Application of GEANT4 toolkit for simulations of high gradient phenomena

Daniel Persson
Abstract

Application of GEANT4 toolkit for simulations of high gradient phenomena

Daniel Persson

To study electron emissions and dark currents in the accelerating structures in particle colliders, a test facility with a spectrometer has been constructed at CERN. This spectrometer has been simulated in the C++ toolkit GEANT4 and in this project the simulation has been improved to handle new realistic input data of the emitted electrons. The goal was to find relations between where the electrons are emitted inside the accelerating structure and the energy or position of the particles measured by the spectrometer. The result was that there is a linear relation between the initial position of the electrons and the width in the positions of the particles measured by the spectrometer. It also appears to be a relation between energy the emitted electrons get in the accelerating structure, which is related to the position, and the energy they deposit in the spectrometer. Further studies where the simulations are compared with real measurement data are required to determine whether these relations are true or not, find better reliability in the relations and get a better understanding of the phenomena.
Populärvetenskaplig sammanfattning

För att forska på de minsta byggstenarna som bygger upp vår värld accelererar man laddade partiklar till hastigheter nära ljushastigheten och krockar dem med varandra i forskningsanläggningar. För att nå dessa extrema hastigheter krävs starka elektriska fält i de strukturer som används för att accelerera partiklarna. Ett fenomen som då kan uppstå är att elektroner från materialet i de accelererande strukturerna kan lossna (emitteras) och bli accelererade. Detta kan leda till följdreaktioner som skadar strukturerna. För att undersöka detta fenomen har en spektrometer, ett instrument som mäter spridningen av de emitterande partiklar, konstruerats i en testanläggning samt en simulering av denna har skapats. I detta projekt har denna simulering utvecklats för att kunna använda ny, realistisk inputdata. Från denna data har simuleringar körts med målet att hitta samband mellan var i den accelererande strukturen elektroner emitteras och den energi eller position som spektrometern mäter. En relation som hittades var ett linjärt samband mellan var i strukturen som elektronerna emitterades och hur mycket spridning i bredd som mätts av spektrometern. En annan möjlig relation som hittades var att det kan finnas ett samband mellan den energi som elektronerna har när de kommer in i spektrometern, vilket är relaterat till deras initiala position, och den energi som de förlorar i spektrometern. För att kunna dra några större slutsatser om relationer och få en bättre förståelse för fenomenet så krävs dock fler studier, där jämförelse med verklig mätdata är mycket viktig.
# Contents

1 Introduction 1
   1.1 Background .......................................................... 1
   1.2 Hypothesis ............................................................. 2

2 Theory 2
   2.1 Field emissions ....................................................... 2
   2.2 Vacuum breakdowns ................................................... 3
   2.3 XBox 2 ................................................................. 3
   2.4 GEANT4 ................................................................. 4

3 Method 6
   3.1 Preparatory work ..................................................... 6
   3.2 Simulations ............................................................ 6
   3.3 Data analysis ......................................................... 8

4 Results 8

5 Discussion 13

6 Conclusions 14
1 Introduction

1.1 Background

To further explore the fundamentals of our world and expand our knowledge of particle physics there is a need for high energy particle colliders. Today the Large Hadron Collider (LHC) at CERN outside of Geneva, Switzerland is the most powerful particle collider, but for precision studies of new physics an electron-positron collider of several TeV energy is needed. One candidate is the Compact Linear Collider (CLIC) which is a 50km long two beam collider that accelerates electron and positron beams up to 3 TeV [1].

The performance and efficiency of linear accelerators are determined by the quality of the radio frequency (RF) structures, also called cavities, used to accelerate the particle beams. These structures are in their basic form metallic waveguides where oscillating electromagnetic fields interacts with the passing beam of charged particles and increase their momentum. Inner surfaces of the structures are subject to field emission of electrons, a phenomenon which occurs on all metal surfaces exposed to high electric field. Intense field emission can lead to discharges at the high acceleration fields. These discharges, also called vacuum breakdowns, cause the collapse of the accelerating field, preventing it from penetrating the cavity. Electrons emitted during field emission process are being accelerated and ejected, resulting in a current up to a few hundred milliamperes, measured outside the cavities [2].

