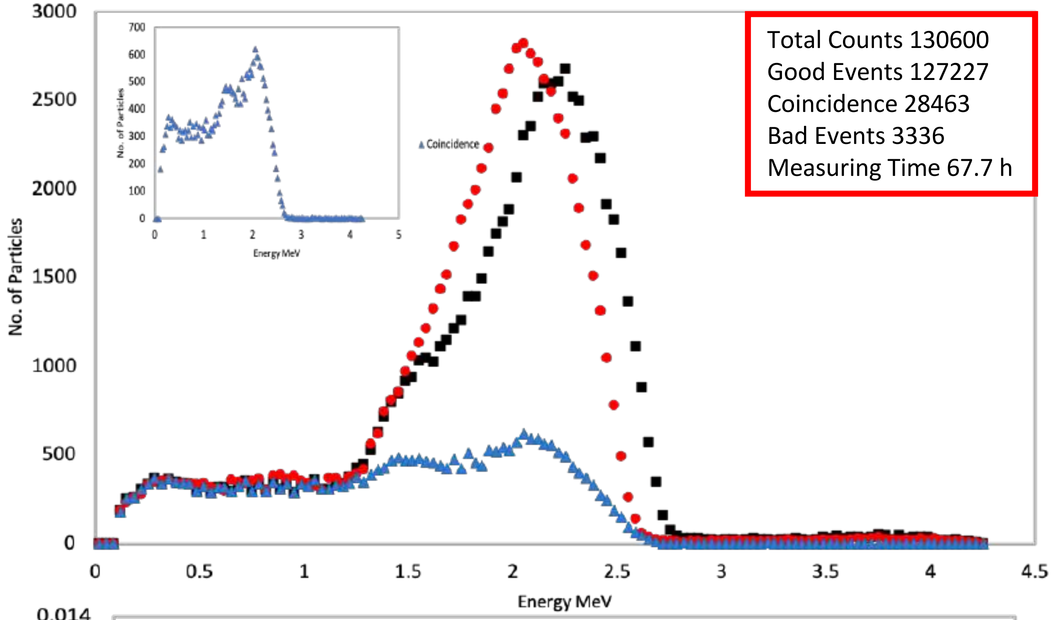
Initial Neutron kinetic energy distributions of AmBe source,1ci activity (Geant4 model).



