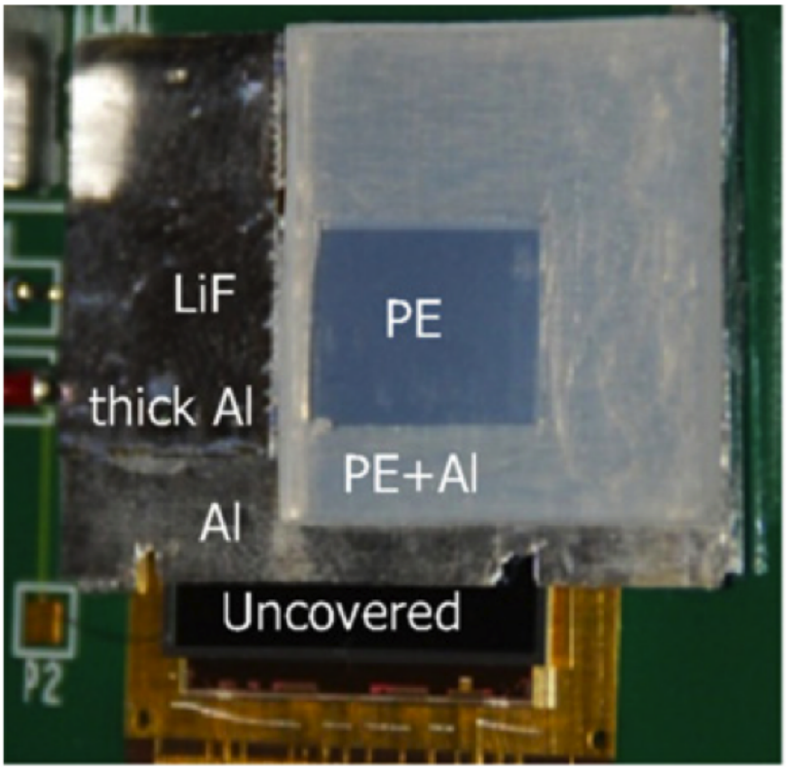
Monte Carlo Studies of two Different Conversion Layers for Neutron Measurements with Medipix Silicon Detector.

September 10, 2013



Picture from: D. Turecek, T. Holy, S. Pospicil, Z. Vykydal, Elsevier; Nuclear Instruments and Methods in Physics Research A 633 (2011) S45–S47

Summer Student Report, CERN September 2013

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1 Introduction

In 2007 the ventilation system of CNGS failed and investigations showed that the failure was due to Single Event Upset (SEU). Since then there has been increased interest in studies of neutron flux, that can potentially cause SEU. Two Medipix detectors have previously been installed in the CMS cavern on a test basis and have shown to work as intended[1]. More Medipix detectors will be installed to provide high resolution measurements of the particle flux in the vicinity of the CMS, focusing on measurements of the neutron flux. The measurements will provide an important basis to know what precautions to take to avoid another failure due to SEU. The measurements will also constitute a valuably reference to the FLUKA simulations of the general flux in the CMS cavern, that can potentially lead to important corrections of the simulations. Furthermore, measurements from the Medipix detectors will act as a cross check on the hadronic forward detector radiation monitoring system (HF radmon). Bonnos spheres are already installed, but can only provide offline measurements, whereas the Medipix detectors offers online measurements.

The Medipix detectors measure the ionization by charged particles, and can differ between different particles from the pattern of activated pixels in an interaction[2]. The detectors can detect neutrons, if these are converted into charged particles in the detector, but the detection efficiency is low. Therefore, to increase the detection efficiency, conversion layers of Lithium Fluoride (LiF) and Polyethylene (PE) are applied to the Medipix detectors to increase the detection efficiency for thermal- and fast neutrons respectively. The picture on the front page shows different conversion layers glued on the Medipix detectors. The aluminium is a beam hardener rather than a conversion layer and is therefore not considered in this study.

