UNIVERSIDAD SAN FRANCISCO DE QUITO

Colegio de Ciencias e Ingeniería

Estimation of proton cross sections in the front end electronics of the hadron calorimeter (HCAL) of the CMS detector at CERN

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HOJA DE APROBACION DE TESIS

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Resumen

Los eventos únicos (SEUs, por sus siglas en inglés) producen errores en la configuración de los circuitos electrónicos instalados en ambientes de aceleradores de partículas. Por esta razón, la caracterización de secciones transversales de protones para los dispositivos electrónicos. El presente trabajo demuestra una prueba de concepto y muestra una metodología para la estimación de secciones transversales de protones basada en secciones transversales de iones pesados en dispositivos electrónicos, en un rango de 10 a 150 MeV.

Abstract

Single event upsets (SEUs) lead to configuration errors in the integrated circuits in particle accelerator environments. Therefore, the characterization of the electronic devices for proton cross section is vital for the SEU rate estimation. The present work demonstrates a proof of principle calculation and shows the methodology for the estimation of proton cross sections in the electronic devices in an energy range between 10 and 150 MeV based on heavy ion test data.

1 Introduction

Since the 1970s, satellite transistor damages have been observed due to the passage of charged particles.[1] After several studies, it was determined that the passage of protons through transistors generate reversible damages in the configuration and the storage of information of electronic elements, the so called single event upsets (SEUs). This phenomenon is also observed in particle accelerator environments.

The large hadron collider (LHC) at CERN (the European Organization for Nuclear Research) is experiencing an increase in the collision energy and luminosity (collision rate). This upgrade translates in higher sensitivity for the electronic devices towards hadron radiation in the electronic elements installed in the surroundings of the detectors, and therefore a threat to information storage.

The CMS experiment, designed for the study of the Higgs boson, super symmetry and other purposes is, together with the ATLAS experiment, one of the two large detectors at CERN. By the time the LHC experiences the upgrade, the effects of the radiation in the CMS detector and its surroundings will change and thus a different characterization of the diverse radiation effects will be necessary. There is a vast variety of radiation damage phenomena that can occur in the electronic devices, from changes in the radiation hardness due to aging [2], to the complete failure of the electronic devices. The main objective of this work is to develop a calculation method that allow the computation of proton cross sections with silicon as a first step towards the estimating the SEU rates in a specific electronic device, namely Virtex-6 field programmable gate array engineered by the Xilinx©corporation. Since there are experimental data available of heavy ion tests for the characterization of their cross sections in silicon for different electronic devices, the approach of the present work presents a proof of principle calculation for the characterization of proton cross sections in silicon at the LHC. The calculations presented in this work represent a simplified method for a quick estimation of proton cross sections in silicon based on J. Barak's work [3].

2 Single event upsets

Single event upsets (SEU) are the result of the effect produced by ionizing particles that strike the lattice of the device and lose their energy due to Rutherford scattering. Due to the passage of energetic particles through electronic devices, charge collection phenomena occur in the transistor, that cause a change in the configuration of such devices. There are regions in the transistors which show a more sensitive behaviour towards SEUs [4]. In particular, a device of interest for SEUs at CERN is the Virtex-6 Field Programmable Gate Array (FPGA) designed by Xilinx©. A current peak appears in the proximity of the pn-junction due to the separation of the electron-hole pairs, while a recombination of the pairs happens in the bulk of the semiconductor. Not all incoming particles that deposit energy on the device will create a SEU, only the ones landing in a sensitive node (sensitive volume) and its surroundings. If a charged particle strikes the pn-junction of a semiconductor, a charge generation takes place and the created carriers form an electric field in the bulk of the semiconductor along the path of the particle. This phenomenon forces carriers to funnel into the junction. This is known as the funnelling effect [5].

3 Radiation effects in particle accelerators

The particles that are responsible for radiation damage in particle accelerators are hadrons, electrons, gamma rays and neutrons. Even gamma rays and neutrons that are not ionizing, can provoke such effects. In the Large Hadron Collider (LHC), at CERN, the radiation environment is determined mostly by the presence of charged hadrons and neutrons. The elastic and inelastic interactions of these particles with the nuclei of the sensitive volume of the electronic device can create SEUs. This is because the recoils (i.e. ions produced by an atomic interaction) can have a high energy deposition per unit length ($\frac{dE}{dx}$) [6].