To study these escaping currents, the Uppsala accelerator group has constructed a magnetic spectrometer operated during high power tests of accelerating structures. These are tests where the accelerating structure are set to full power without any electron beam being present and only the electrons from field emission will be accelerated. The tests are performed at the XBox 2 test facility at CERN and to complement the real setup, the spectrometer has been simulated in the toolkit GEANT4 in a previous project [3]. This simulation uses simple, non-physical distributions of electrons arriving to the spectrometer as input and does not, as expected, match the experimental data. Recently a detailed RF simulation of the field emission, the source of electrons inside an accelerating structure, become available [4]. This could be used for realistic input to the simulation of the spectrometer.

In this project the previous simulation of the spectrometer setup will be developed further to study the field emission and the escaping currents measured during experiments. This includes learning how to use the existing simulation, modification so it can handle the realistic field emission as input and study the effects of different inputs. By collaboration with the PhD student creating the realistic simulation of the processes occurring inside the accelerating structure in the electromagnetic simulation software CST STUDIO, a study of a possible relation between the positions of the field emissions of electrons inside the structure and the energy and/or position of the particles measured by the spectrometer will be done. This possible relation would give a starting point in further research in which the simulation data will hopefully match data from real experiments and give a better understanding of the physics behind RF breakdowns. The goal of the project is to conclude if there is such a relation and in that case what the relation is.
1.2 Hypothesis

The expected outcome of the simulations with the realistic input data is that there is a relation, linear or more complex, between where the electrons are emitted in the accelerating structure and the energy and/or position measured by the spectrometer.

2 Theory

2.1 Field emissions

The main drawback of linear accelerators compared to circular is that the particles must be accelerated to full energy within a single pass through the machine. To reach the desired energies of several TeV, the electric field gradient used to accelerate the particles need to be very high. In CLIC this gradient needs to be 100 MV/m for the particles to reach 3 TeV [1], significantly higher than the field gradient of 5 MV/m in LHC [5]. In addition to the engineering difficulties of creating such a large field gradient, another problem that occurs at such extreme environments is field emission of electrons from the accelerating structures.

When no electric field is applied to the accelerating structure, the electrons in the metal structure are prevented from escaping into the vacuum inside the structure by a potential barrier. This can be modeled as a square well potential where the Fermi level, i.e. the potential in the metal, and the potential of the vacuum are separated by the work function $\phi$ of the metal, see figure 1. When a strong electric field is applied, the potential of the vacuum is bent, as line AB in figure 1, which makes it possible for the electrons to tunnel through the barrier and enter the vacuum. This is what is called field emission of electrons and can be described the Fowler-Nordheim theory [6]. The stronger the electric field, the steeper the slope of the potential which lead to a higher probability of electrons entering the vacuum of the structure. This is a quantum mechanical effect and could never happen according to classical mechanics. These escaping electrons are believed to be precursors for vacuum breakdowns and if the amount of field emitted electrons increase rapidly, it is likely that they will cause a breakdown. This is a major problem when developing accelerators with a high electric field gradient, such as CLIC.

![Figure 1: Fowler-Nordheim theory for quantum tunneling of electrons when high electric fields are applied](image)
2.2 Vacuum breakdowns

The vacuum breakdown is a complex phenomena that is not yet fully understood. There are many different models trying to explain the process and most of them assumes that field emission of electrons is the key factor to initialize the process. When the RF field is applied to the accelerating structures, field emission of electrons can occur from the surface of the structure. These electrons are affected by the accelerating electromagnetic wave, supposed to only accelerate the electron beam, and are ejected out of the structure. The ejected electrons, that can be measured as a current outside the structure, are referred to as dark current [2].

Where the field emissions have occurred, models predict that there is a mechanical erosion of the surface which triggers the breakdown. Neutral fragments caused by the erosion are ionized by the dark current forming a plasma. More electron emission from the surface occurs which liberates more neutral fragments that can be ionized and the density of the plasma increases fast. The plasma forms a sheath potential preventing the RF field to penetrate the cavity and reflecting it back. Instead the RF field can accelerate electrons in the plasma and ejecting them out of the structure. The measured current of these ejections is called breakdown current and is more than a magnitude larger than the dark current. The remaining ions are affected by the repulsive Coulomb force which can cause them to explode and damage the structure. The field emitters melt and the bombardment of ions and electrons create new emitters. These emitters will experience the same process. This is called the RF breakdown and causes loss of energy in the particle beams and luminosity in the detectors. To stop the breakdown the RF power needs to be shut down and to prevent damage of the accelerating structures it is of great importance that the breakdowns quickly are detected and cancelled. To reduce the number of breakdowns there is a need for a better understanding of the process [2].