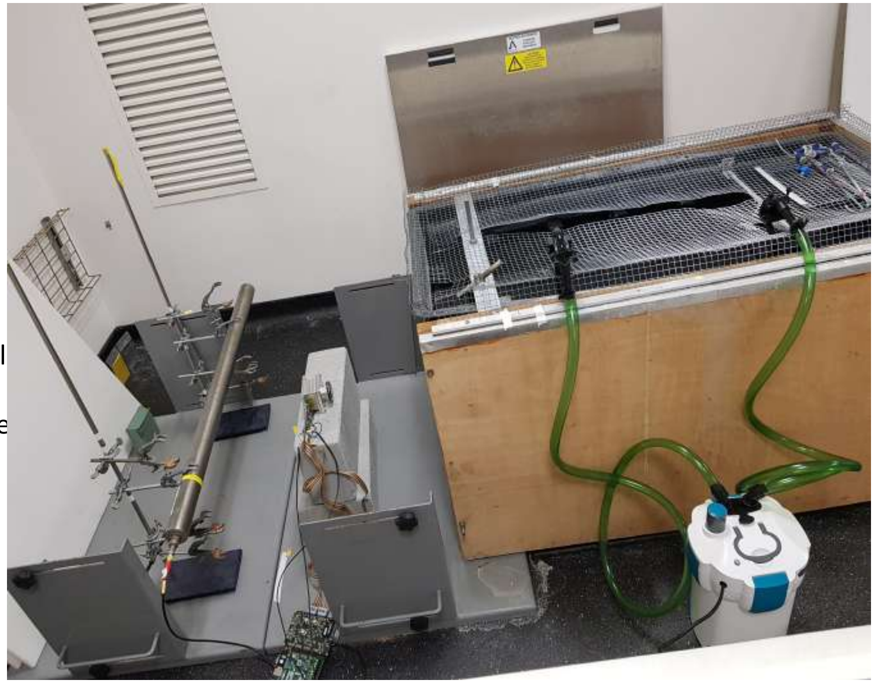


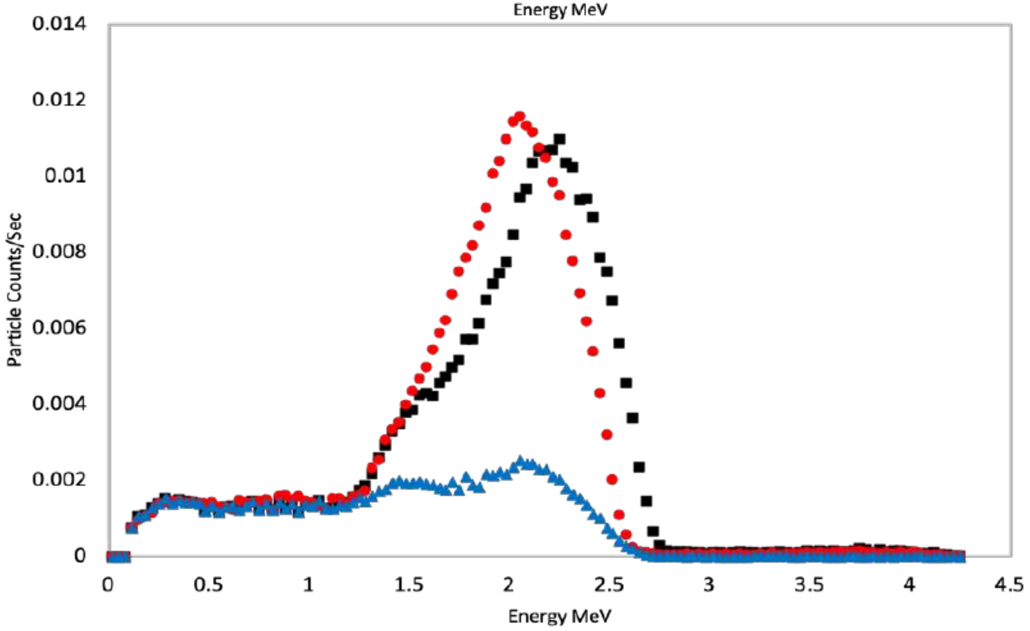
Energy spectrum collected from AmBe source and He3 detector.

Si based neutron detector experimental and validation results



Exp. Setup:
AmBe Source 1 Ci at CTL lab – University of Liverpool
Source positioned at 20 cm depth in the water tank.
Detector positioned at 40 cm away from the water tank.
Count time 67.7 hours.



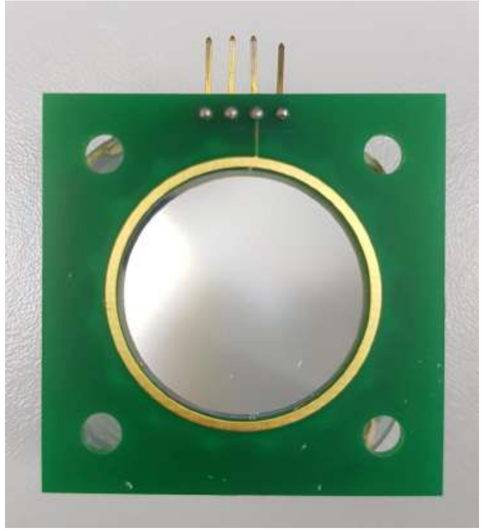


The Total and Coincidence Energy Distribution of Triton and Alpha Particles, where (Above) the total counts and (Down) the counts per second.

Efficiency	6LiF counts	Efficiency result based on He3 experiment	Efficiency result based on He3 modelling
Maximum Efficiency	0.64 cps/cm^2	4.2 ± 0.65 %	5.42 ± 0.65 %
Coincidence Efficiency	0.12 cps/cm^2	0.8 ± 0.43 %	1 ± 0.43 %

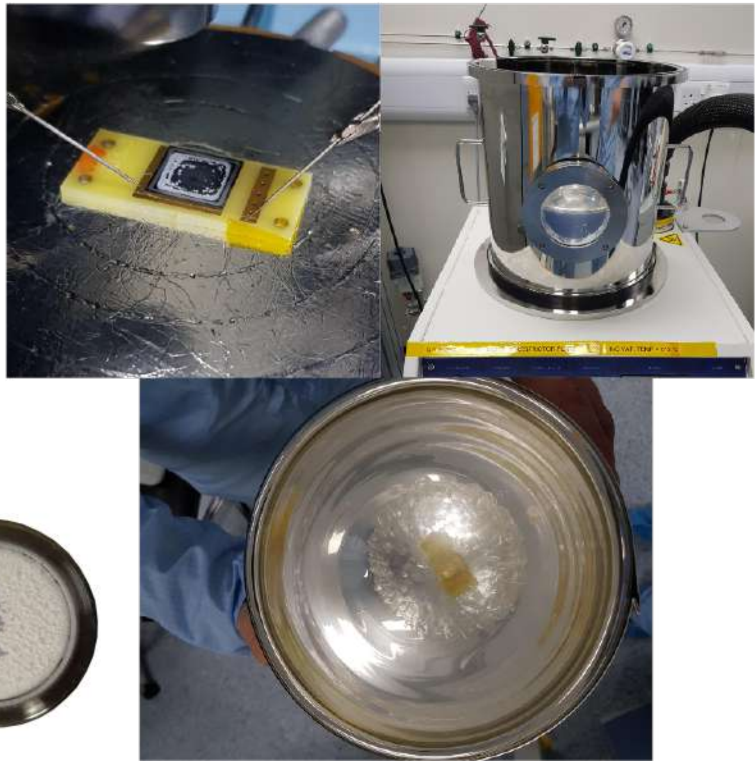
Summary and Future work

- The experimental result of the Si(6LiF) diodes with neutron (AmBe) source agreed with the simulation model which provide a promising result for the developed prototype system.
- Working on fabricate different designs of the neutron detector in Liverpool Semiconductor Lab LSDC.
- Test beams with the Si based neutron system at clinical X-ray and proton beam facilities within different energies in collaboration with our clinical partner Rutherford Cancer Centres.