4 Estimation of proton cross sections

The produced ions (secondary ions) by the interaction between the protons and the silicon target are responsible for the SEUs in the device, it is necessary to consider the total cross section of the proton in a silicon target in order to produce an ion i [7]. The differential cross section of the produced ion in silicon as a function of the ion's energy the solid angle is given by:

$$\frac{\partial^2 \sigma}{\partial T_i \partial \Omega} \tag{1}$$

where T_i stands for the initial energy of the produced ion. The values for this cross section can be found in the Evaluated Nuclear Data File (ENDF) [8]. Since it can be considered that the interactions between protons and silicon are isotropic, [9], the differential cross section becomes:

$$\frac{\partial\sigma}{\partial T_i} \tag{2}$$

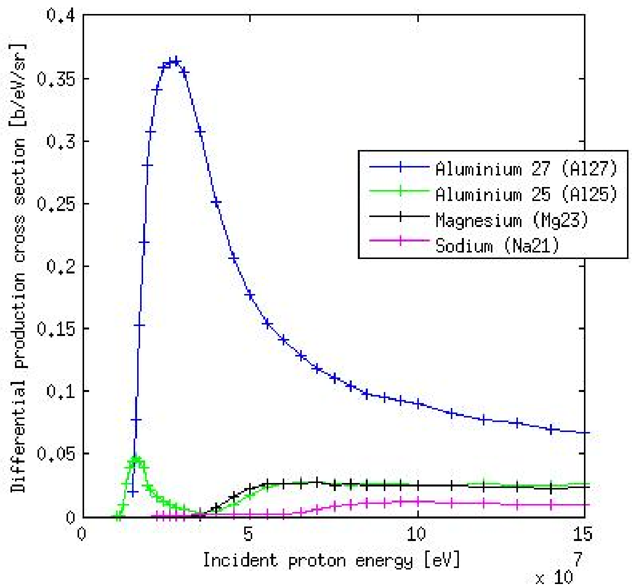

Figure 1: Differential cross section with respect to energy and to solid angle for different produced ions vs. proton energy

Figure 1 shows a comparison between the probability of production of some elements by the interaction of protons in silicon. It is evident that the most probable element to be found is Aluminium-27 and this probability quickly decreases for other isotopes/atoms.

To calculate the cross section of the production of an ion in the interaction between a silicon target and an incident proton (p^+)in the whole energy spectrum, the following integration is needed:

$$\sigma_i\left(E_p, T_i\right) = \int_{E_i}^{\infty} \frac{\partial\sigma_i(E_p)}{\partial T_i'} dT_i' \tag{3}$$

For the total cross section σ_{tot}, for a certain incident energy of the original proton E_p,

$$\sigma_{tot}(E_p) = \sum_i \sigma_i(E_p) \tag{4}$$

The probability density p that all posible ions, created by the interaction between a proton and a silicon target, interact in the target length l is given by

$$p(E_P, L) = n_{Si} \sum_{i,j} \sigma_i(E_p, E_i^j(L)) \left|\frac{dr}{dL}\right|_{L=L_j^i} \tag{5}$$

where n_{Si} is the number of silicon atoms per unit volume, dr the differential path length that a produced ion i travels before it deposits almost all of its energy. This total distance is expressed as R_i. The index $j = 1, 2$ represents values before and after the Bragg peak. This can be derived as follows. First, let us define n_A as the number of atoms that cross an area A:

$$n_A = \Phi A \tag{6}$$

where Φ is the fluence (particles that travel through a unit area) of the incident protons. Now, let us consider n_B that represents the number of interactions between the protons and the silicon device in a volume $A \times l$. This is:

$$n_B = n_{Si} \times A \times l \times \sigma \times \Phi \tag{7}$$

With this equation, the differential probability is

$$\frac{n_B}{n_A} \tag{8}$$

The differential probability density, per energy range (L) is, then:

$$dp_i = n_{Si} d\sigma \times \frac{dr}{dL} \tag{9}$$

In order to calculate $\left|\frac{dr}{dL}\right|_{L=L_j^i}$, it is necessary to analyse this phenomenon as follows. The range R_i is defined as:

$$R_i(E_i) = \int_0^{E_i} \frac{dr}{dE_i} dE_i = \int_0^{E_i} \frac{dE_i}{\frac{dEi}{dr}} = \int_0^{E_i} \frac{dE_i}{L} \tag{10}$$

where $L(= L_n + L_e)$ is the total linear energy transfer, composed by the electronic (L_e) and the nuclear (L_n) contributions. From the equation above, it is possible to calculate the following:

$$\frac{dr}{dE_i} = \frac{dr}{dL}\frac{dL}{dE_i} \tag{11}$$

Thus,

$$\frac{dr}{dL} = \frac{\frac{dr}{dE_i}}{\frac{dL}{dE_i}} \tag{12}$$

$\frac{dr}{dE_i}$ can be evaluated by using the SRIM© (Stopping and Range of Ions in Matter), that uses the linear energy transfer (L) and energy E_i of an ion i, [10] data and $\frac{dL}{dE_i}$ can be evaluated by deriving the following function with respect to the energy E_i:

$$L(E_i) = exp\left(\frac{a + cE_i + eE_i^2}{1 + bE_i + dE_i^2}\right) \tag{13}$$

The coefficients a, b, c, d, e in equation 13 can be found fitting the tabulated data of the program SRIM© [10] with different fitting code programs.

It is necessary to calculate two different sets of coefficients for the electronic range (L_e) and the nuclear range (L_n). The resulting functions are, for Aluminium:

$$L_e(E_i) = exp\left(\frac{5.2 + 10.5E_i - 0.004E_i^2}{1 + 1.3E_i}\right) \tag{14}$$

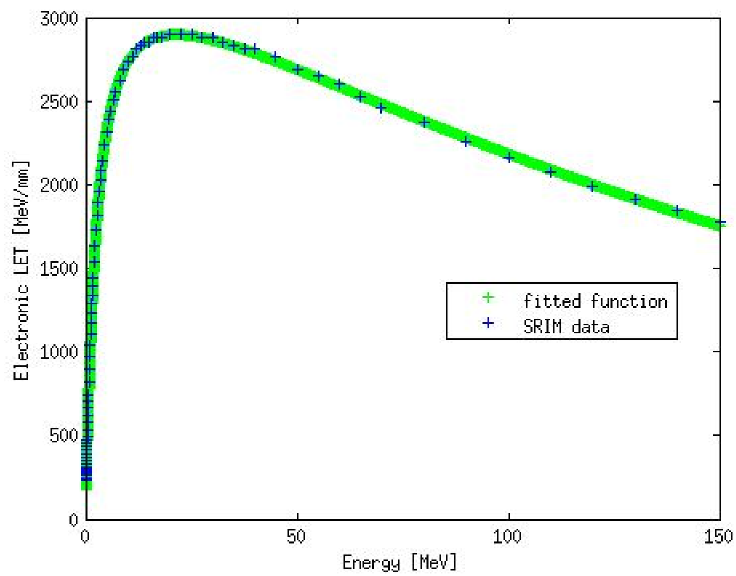

Figure 2: Electronic linear energy transfer L_e for Aluminum ions in Silicon with respect to the energy of incident proton

$$L_n(E_i) = exp\left(\frac{5.9 + 10.5E_i + 0.15E_i^2}{1 + 2.7E_i + 0.15E_i^2}\right) \tag{15}$$

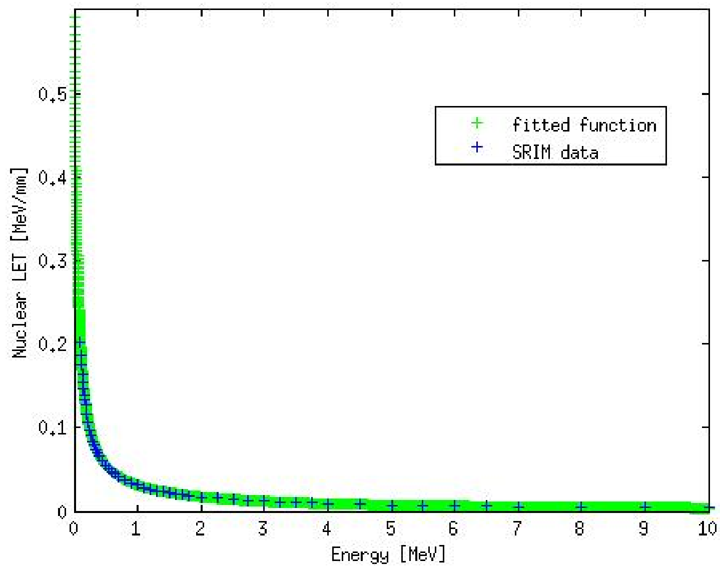

Figure 3: Nuclear linear energy transfer L_n for protons in Silicon with respect to the energy of incident proton