2.3 XBox 2

To investigate field emissions and vacuum breakdowns in accelerating structures, the XBox 2 test facility has been constructed. The facility is designed to study the accelerating structures and their behavior under high power. As a part of this setup, the spectrometer developed by Uppsala accelerator group is attached. The spectrometer measure the spatial and energy distribution of electrons and ions from dark current and vacuum breakdowns in the structures. Combining these measurements with measurements of the incident, reflected and transmitted RF power, the location of the breakdown inside the structure can be correlated and hence give a better picture of the breakdown phenomena [2].
The measurement setup is combined by two parts. The first part is the accelerating structure in which the breakdown occurs, seen to the left in figure 2a. A single RF pulse is sent into the structure and since no electron beam is present, only electrons in the dark and breakdown currents are accelerated. The electrons then enters the second part, the spectrometer. First they go through a 5 mm thick, electrically insulated tungsten collimator with either a single slit or a pin-hole pattern. In this project only the slit will be used, which have a width of 0.5 mm and a height of 10 mm. The electrons then enters a magnetic field, with the strength of a few millitesla, which gives different trajectories to electrons of different energies. They then hits a YAG:Ce fluorescent screen where the position and energy can be resolves and a 2 mega pixel, 50 frames per second CCD camera registers the pattern on the screen. YAG stands for Yttrium aluminum garnet which is a crystalline material and YAG:Ce is YAG that has been doped with cerium. The setup of the spectrometer can be seen to the right in figure 2a and a schematic of the whole construction can be seen in figure 2b. Two Faraday cups are placed to the left of the accelerating structure and to the right of the spectrometer to measure the emitted charges. To monitor the amplitude and phase of the incident, reflected and transmitted RF field, directional couplers are installed at both sides of the accelerating structure [2].

2.4 GEANT4

GEANT4 is a Monte Carlo toolkit developed by CERN for detailed studies of high energy physics and simulations of particles passing through matter. It uses the object orientated programming language C++ and have many other applications beside accelerator physics, such as medical physics, space engineering and biochemistry [8]. The toolkit allows the user to set up a detector geometry with a given set of physics acting inside it. In this geometry a particle source can be created, from which primary particles with different initial parameters, e.g. energy and momentum, and a distribution are created and these particles can be tracked through the geometry. When these particles interact with the materials according to the given physics, new so called secondary particles can be created and these will also be tracked. To resemble the detection in real particle colliders, where the particles only can be tracked in the detectors, the user can include sensitive detectors in the geometry. When a particle hit a sensitive detector, information of the hit such as position, energy deposit and time of the hit can be recorded. This information is stored in so called nTuples, which are tree structures that
can be compared with matrices where each column represents a saved quantity and each row represents a hit. These nTuples can be exported from the toolkit to different analysis programs for interpretation, in this project the program ROOT which is a data processing program developed by CERN. The main advantage of ROOT is that it saves data in a compressed binary form, which is preferable when handling with large data batches such as data from accelerators. The program is primary developed for use with C++ and contain powerful tools for mathematical and statistical operations as well as plotting and fitting functions [9].

The geometry of the simulated spectrometer in GEANT4 can be seen in figure 3. The geometry consists of two beampipes (green, with one inside the magnetic field), a magnetic field (red), a collimator (blue) and the fluorescent screen, which is a sensitive detector (white). The screen records the position and the deposit energy of a hit and if it was a primary or secondary particle. The particle source is placed to the left of the visible beampipe, where the particles would enter from the accelerating structure, and can be fully customized by the user [3]. In the geometry there is a coordinate system defined. Origin is placed at the center of the collimator with the x-axis parallel with the beampipes, the y-axis along the width of the slit in the collimator and the z-axis along the height of the slit. The particle source is placed at -300 mm along the x-axis.

In the previous project two mono-energetic beams of particles with different distribution shapes and dispersions have been used. These distributions did not match the experimental data from XBox 2, which was expected since the distributions was non-physical. In this project these distributions will be changed to the detailed RF simulation of the field emission. From these inputs and the hit information from the screen, a relation will be examined.