Trenched Si diode, 6LiF 1µm thick

A Si sensor coating with 6Li2CO3 and a Parylene layer in Liquid Argon with vacuum chamber



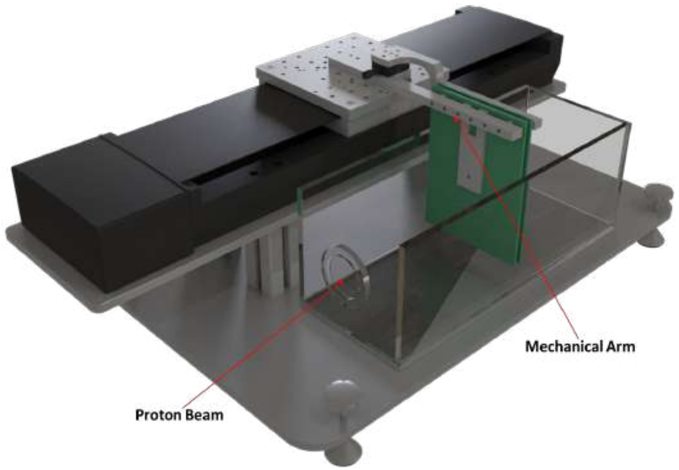
A Si diode coating with 6Li2CO3

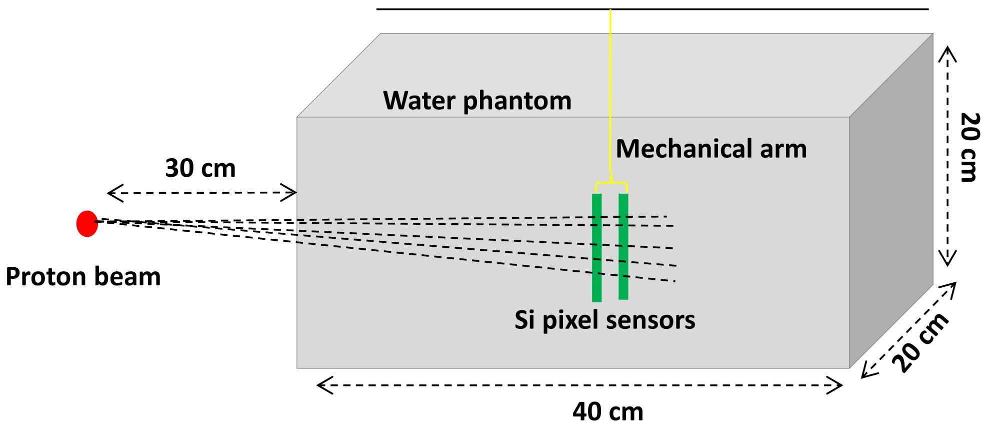
Thank you for attention and stay safe!

Backup slides!

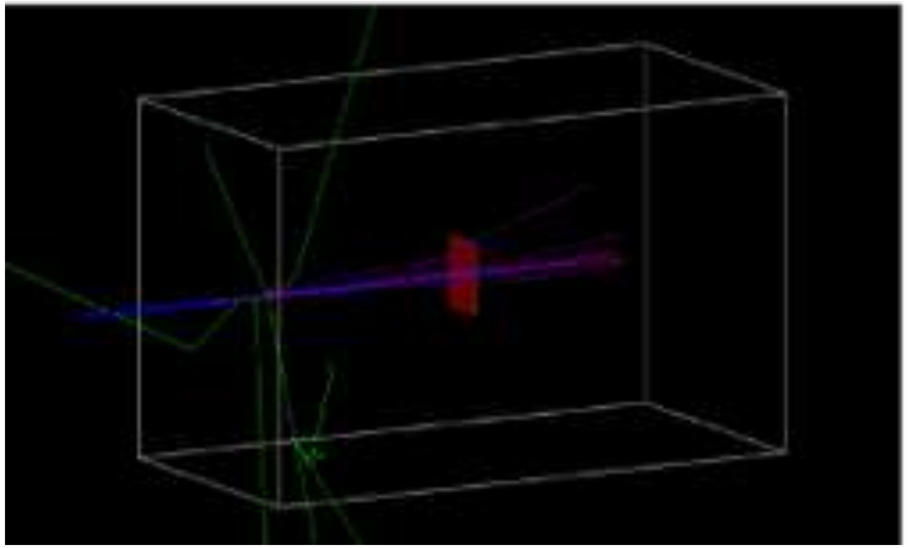
Geant4 modelling of Si detector system and monitoring the proton therapy

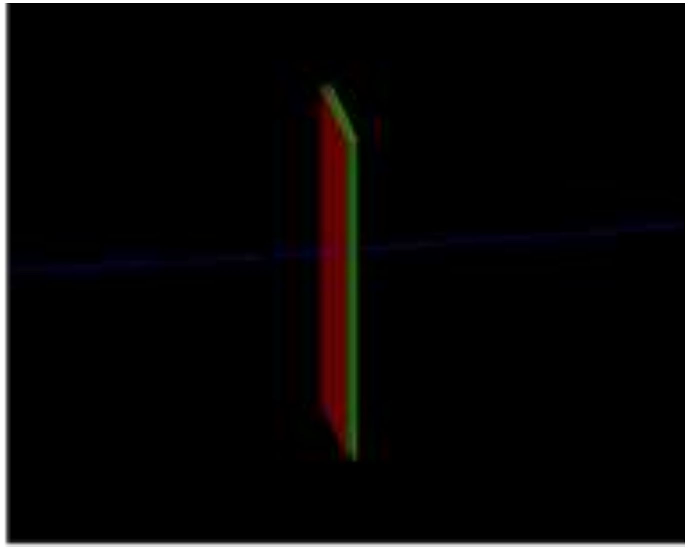
A water phantom contains two silicon pixel sensors 50 µm thick, each detector is 4x4 cm^2 contains 800 pixels. The Si pixels shift inside the phantom via mechanical arm in order to monitor the energy deposited distribution, the proton fluence and the Bragg-Peak curve.