FLUKA has proved to be a successful tool to simulate of the general particle flux in the CMS detector and -cavern, but simulations of single sub detectors of small geometry, i.e. of the order 1 μm to 1 mm, are less experienced by FLUKA experts. In this report, we present the results of FLUKA simulation studies on how conversion layers of PE and LiF effect the detection efficiency of neutrons in the Medipix detectors. The studies aim to answer firstly, if FLUKA is a well suited tool for simulation studies of single, small-scale detectors and secondly, if LiF- and PE conversion layers do increase the detection efficiency of neutrons and for what energies of the incoming neutrons, they provide an increase (or decrease) in the efficiency.

2 About the Medipix Detector and Conversion Layers

2.1 The Medipix Detector

The Medipix detectors are hybrid silicon pixel detectors. The are composed of a 300 μm silicon layer with a bias voltage from the top to the button, where 256 $\times$ 256 bump bondings connect the silicon to a read-out chip and provide a pixelised signal. The detectors that have been installed on a test basis are second generation Medipix detecotors, Medipix 2, whereas the detectors that are to be installed during the long shut down are Medipix 3 detectors. The Medipix 3 has the opportunity to gather the pixels in groups of four, giving each group a total of eight energy threshold. Since one pixel only has two energy thresholds, the Medipix 3 detector has a much better resolution w.r.t. the measured energy deposited in each interaction compared to its predecessor.

2.2 Conversion Layers

Fast neutrons can interact directly with silicon and produce an α-particle via $\mathrm{n} + {}^{28}\mathrm{Si} \rightarrow \alpha + {}^{25}\mathrm{Mg}$ or a proton via $\mathrm{n} + {}^{28}\mathrm{Si} \rightarrow \mathrm{p} + {}^{28}\mathrm{Mg}$, but the cross sections for these processes are small[4]. Therefore, conversion layers are required to obtain a reasonably detection efficiency. Neutrons can interact by inelastic scattering with Lithium and produce α-particles and tritons via $\mathrm{n} + {}^{6}\mathrm{Li} \rightarrow t + \alpha$. This process has highest cross section for low energies, i.e. for thermal neutrons[4]. Lithium is applied to the detectors in the composed material LithiumFluoride (LiF). The other conversion layer material is Polyethylene (PE). The main constituent of PE is hydrogen, and the neutrons can scatter elastically with the hydrogen nuclei. Since protons and neutrons almost have the same mass, the neutrons can "kick out" the protons from the PE, thereby producing a free proton. The same principle underlies the fact that PE is an effective shielding/moderator material.

The two Medipix detectors, that was installed in the CMS had 1.3 mm thick PE- and 20 μm thick LiF conversion layers[5].

3 Set-up - necessary settings in FLUKA

The FLUKA package is a Monte Carlo simulation program written in Fortran and it has a python GUI called flair. FLUKA has many applications spanning from proton and electron accelerator shielding to target design, calorimetry, detector design, neutrino physics, radiotherapy etc.[6]

In this study, a simple geometry is used, with a 300 μm thick silicon layer with an area of 1.4 cm $\times$ 1.4 cm, irradiated by a monoenergetic neutron source homogeneously distributed over an area that exactly corresponds to the area of the silicon layer. The area corresponds to the size of the physical silicon layer on the Medipix 2 and 3 detectors. The beam is initialised with zero angle w.r.t. the silicon and from a distance of about 10 cm. Simulations with the same source, but with an additional layer of either a PE- or a LiF conversion layer directly in front of the silicon layer is done. The conversion layer has the same area as the silicon layer, but differs in thickness: 10 μm, 32 μm and 1 mm was used in case of the LiF conversion layer, and 1 mm and 3.2 mm was used in case of PE. The final simulations is run with 30 energies evenly spread on a logarithmic scale from 0.01 eV to 3200 GeV, with 500'000 primaries (primaries is the number of incoming neutrons) and 5 cycles.

At the CMS, FLUKA has previously been used to simulate the total particle flux, which is an important tool for the hardware group. However, FLUKA has not previously been used for simulations of single sub detectors of small geometry, i.e. ranging from 1 μm to 1 mm. In order to obtain meaningful results, special settings have to be applied to the simulations. Furthermore, FLUKA has a high energy- and a low energy library for neutrons, which also requires some attention when setting up the simulations. The following is a list of cards, that need to be considered in order to get reasonably results from the simulations.