Since the incident protons that will be considered in this analysis have energies between 100 keV and 150 MeV, the secondary ions that are produced by the impact of protons in this energy range have to be considered. The probability of production of Al, Mg, Na and Ne (based on the JENDL library from ENDF) is shown in figures 4, 5, 6 and 7, respectively:

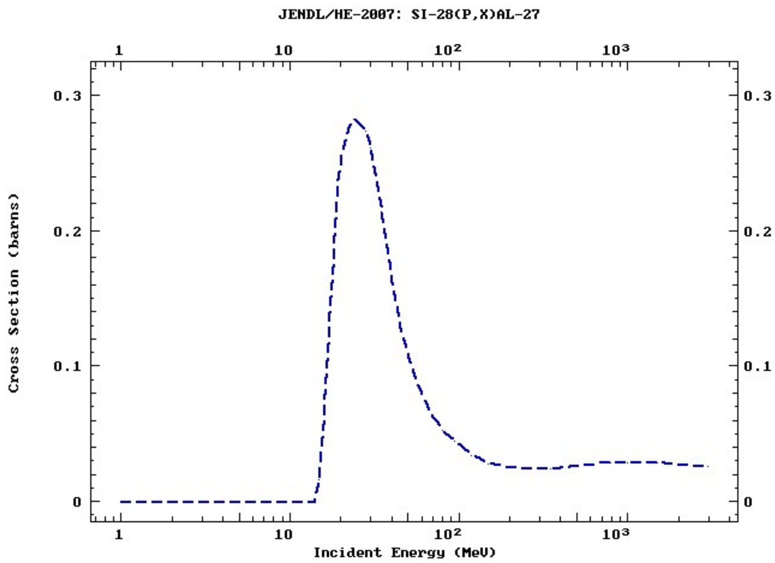

Figure 4: Cross section for the aluminium (Al-27) production in an interaction of a proton and silicon based on the JENDL/HE library data

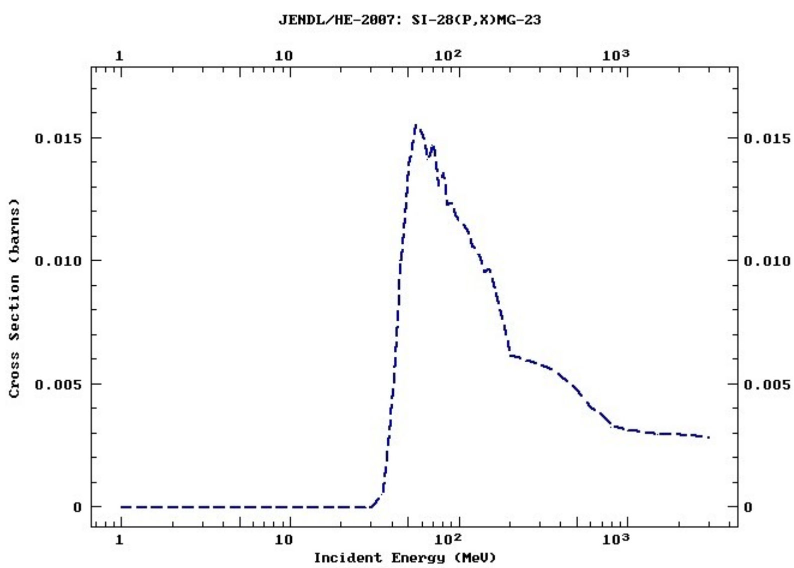

Figure 5: Cross section for the magnesium (Mg-23) production in an interaction of a proton and silicon based on the JENDL/HE library data