The layout flowchart of the experiment and the water phantom structure.





A snapshot of a proton traversing the Si pixels detector construction in the Geant4 toolkit.

Absorbed dose and Equivalent dose formula

Radiation absorbed dose formula

Dose (Gy) = Energy(Joul) / m(Kg)

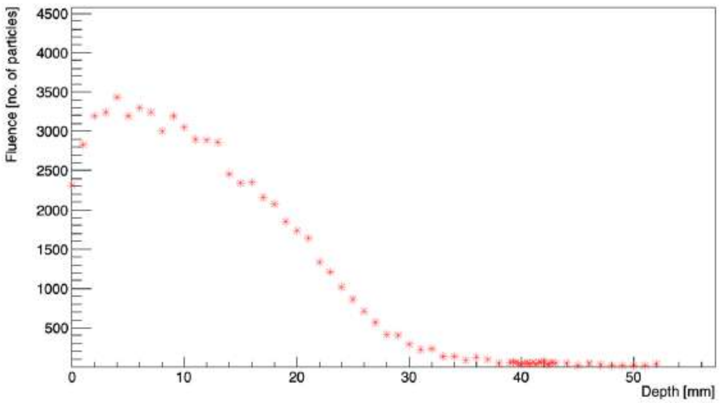
Radiation equivalent dose formula

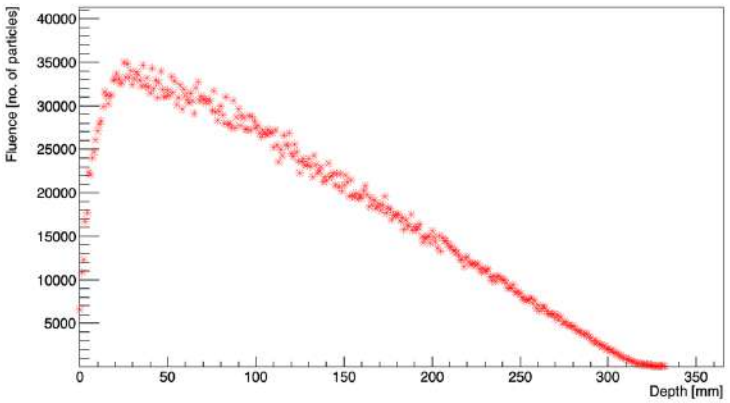
$H_T = \sum_R W_R \cdot D_{T,R}$

Where, H_T is the equivalent dose in Sieverts (Sv).
$D_{T,R}$ is the absorbed dose in Gray (Gy).
RW_R is the radiation weighting factor.

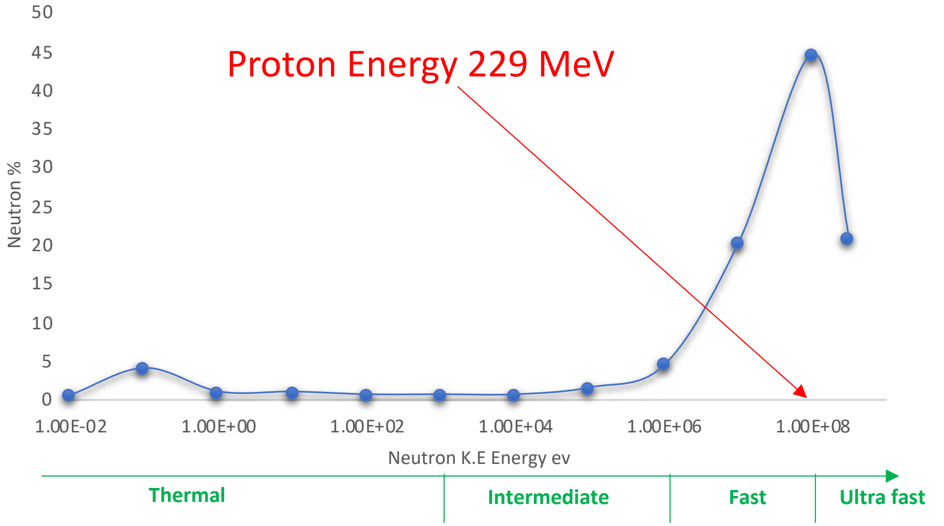
Radiation type and energy	Radiation weighting factor, w_R
Photons, all energies	1
Electrons, myons, all energies	1
Neutrons below 10 keV	5
from 10 keV to 100 keV	10
from 100 keV to 2 MeV	20
from 2 MeV to 20 MeV	10
over 20 MeV	5
Protons over 2 MeV	5
Alpha particles, fission fragments, heavy nuclei	20

The Table represent the radiation weighting factor of different type of radiation.





The fluence of neutrons that generated as a result of nuclear interactions during proton therapy with energy 70 and 230 MeV.



The kinetic energy distribution of the produced neutrons as a result of nuclear interactions from proton therapy at energy 229MeV.