1. STEPSIZE. Before the step size was adjusted, the simulations gave zero energy deposited in an energy range from about 10^{-8} to 10^{-2} MeV per incoming neutron. The zero values was obtained both for silicon without a conversion layer and with PE and LiF respectively. When a step size of 1 μm is applied[1], the simulations give non-zeros values in the same energy range.

[1] By changing WHAT(5)

2. PART-THReshold. The card PART-THReshold adjusts the threshold at which a particle is not followed any more, and its energy is deposited in the surroundings. Reducing the particle threshold for protons gave the same result as reducing the step size, i.e. non-zero values were obtained in the energy range 10^{-8} to 10^{-2} MeV per incoming neutron. However, when using the PART-THReshold card, it happened several times that the ASCII output files from the two USRBIN cards were not generated. Since that bug appeared when the PART-THReshold was present and not when the card was not present, there is a chance that the PART-THReshold is the reason for the bug. Therefore, and because the same results could be obtained by adjusting the step size, the PART-THReshold card was not used for protons.

   The threshold energy for neutrons was lowered from the default value of 10^{-14} GeV to 10^{-17} GeV. Without that setting, the simulations gave discontinuous results in the limit between (what FLUKA consider as) low energy neutrons and high energy neutrons, i.e. at 20 MeV.

3. The LOW-NEUT card activates transport of neutrons with energies smaller than 20 MeV.

4. The ION-TRANS card activates ion transport. This card was activated for "HEAVYION" in the simulations.

5. The EMF card activates transport of electrons, positrons and photons.

See more about the cards in the FLUKA manual and the FLUKA mailing list, which can be found at the FLUKA website[6].

3.1 FLUKA limitations

FLUKA provides event by event and region by region based scoring with the card EVENTDAT. One event is one primary entering the system. It is count as an event also if no interaction occurs. The FLUKA geometry is split up in regions with different properties. E.g. in this study, the silicon layer is one region and the conversion layer is another region. EVENTDAT can be used to calculate the maximal efficiency by looking at the output event by event and study the energy deposited in the silicon. If the energy deposited is higher than a threshold energy of 1.12 eV, corresponding to the band gap energy of ^{28}Si at room temperature[7], the event is considered as detectable. Thereby an efficiency can be calculated.
However, only energy deposited by ionization (IED) is measurable. Non ionization energy deposition (NED) can e.g. be caused by a displacement of the silicon lattice and do not give a detectable signal. When the primaries are charged particles, the NED is order of magnitudes lower than IED and can be neglected, but for neutrons the NED is comparable to IED for some energy ranges. The EVENTDAT card can only give the total energy deposited, not the ionizing energy deposited. Therefore, the efficiency obtained with EVENTDAT is a maximal efficiency and not a detection efficiency. The maximal efficiency only equals the detection efficiency, when all energy deposited is ionizing energy, that is for ION $\gg$ NED. With the card USRBIN, one can obtain the NED and IED region by region, but not event by event, i.e. it is possible to get NED and IED for each cycle, but only the average energy deposited by all primaries in that cycle. It is possible to run the simulations with one primary and many cycles per run, thereby converting the USRBIN score into an event by event scoring card, that can measure both IED and NED. However, this method is far too inefficient to obtain results with good statistics within a reasonable time frame.

4 Results

Figure 1 shows the maximal efficiency in the silicon layer, i.e. how big a part of the incoming neutrons interact with the silicon and deposit any energy higher than 1.12 eV, which is the band gab in silicon and therefore the lowest energy that can cause creation of free electrons and holes. The maximal efficiency should not be confused with the detection efficiency, that is the probability, that ionizing energy is deposited in the silicon.
Figure 1 implies that both LiF- and PE conversion layers of thickness 1 mm or larger, cause a significant increase in the maximal efficiency for energies larger than 1 MeV. The higher the energy, the larger is the increase. There are no qualitatively difference of the effect of the PE- and the LiF

conversion layers, but a comparison of PE- and LiF conversion layers of 1 mm indicates that LiF is more effective for the same thickness. Non of the conversion layers change the efficiency between 1 eV to 1 MeV, whereas conversion layers with 1 mm LiF and with 3.2 mm PE cause a minor fall in the maximal efficiency for energies lower than 1 eV. There is a clear tendency that the thicker the layer is, the larger is the difference from the efficiency in the silicon without a conversion layer.