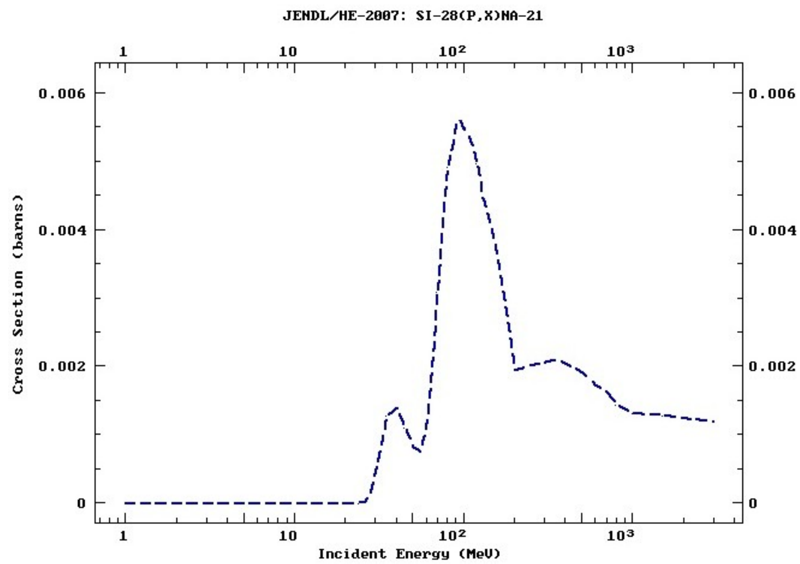

Figure 6: Cross section for the sodium (Na-21) production in an interaction of a proton and silicon based on the JENDL/HE library data

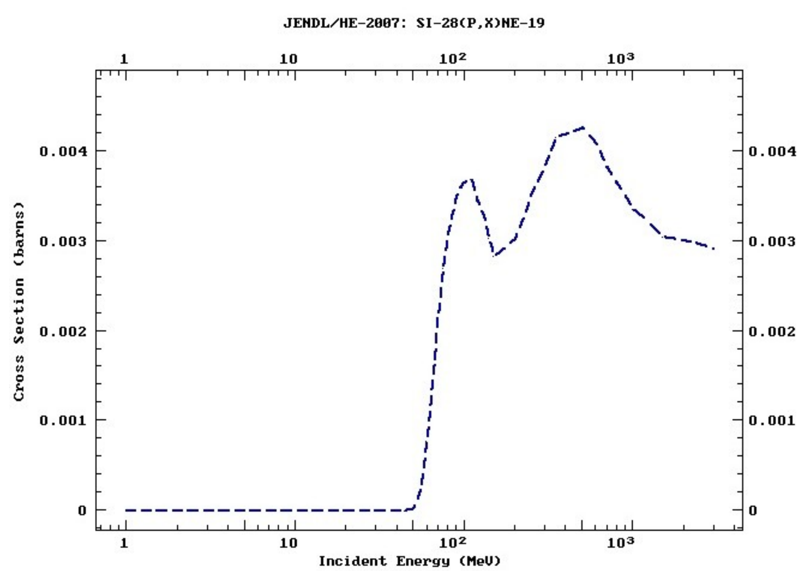

Figure 7: Cross section for the neon (Ne-19) production in an interaction of a proton and silicon based on the JENDL/HE library data

As it can be seen on figure 7, the cross section for the production of a Neon atom for an incident proton energy of 100 MeV in silicon is $\approx$ 0.0038 barns (10^{-28} m^2), while at the same energy, the cross section for the production of an Aluminium ion is $\approx$ 0.05 barns (see figure 4). The cross section for the production of Mg is $\approx$ 0.012 barns (figure 5) and for Na $\approx$ 0.0055 barns (figure 6). This is why, in this energy range, the elements that are most likely to be produced are Al, Mg, Na.

With these results, it is possible to extract the cross section for the proton-silicon interaction with the tabulated cross section of the heavy ion (σ_{hi}) case:

$$\sigma_p(E_p) = \int_0^\infty p(E_p, L)\sigma_{hi}(L)dL \tag{16}$$

To estimate the cross section for the interaction of a heavy ion with silicon, the following calculation can be performed [3]:

$$\sigma_{hi}(L) = \sigma_{hi\infty}\left\{1 - \exp\left(-\frac{L - L_0}{W}\right)^s\right\} \tag{17}$$

where $\sigma_{hi\infty}$ is the value of saturation for $\sigma_{hi}(L)$, L_0 the threshold linear energy transfer, W the width parameter and s the power parameter for the Weibull function. The estimation for these values should be calculated with a trial and error fit. The Xilinx© corporation has characterized the proton cross section (σ_p) and the heavy ion cross section (σ_{hi}) for the model XQVR300 of a field programmable gate array (FPGA) Virtex as follows[11]:

$$\sigma_p(E_p) = \sigma_{p\infty}\left\{1 - \exp\left(-\frac{x - 10}{30}\right)^2\right\} \tag{18}$$

where $\sigma_{p\infty} = 2.2 \times 10^{-14}$ cm^2, E_p is the incident proton energy, given in MeV.