A Si based neutron detector Geant4 modelling compare of two simulation methods

Two Geant4 simulation studies had been done:

- Modelling a thermal neutron source irradiate the proposed detector with varying of neutron converter material thickness.
- Defined an Isotropic source generate Alpha and Triton particles from the neutron converter material itself within different converter thickness.

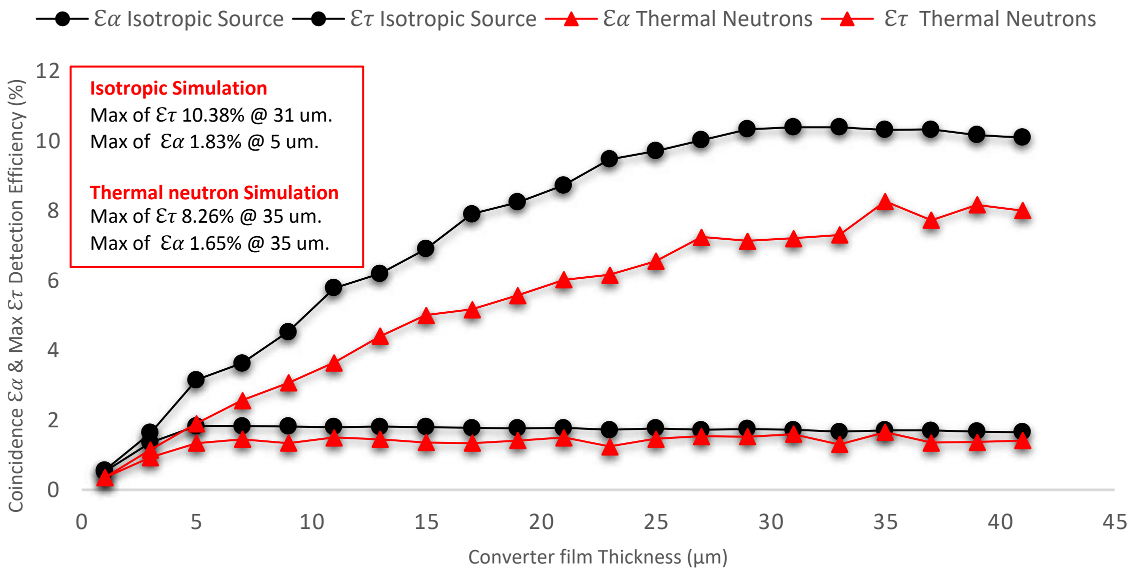
The both simulation models provide similar efficiency results with maximum variation by 2%.

Total and coincidence detections efficiency calculation formula

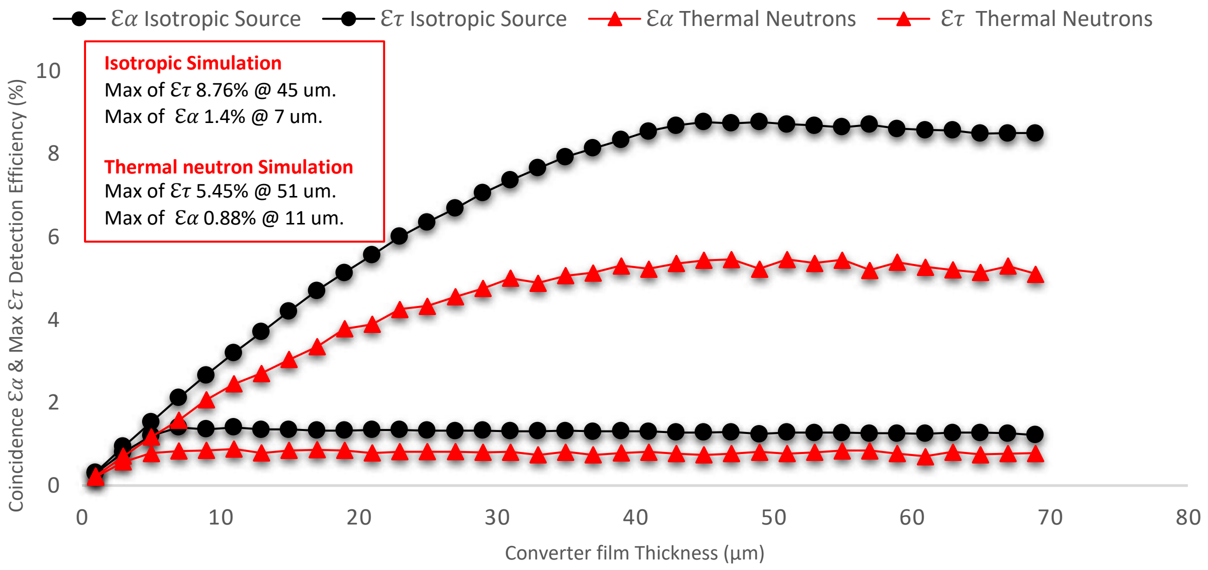
$$\varepsilon_n = \frac{n}{N} \times \{\, 1 - \exp(- \frac{N_A}{\omega_A} \times \rho\, \sigma\, x)\, \}$$

Where: n the number of particles detected by the detector.
N the total number generated inside the converter.
N_A the Avogadro number which is equal to 6.022×10^{23} /mol.
ω_A the atomic or the molecular weight of the converter [ω_A for ^{6}LiF = 25 g/mole and ω_A for ^{6}Li = 6 g/mole].
ρ the density of the converter which is [2.539 g/cm³ for ^{6}LiF and 0.462 g/cm³ for ^{6}Li].
σ the cross section which is 940 barn for ^{6}Li.
x the converter thickness.