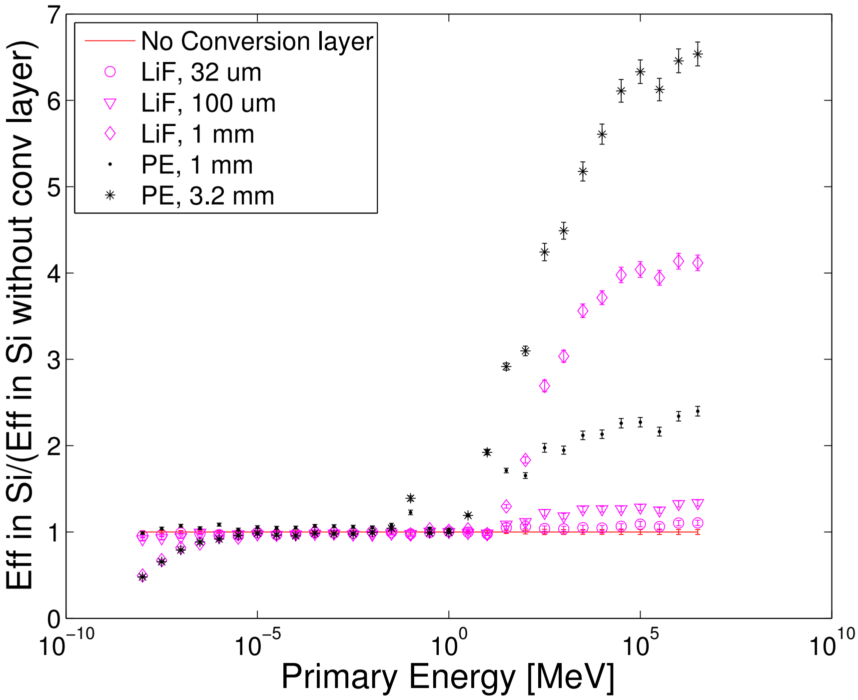
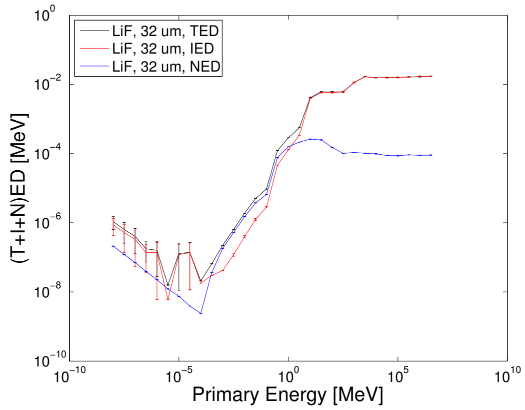


Figure 1: Efficiency in the silicon layer with 2 different conversion laye, each with different thickness. Also simulations without a conversion layer is shown. The data is normalised to the efficiency in the silicon without a conversion layer.

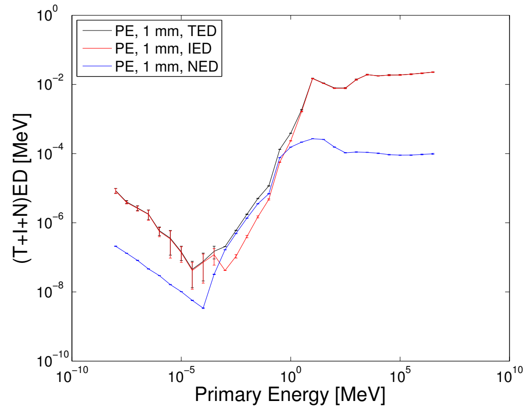
The two plots at figure 2 show that the non ionisation energy deposition (NED) is only negligible for very high energy neutrons. The maximal efficiency is only a good approximation of the detection efficiency when the IED $\gg$ NED. From figure 3(c) it is seen that the IED in the silicon is practically unchanged with a LiF conversion layer compared with the silicon without a conversion layer. Large fluctuations are seen at about 10 eV (10^{-5} MeV). Looking at figure 3(b) reveal that the ionising energy deposited in the silicon without conversion layer is very close to zero at around 10 eV. From one energy ($3.2 \cdot 10^{-7}$ MeV) to the next ($1.0 \cdot 10^{-6}$ MeV), there are suddenly no errorbars, and the data points seems to be fixed at a value close to 10^{-8} MeV. This could be a limitation in the simulation and do not look physically likely. These values close to zero cause peaks and fluctuations in the normalised data on figure 3(c) and 3(d) around 10 eV.