Figure 3: The spectrometer geometry in GEANT4 with beampipes (green), collimator (blue), magnetic field (red) and screen (white) [3].
3 Method

3.1 Preparatory work

In order to get into the theory behind the project, there was a need of literature studies in the beginning of the project. This included studies of how accelerator physics works, how particles behave in strong electromagnetic fields and why there is a need for a linear particle accelerator. Further read-in on field emissions, vacuum breakdowns and previous work in the XBox 2 project was necessary. To be able to perform the modifications and run the simulations, a repetition of object orientated programming in general and learning basic C++ in particular was done.

The GEANT4 toolkit requires Linux operative system to run. To run it on a Windows computer, a virtual machine, which allows the user to set up a guest environment as a program in a host environment, was used. Using a virtual machine requires a virtual machine player and a virtual machine environment. In this project VMWare Workstation 12 Player [10] was used as player and an environment, which included GEANT4 and ROOT, was downloaded from the GEANT4 website [11].

3.2 Simulations

To learn how to use the GEANT4 toolkit, a set of examples with different difficulty is provided. These were used to get knowledge of how the different classes used by the toolkit was connected and how to use macro files, i.e. text files which tell the code what parameters to use. The simulation of the spectrometer is based on one of these examples and a deeper study of it gave the necessary knowledge of the toolkit before starting to work with the spectrometer.

Working with the simulation of the spectrometer, the most crucial part was to find a good way to import data from an external file. The first part was to change the source of particles. In the previous version, a class in which particles are created from a given region with a specific probability was used. This class was changed to one where the user can set the staring parameters, where the staring position, momentum and energy was the most important. The next step was to make it possible to read these data from an external file. This was done by using a `ifstream`, a function in the `fstream` class in C++ which opens and continuously read a file. To change which file to be read, a function was implemented so the filename can be set in the macro file. A modification to skip particles with a momentum aiming away from the spectrometer was also included. The real spectrometer is not perfectly built, so a parameter that allows for sideways movement of the slit was implemented. The screen material was also modified from cerium in the previous version to cesium iodide, a fluorescent material like YAG:Ce in the real screen and with a similar density. Since the density of the screen material affects the interaction between the screen and the particles there would be preferable to use YAG:Ce. Since GEANT4 allows the user to construct material, this would be possible. In this project however, there was not enough time to contact the manufacturer of the screen material to get the exact properties of each element in the material and build it in the simulation.
To store the data from the simulations, the nTuples were updated. This was done by saving initial position and energy for the particles that hit the screen and a separation between primary and secondary particles for individual analysis. The definition of how a value was registered was also changed from the previous version, in which all secondary particles in an event was registered as entries in the nTuples. In the new version there is one registration per primary particle which saves the total number of hits from all particles, primary and secondary. The deposited energy was redefined as the total deposited energy from all particles, created by one primary particle, hitting the screen. The position of the hits was split up in two entries, the position of the first particle that hits the screen and the mean position of all particles hitting the screen. All these values are saved both to the nTuple of total hits and the nTuples for primary and secondary particles.

Running the simulations, two different input files was provided from the PhD student. The first one is referred to as *short cavity* and is simulated from a 199.968 mm long accelerating structure and the second one is referred to as *long cavity* and is simulated from a twice as long, 399.936 mm, structure. The two files have been simulated using two set of parameters. The data in both files gives the position of the field emissions and the energy the electrons would have after being accelerated in the accelerating structure. So instead of accelerating the electrons in GEANT4, the electrons is provided with an initial energy. The difference in initial energy can be seen in figure 4, where the entrance of the spectrometer is at -300 mm om the x-axis. The two files contains $4 \cdot 10^5$ and $1.5 \cdot 10^6$ particles respectively, so to be able to generate more data for qualitative analysis, two files with $4 \cdot 10^6$ and $5.5 \cdot 10^6$ particles respectively were created. These are referred to as *short simulated cavity* and *long simulated cavity*. This was done by separating the provided files into the different peaks seen in figure 4. From these separations, distributions of initial position and momentum was calculated and from these distributions $5 \cdot 10^5$ particles was created for each peak. All four files were used in simulation with different magnetic fields in the range of a few millitesla, from which data was saved and exported to ROOT. In ROOT graphs and histograms were made for the data analysis.