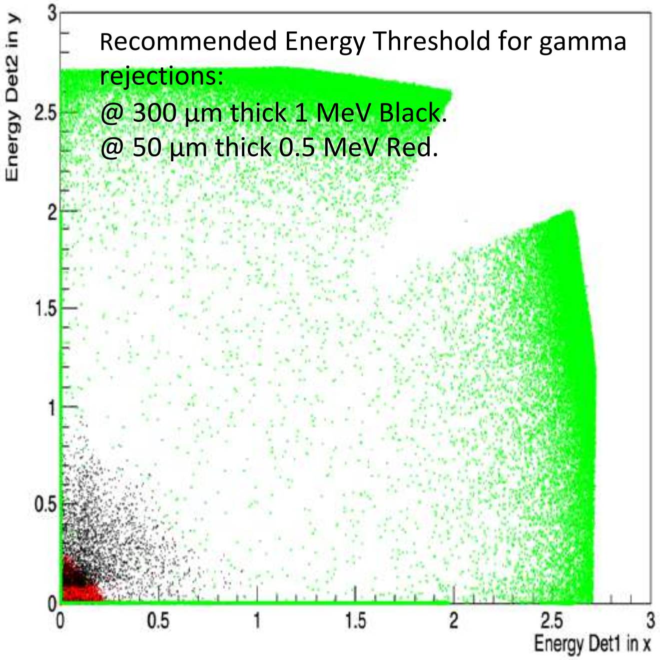
Converter material 6LiF Film



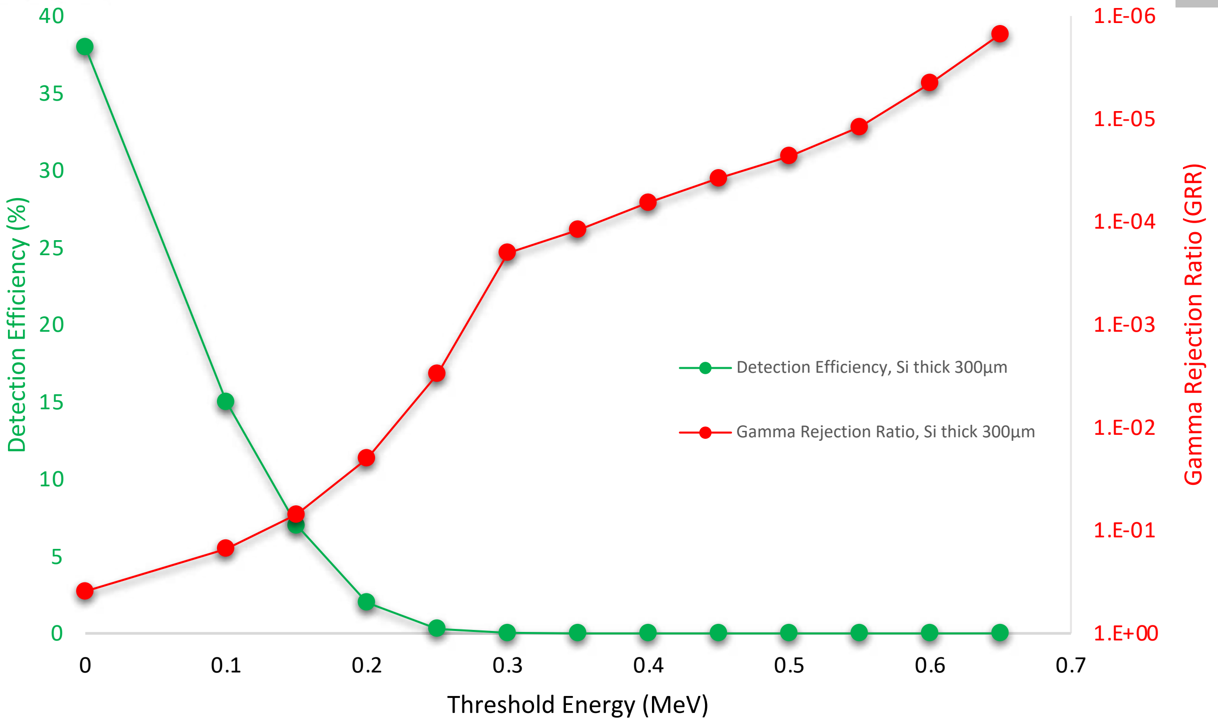
Converter material 6Li2CO3 Film



Geant4 modeling of gamma rejection ratio estimation



Particle energy distributions on the both sensors where red the gamma edep (50 µm thick), black the gamma edep (300 µm thick) and green the edep of alpha and triton edep (10 µm 6Li).



The effect of threshold energy on both gamma detection efficiency and gamma rejection factor for Si diode with 300µm thick.

Determine the Gamma Rejection Ratio (GRR) Equation

$$GRR = \frac{Total\ Gamma\ Counts - Total\ Background\ Counts}{Q\gamma \times BR \times \Omega \times Time}$$

The number of gammas incident can be calculated from the source activity and the test geometry.