Figure 3(c) and 3(d) indicates that the PE conversion layers increases the IED with about a factor 20 for the thermal neutrons (energies less than 1 eV) and there is clearly also a peak at about 10 MeV, where the IED in the silicon with PE conversion layer reaches a value, that is about 7 times higher than in the silicon without a conversion layer. The peak matches well with the expectations for the PE conversion layers, but the significant increase in ionising energy deposited by thermal neutrons is not expected.

For Energies higher than 10 MeV, where IED $\gg$ NED, the maximal efficiency is a good approximation to the detection efficiency. In this energy range, the simulations show some very unexpected results. It was expected that the LiF conversion layers amplified the detection efficiency for thermal neutrons, but the simulations show that they amplify the detection efficiency for the fast- and high energetic neutrons and not for the thermal neutrons. Furthermore, the ionizing energy deposited in the silicon for thermal neutrons increases when a PE conversion layer, which was not expected either.

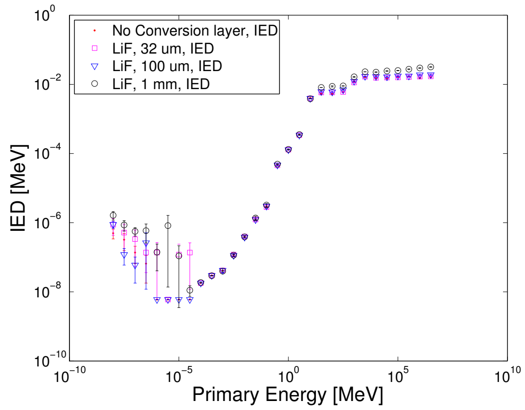


(a) Energy deposited in silicon with 32 μm LiF conversion layer

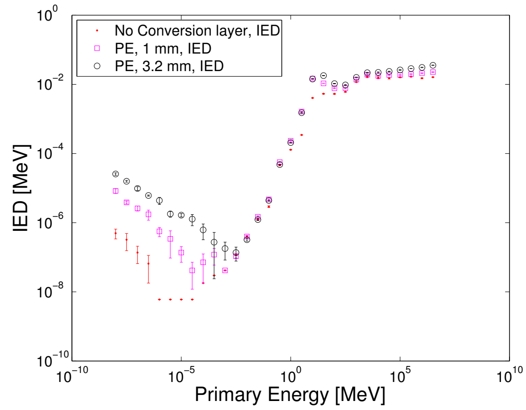


(b) Energy deposited in silicon with 3.2 mm PE conversion layer

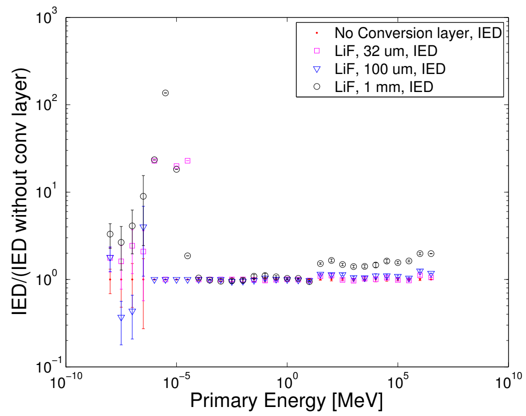
Figure 2: Energy deposited in silicon. The plots show the total energy deposited (TED), ionising energy deposited (IED) and non ionising energy deposited (NED) respectively.