![Short cavity](image1)

![Long cavity](image2)

Figure 4: Initial energy relative initial position for electrons inside the cavity. The short cavity is seen to the left and the long to the right,
3.3 Data analysis

One important thing to take in consideration is that the real spectrometer only registers when particles hit the screen, not their deposited energy. To investigate this, the number of particles hitting the screen relative the initial position of the electrons inside the cavity was compared. The distance into the cavity was split up in the peaks seen in figure 4 and was defined as the mean distance of all particles hitting the screen from each peak.

To compare the deposited energy of the particles hitting the screen, the same division was made in the position inside the cavity. The deposited energy was defined as the mean of all particles hitting the screen from each of the peaks. Plots of the initial position and momentum in the yz-plane for particles in the first and last peaks was created for comparison of their initial conditions.

To investigate the position of the particles hitting the screen, the hitting positions in the yz-plane was plotted for three different field strengths. These are highly important plots since this is what the camera sees in the real experiments and the only thing that can be directly compared between simulation and experiment. A comparison of the number of hits in the y-direction at different magnetic field was also performed. According to the Lorentz force, the charged particles should experience a force acting on them when entering the magnetic field and the stronger the field the stronger the force. This will lead to charged particles with low energy will be affected more and probably miss the screen while more energetic particles will be less affected and hit the screen. The result of this theoretically is that the hitting position should get more blurred out with stronger magnetic fields.

From this a closer analysis was made of the result with no magnetic field. Since the electrons being extracted closer to the collimator can hit the slit with a larger angle relative the x-axis than the electrons emitted further in, the width of the hitting position relative the initial position was investigated. This was done by plotting the root mean square (RMS), a measurement of the spread relative the mean value, relative the initial position in the cavity.

4 Results

The simulations resulted in a number of plots and histograms trying to explain the behavior of electrons emitted during field emissions. The number of particles hitting the screen from each of the peaks can be seen in figure 5.
Figure 5: Number of particles hitting the screen relative to their initial position in the cavity.

The mean deposited energy at the screen for electrons from each peak is shown in figure 6. The top graphs show the results of the provided input files while the two at the bottom shows the result for the simulations with the created files.

Figure 6: Mean deposited energy for particles hitting the screen relative to their initial position.
The initial positional distribution in the yz-plane can be seen in figure 7. These are the cross section of where the particles are emitted in the structure for the first and last peaks. The short cavity is at the top with the peak furthest in the cavity to the left and the peak closest to the exit to the right. At the bottom the long cavity is seen with the furthest peak to the left and the closest to the right. The initial momentum for the same cross sections in the yz-plane is shown in figure 8, where the division in the figure is the same.

Figure 7: Initial position in the yz-plane for closest and furthest peaks.

Figure 8: Initial momentum in the yz-plane for closest and furthest peaks.
The hit image on the screen in the yz-plane for magnetic field strengths of 0, 2.5 and 5 mT can be seen in figure 9. The result for the short cavity is to the left in the figure and the long cavity to the right.

Figure 9: Hit image in the yz-plane.
The y-position of the particles hitting the screen is shown in figure 10. Here the magnetic field is varied between 0-5 mT. The RMS relative the initial position with no magnetic field can be seen as the black dots in figure 11. Linear approximations of the points have been done, where the first points have been neglected in the long cavity due to the low hit intensity, and the polynomials of the approximations can be seen in table 1.

![Figure 10: Hit intensity in the y-direction for different magnetic fields.](image)

![Figure 11: RMS in y-direction relative initial position in the cavity with no magnetic field.](image)

Table 1: Linear approximations of RMS relative initial position in cavity.

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Polynomial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short</td>
<td>-0.000562x + 0.478</td>
</tr>
<tr>
<td>Short simulated</td>
<td>-0.000384x + 0.437</td>
</tr>
<tr>
<td>Long</td>
<td>-0.000687x + 0.503</td>
</tr>
<tr>
<td>Long simulated</td>
<td>-0.000484x + 0.472</td>
</tr>
</tbody>
</table>
5 Discussion