$Q\gamma$ = Co^{60} Source Strength in Becquerels.

BR = Branching Ratio for Co^{60} = 2.

Ω = Source Detector Fractional Solid Angle.

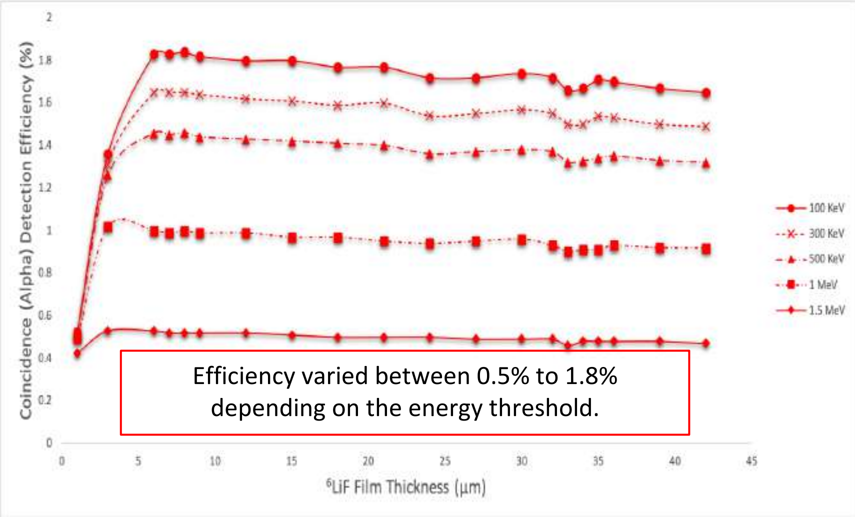
$$\Omega = \frac{1}{\pi} arctan\left[\frac{W \times L}{4 \times D \times \sqrt{\frac{W^2}{4} + \frac{L^2}{4} + D^2}}\right]$$

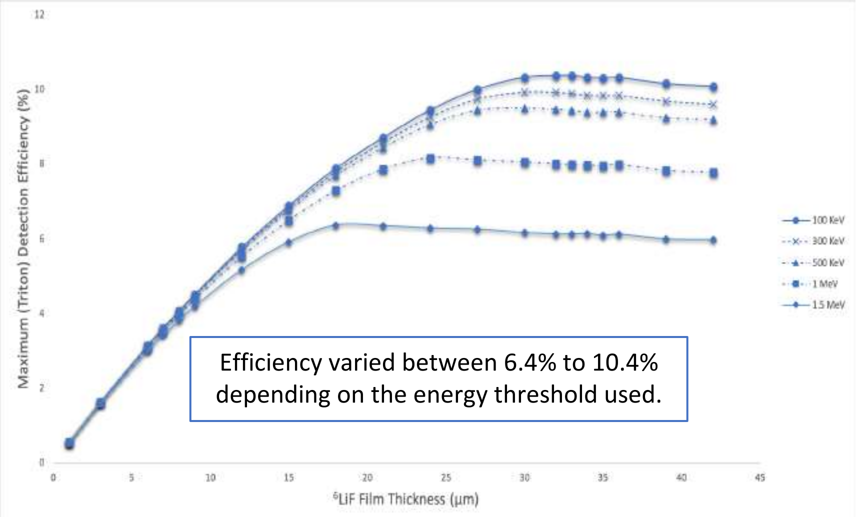
Where:

W = Detector Width. L = Detector Length.

D = Distance from Source to Detector.

Energy threshold effect on coincidence (Red) and maximum (Blue) efficiencies for Si(6LiF).





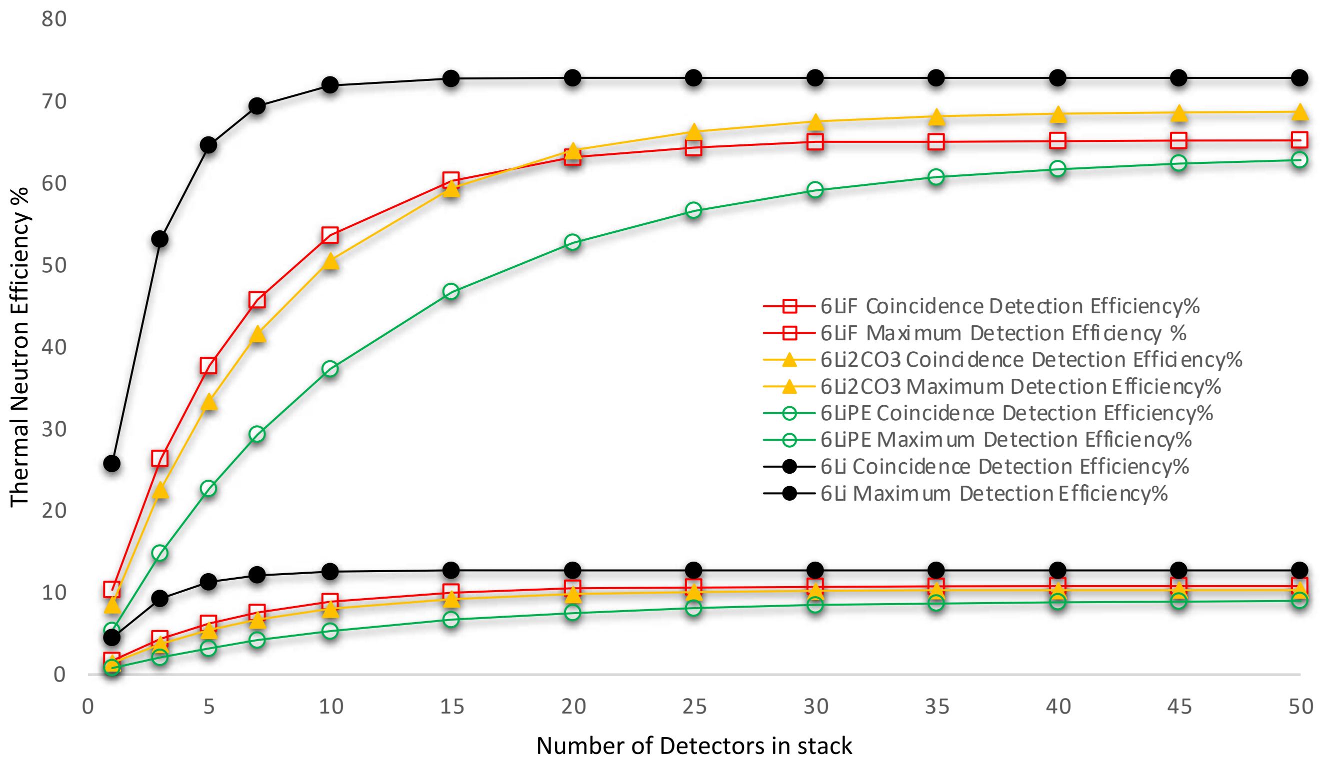
A Si based thermal neutron detector Geant4 modelling of detectors in stack