$$\sigma_{hi}(L) = \sigma_{hi\infty} \left\{ 1 - \exp\left(-\frac{L - 1.2}{30} \right)^2 \right\} \tag{19}$$

where $\sigma_{hi\infty} = 8 \times 10^{-7}$ cm^2 and L, the linear energy transfer, has $\frac{\mathrm{Mev}}{\mathrm{cm^2/mg}}$ as units.

5 Estimation of Aluminium production cross section for proton projectiles in silicon targets

For the estimation of the total proton cross section in Silicon, first it is necessary to calculate the probability of production of other atoms due to inelastic scattering for the interaction of a proton and a silicon atom. The reason for this is that a proton alone is not able to deposit enough energy in the sensitive volume to produce an upset. To begin with the analysis, we consider the atom that is the most probable to be produced in a reaction of an incident proton in a silicon target, i.e., Aluminium (Al) [3].

For the production of Al, in the interaction of an incident proton energy of the energy of 150 MeV the following nuclear reactions can be involved:

$$
\begin{aligned}
{}^{28}_{14}\mathrm{Si} \;\; + \;\; \mathrm{p}^{+} \rightarrow \;\; {}^{27}_{13}\mathrm{Al}^{-} \;\; + \;\; 2\mathrm{p}^{+} \\
{}^{28}_{14}\mathrm{Si} \;\; + \;\; \mathrm{p}^{+} \rightarrow \;\; {}^{26}_{13}\mathrm{Al}^{-} \;\; + \;\; 2\mathrm{p}^{+} \;\; + \;\; \mathrm{n} \\
{}^{28}_{14}\mathrm{Si} \;\; + \;\; \mathrm{p}^{+} \rightarrow \;\; {}^{25}_{13}\mathrm{Al}^{-} \;\; + \;\; \alpha \\
{}^{28}_{14}\mathrm{Si} \;\; + \;\; \mathrm{p}^{+} \rightarrow \;\; {}^{24}_{13}\mathrm{Al}^{-} \;\; + \;\; \alpha \;\; + \;\; \mathrm{n}
\end{aligned}
\tag{20}
$$

where p^{+} represents a proton, n a neutron and an α particle is composed by two protons and two neutrons. The cross sections of the previously mentioned interactions can be obtained from the Evaluated Nuclear Data File (ENDF) [8]. There, it is possible to find the differential cross sections ($d\sigma$) as a function of the energy of the produced ion i, T_i, and the solid angle (Ω) i.e., $\frac{\partial^2\sigma}{\partial\Omega\partial T_i}$, described in equation 1. With this information, it is possible to calculate the probability of the energy deposition (based on equation 9), of the created ion as a function of the range of that ion [3]:

$$
p_i = n_{Si} \int_{E_i}^{\infty} \frac{\partial^2\sigma}{\partial\Omega\partial T_i} dT_i \left|\frac{dr}{dL_i}\right|_{L_i}
\tag{21}
$$

where n_{Si} is the number of Silicon atoms per unit volume and $\left|\frac{dr}{dL_i}\right|_{L_i}$ the inverse change of linear energy transfer (LET) per distance for a given energy of an Aluminium atom. E_i represents the energy of the produced ion for a certain energy of the incident proton. Equation 21 will be explained in detail in section 4.