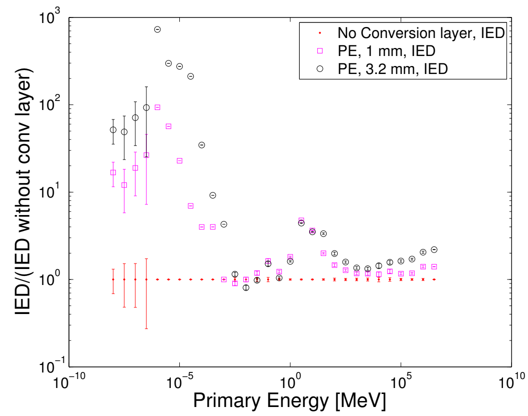
(a) Ionising energy deposited in silicon with respectively 32 μm and 100 μm LiF conversion layers and without a conversion layer. Not normalised.



(b) Ionising energy deposited in silicon with 3.2 mm PE conversion layer and without a conversion layer. Not normalised



(c) As (a), but normalised.



(d) As (b), but normalised

Figure 3: Ionising energy deposited (IED) in silicon. The data in (c) and (d) is normalised to the ionising energy deposited in the silicon without a conversion layer. The y-axis on (a) and (b) is the average ionising energy pr primary (not only the primaries that interacts, but all primaries)

The detection efficiency should increase with increasing cross sections between neutrons and conversion layer. It should be noted that only processes creating charged particles are to be taken into account. Even though there is a coherence between the cross section and the detection efficiency, the relation is not trivial. Firstly, the energy deposited increases with increasing energy of the incoming particle (primaries), so the results should be normalized with the primary energy before comparison. However, this can easily be done. Secondly, some of the produced, charged particles do not reach the silicon layer before all their energy is deposited in the conversion layer, especially if the conversion layer is thick. That effect is substantial for α-particles produced in the LiF conversion layer, having the consequence that the LiF conversion layers must be relatively thin. However, the cross section for α production via inelastic scattering in Lithium (in the LiF conversion layer) is of order of magnitude 1000 barns for thermal neutrons. Even though the relation is not trivial, that effect ought to be evident in the simulations, but seems completely absent. The reason is unknown. It is possible, that FLUKA do not include the neutron-alpha channel at all.

5 Conclusion and perspectives

This report aims to answer two main questions. The first is if FLUKA is a good tool for analysing small scale neutron detectors. These studies suggests that FLUKA is not very well suited for such analysis. Firstly, several settings have to be changed before any reasonable results can be obtained, that is e.g. reducing the step size, activating transport of low neutrons and reducing the particle threshold for neutrons. Secondly, there is no way to get the detection efficiency in an expedient way. Thirdly, if good statistics are required, the output files becomes large and are therefore cumbersome and time consuming to work with. Finally, and of greatest importance, the results for LiF conversion layers do not have the expected coherence with the corresponding cross section, and it is therefore doubtable if the simulation results are reliable. One possible reason is that FLUKA lacks the neutron-α channel, which is essential for the LiF conversion layers.

An alternative to the FLUKA simulation tool is GEANT, which is used by the ATLAS group. Other alternatives are MCNPX and MARS (Fermilab), where MCNPX is the best tool to simulate neutron transport below 20 MeV.

The second main question is how the conversion layers of LiF and PE effects the detection efficiency of the Medipix detector. No final conclusions can be drawn on basis of the studies presented here, since, for reasons mentioned earlier, the simulations are not necessarily reliable. However, the simulations do raise some important questions to the previous use of conversion layers of PE and LiF, since the simulations failed to verify the expected effects. Further investigations on the conversion layers must be performed before any conclusions can be drawn about their effects.

Measurements with the Medipix detector with different conversion layers could help to improve and benchmark the simulations. These measurements have not been done in this study because the necessary equipment was not available during the project period.