- **Triton Efficiency**

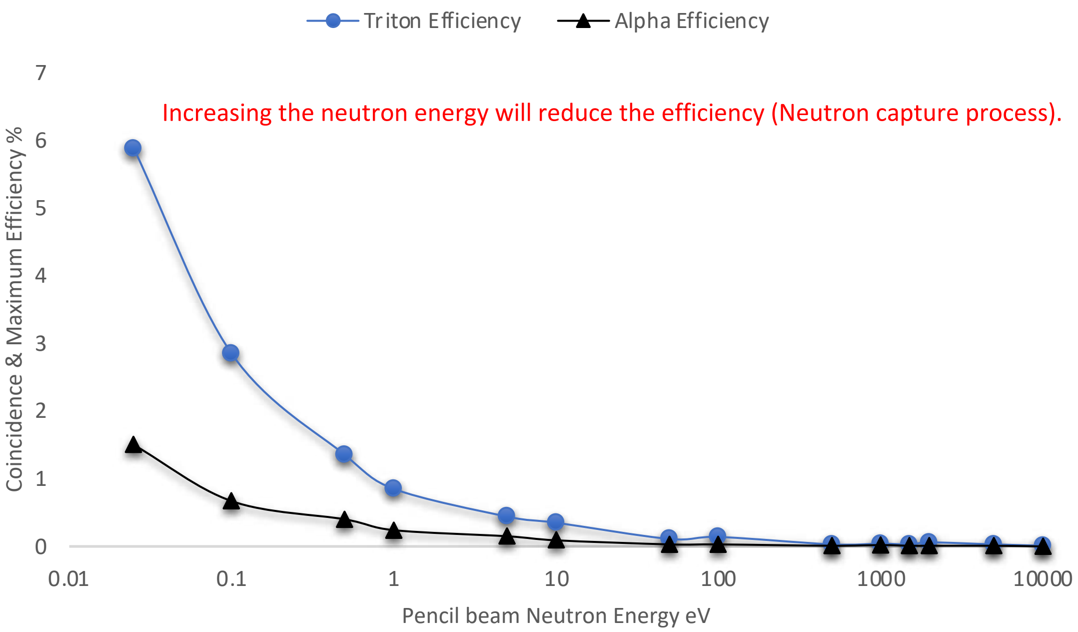
Maximum Triton efficiency for 1 layer is 26%, 7 layers 70% and can be reach up to 73% with 25 layers.

- **Alpha Efficiency**

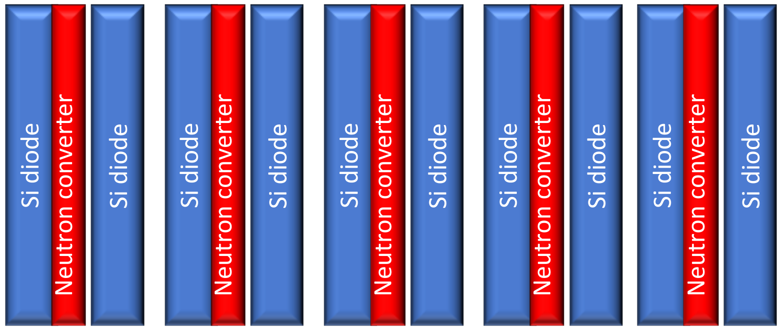
Maximum Alpha efficiency for 1 layer is 5%, 7 layers 12% and can reach up to 13% with 20 layers.



Variation of the thermal neutron detection efficiency as a function of the number of the sandwich detector in a stack detector for different neutron converter materials.



The neutron Detector response for range of neutron energies, the converter material is 6LiF film 20µm thick.



Schematic of a stacked detector with different converter materials.