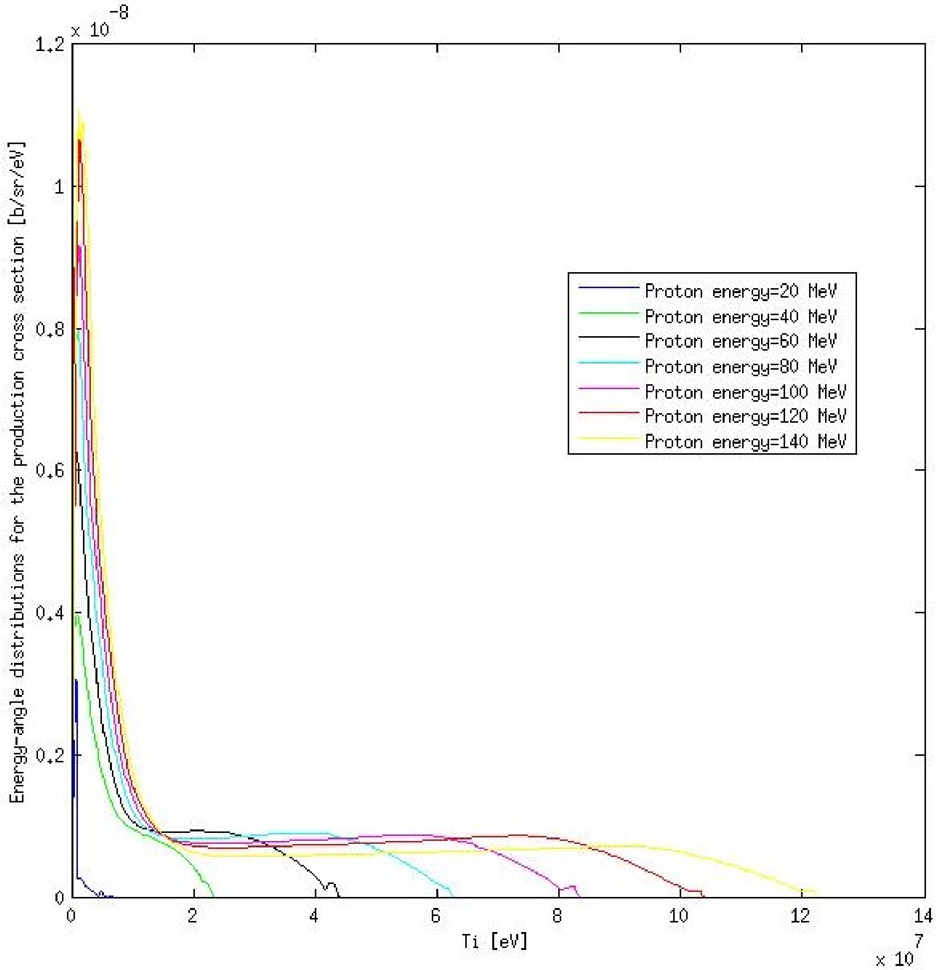

Figure 8: Differential cross section with respect to solid angle and energy for different proton energies integrated by the total number of ions vs. energy of the produced Aluminium-27

Figure 8 shows the differential cross section of the $^{27}_{13}Al^{-}$ produced for different incident proton energies in the interactions with silicon. It is possible to observe, that the produced Al-atoms are found in the order of magnitude of the MeVs.

6 Results

As an example of the calculation of the probability density, which is expressed by equation 21 for the production cross section of a certain ion, consider figure 9. This figure shows a peek of probability density of $0.6\frac{\text{mm}}{\text{MeV}}$ at a linear energy transfer L $\approx$ 1.8366 $\frac{\text{Mev}}{\text{mm}}$. Similar calculations for the probability densities for incident protons at 20, 40, 60, 80, 100, 120 and 140 MeV are performed.

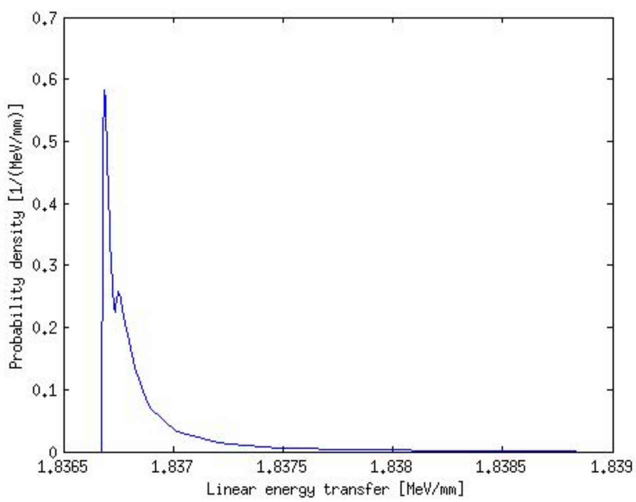

Figure 9: Probability density for the creation of an Aluminium ion by an incident proton of 20 MeV of energy as a function of its linear energy transfer L