The number of particles hitting the screen relative their initial position inside the cavity can be seen in figure 5. The two input files give two different behaviors. In the short cavity, there seem to be a linear relation between the emission position in the cavity and the number of hits. In the long cavity, there seem to be less of a relation between the emission position and the number of hits. Particles being emitted close to the exit of the cavity do not hit the screen at all, which can be partly related to the low number of particles created there, as seen in the long cavity in figure 4. Looking at the initial position in the yz-plane of the particles in the long cavity in figure 7, there is a larger spread of the position relative the center of the cavity in the closest peak compared to the furthest. This also explains why no particles hit the screen, since the difference in initial momentum in the yz-plane between the peaks is pretty similar, as seen in figure 8. This lead to particles arriving to the collimator from the closest peak have less probability of hitting the slit than those emitted further in. Comparing the initial position and momentum of the short cavity in figure 7 and 8, there is a smaller difference between the peaks which explains why there is a more linear relation. After the low number of hits in close to the exit in the long cavity, there is an increase which could be interpreted as linear up to 200 mm into the cavity before dropping again. This could mean that the hit intensity peaks for electrons created approximately 200 mm inside the cavity, but such a conclusion cannot be made since the behavior of the short cavity cannot be studied for larger distances. The conclusion that can be made is that the hit intensity seems to increase with the more energetic particles further into the cavity up to 200 mm. The exact relation cannot be analyzed at this point since the two input files contains different number of particles. A comparison between the two files would be more interesting if their number of inputs were similar and a more exact relation would be interesting when the screen is made of YAG:Ce.

The deposited energy for different positions inside the cavity can be seen in figure 6. The behavior for the short cavity is similar in both the provided and the created file. There is a small rise from the initial peaks which seems to be linear before it stabilize around 0.6-0.7 MeV in deposited energy around 80 mm inside the cavity. Looking at the initial energy in figure 4, this corresponds to when the particles have up to 18 MeV of energy. In the long cavity there is a messy behavior in the first peaks of the provided file, this depending on the low hit intensity, before stabilizing at around 0.6-0.7 MeV. The behavior of the first peaks gets better in the created file, were there also is a rise in deposited energy, which could be interpreted as linear, up to a point of 0.6-0.7 MeV like in the short cavity. The difference is that the deposited energy drops a bit after that point before it seems to stabilize. The highest deposited energy in the long cavity is around 180 mm inside the cavity, which corresponds to 17-18 MeV in energy and a few particles higher than that. From these results there seem to be a linear relation between the deposited energy and the initial energy of the particles up to 15-20 MeV, which is related to their initial position. But since the energies relative the initial position is different in the long and short cavity, no direct relation between deposited energy and initial position can be concluded. A comparison between real measurement data and simulations is needed to show which of the provided input files gives the right initial distribution.
The hit image seen in figure 9 shows that most particles are hitting the screen more blurred out and moved to the left with stronger magnetic fields, according to the Lorentz force. But the number of particles hitting the screen to the right has also increased. This turned out to be an effect where particles was accelerated into the beampipe in the magnetic field and scattered by so called multiple scattering effect [12]. The scattered electrons contribute to a background noise that has to be dealt with in both the experiment and the simulation. Since the effect was found late in the project there was not enough time to investigate this further. This lead to only non-scattered particles being considered in the investigation of the hitting position and the y-position of these particles hitting the screen, seen in figure 10, follows the predicted behavior. With no magnetic field the hits are close to the center line of the slit and gets more and more spread out with filed strengths up to 5 mT.

The comparison of the RMS in the y-direction relative the initial position in figure 11 shows a linear pattern in both the short and long cavity. The first degree polynomials of the linear approximations in table 1 also shows that they are almost alike in all simulations. This gives a strong indication that the relation between initial position inside the cavity relative the RMS is linear. To conclude the exact relation more simulations and comparisons with real data are needed.

6 Conclusions

The main conclusion that can be made is that further studies in the subject is needed. Primary a comparison with real measurement is needed to conclude which type of input file is more realistic. More investigations of the scattered particles are also important to understand background noise situation in the experimental results.

A linear relation between where in the cavity the electrons are emitted relative the RMS of the hitting position on the screen in the spectrometer has been concluded. The closer to the spectrometer the electrons are emitted the larger the RMS. There is also a possible relation between the energy of the emitted electrons and the deposited energy on the screen. This relation could be linear up to initial energies of 15-20 MeV, after which the deposited energy is the same. The energy of the electrons is related to the initial position and more studies could conclude a direct relation between initial position and deposited energy. These relations could be used to distinguish the origin of the dark current source in the experimental setup.
References


Springer-Verlag Berlin Heidelberg