6 Acknowledgement

I want to thank Srinidhi Bheesette, my colleague and fellow summer student, for great company. I also want to give thanks to Slawomir Tadeja for help and support with installation and to Sophie Mallows, Moritz Guthoff and Igor Kurochkin for help with FLUKA issues. Thanks to Anne Dabrowski for organizing meeting and for being an exceptionally good and active listener at group meetings. I also want to thank Martin Sparre and Andreas Skielbo who recommended me to apply for the CERN Summer School. Thanks to my beloved and beautiful wife Kristina for support. I also want to thank the Summer School team for a well organised summer school.
Finally, I want to direct a great thank to my supervisors, Arkady Lokhovitskiy and Alan Bell. It has been a true pleasure to work for and with you!

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[6] *http://www.fluka.org*

[7] *http://www.ioffe.rssi.ru/SVA/NSM/Semicond/Si/bandstr.html*

7 Appendix

7.1 Thickness of LiF

How the thickness of LiF was calculated from the quantity a, that is given in Z.Vykydal et al.[5] and the density of LiF ρ, that is given in the FLUKA material database.

$$\text{Thickness of LiF} = \frac{V}{A} = \frac{(m/\rho)}{A} = \frac{(a \cdot A)/\rho}{A} = \frac{a}{\rho} = \frac{5\ \text{mg/cm}^2}{2635\ \text{mg/cm}^3} = 20\ \mu\text{m},$$

where V is the volume and A is area of LiF.

7.2 GUI

In addition to the work presented in this report, a graphical user interface has been developed to provide an easy way to create new simulations and plot them. See screenshot of the GUI at figure 4. The GUI is made in Matlab.

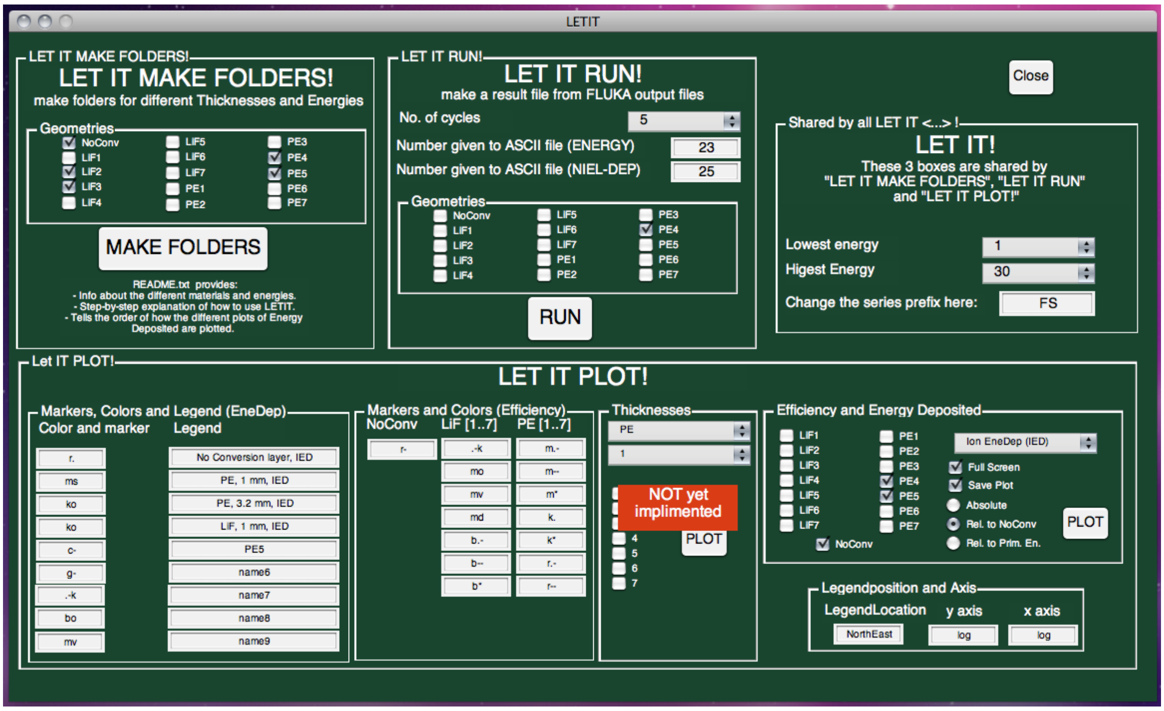

Figure 4: The GUI makes it easier to make new simulations and plot them.