Following the same procedure, the cross sections for magnesium and sodium are calculated for incident protons in silicon with different energies. With this information, the total proton cross section for the interaction between an incident proton and a silicon target (see equation 16) based on heavy ion test data is obtained and shown in figure 10:

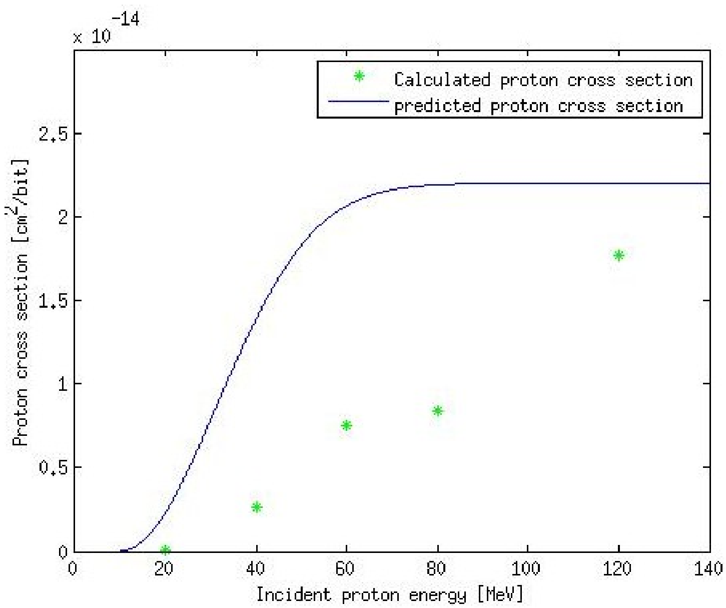

Figure 10: Estimation of the total proton cross section in an incident proton energy range of 20-150 MeV

In figure 10, the continuous line corresponds to equation 18, while the points below this curve are obtained by applying equation 16.

7 Discussion

Despite the fact that only three elements (Al, Mg and Na) and are considered in the calculations shown in figure 10, it was possible to obtain an acceptable result for the calculation of the proton cross sections of protons in silicon based on heavy ion tests since the presented calculations are of the same order of magnitude as predicted by the model. It is also evident, that the effect of the more massive produced atoms gain importance while the incident energy increases and the effect of light ions decreases. This fact is clear due to the closeness of the calculated point for an incident proton of 120 MeV to the predicted cross section curve. Other effects that are also neglected for these calculations, and that probably responsible for the small discrepancy between the calculated cross sections and the predicted ones have to do with the following reason. The fact that the light ions (the recoils of the interaction of the proton and the silicon atoms) and that contain enough kinetic energy to react again with the semiconductor atoms are not considered and are, in some cases, responsible for the creation of new ions. The radiation environment of the CMS detector contains many more particles than protons. This is the reason why it is important to know the flux of these other particles and their energy distributions to predict more accurately the effects of radiation in semiconductors.

8 Conclusions

The Large Hadron Collider (LHC) at CERN will experience an increase in the energy of the colliding particles and the number of collisions by 2018. 3000 fb^{-1} will be collected between the years 2018 and 2022 (until 2017 100 fb^{-1} are expected). The proof of principle calculations shown in the present work for the estimation of proton cross sections in silicon appears to be accurate. The Single Event Upset rate calculation can be estimated based on this work. Its importance becomes more evident when the LHC experiences a larger scale upgrade. The natural follow-up of this work is the estimation of the single event upsets rate for a Virtex-6 field programmable gate array, once the physical properties of this device are obtained. If the sensitive volume of a device is well characterized, i.e., the critical region and its dimensions is defined, it is possible, with the calculation method presented in this work, to establish the SEU rate. There are many variables that can have an impact on the configuration change of electronic devices, for example the applied reverse bias, the doping elements, etc. To perform these calculations taking into account all of these variables will be practically impossible. That is the reason why a very accurate characterization of the SEU rate will only be possible with computer simulations performed, for example, using the Sentaurus program.

9 Acknowledgements

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