FIXING THE DUBNA MODEL FOR THE SIMULATION OF SPDs FOR ALICE

Daniel Costantino; The College of New Jersey

Mentors: Dr. Thomas Humanic, Dr. Bjorn Nilsen; The Ohio State University

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Abstract

For The Ohio State University’s Research Experience for Undergraduates in Physics, I was assigned to work with Dr. Thomas Humanic on a project dealing with heavy ion collisions. Under Dr. Bjorn Nilsen, a post doctoral researcher working for Dr. Humanic, I worked on a computer simulation for Silicon Pixel Detectors to try to fix discrepancies between its results and measurements taken from a test beam. The SPDs are the two innermost layers of the six layer Inner Tracking System (ITS), and they are a critical part of ALICE, A Large Ion Experiment, which will be located at CERN.

Background on ALICE

ALICE is a detector that is being designed and built by institutions around the world to measure the properties of a Quark Gluon Plasma created by CERN’s Large Hadron Collider (LHC). By colliding lead ions at a high enough energy, the scientists working on ALICE hope to create and study the properties of a Quark Gluon Plasma. In this state of matter, the quarks are not confined within hadrons and it can only occur at extremes of temperature and/or pressure [1].

The strong nuclear force has a charge associated with it just as the electromagnetic force does. However, unlike electric charge which can have three elemental values, positive, negative or neutral, the strong charge can have one of seven elemental values, red, green, blue, anti-red, ant-green, anti-blue, or neutral, and is called color. Each quark is assigned a color, red, green, or blue, to explain how they can interact to form different particles. Any hadron formed by three quarks, such as a proton, must contain one quark of each color which makes the total neutral or white. All other hadrons consist of a quark and an anti-quark rather than three quarks. For these particles,
the quark and anti-quark must have opposite colors; a pion with a red quark would need to have an anti-red anti-quark; this combination results in a neutral particle [2].

Due to the nature of the strong nuclear force, quarks cannot be isolated from other quarks. This is because unlike the electromagnetic force, the strong force varies directly rather than inversely with distance, and isolating a quark would require much more energy than the energy needed to create a quark-anti-quark pair from the vacuum [3]. However, when nuclear matter is at an extreme temperature and/or pressure, such as those that will be generated in the LHC, it is theoretically possible that the protons and neutrons “melt” into their component quarks to form Quark Gluon Plasma. The quarks in this phase of matter are free to move throughout the plasma because of the proximity of other quarks. Therefore it is also referred to as Quark Matter.

ALICE will detect whether or not Quark Gluon Plasma was created from the particles that are formed by the collision between the lead ions. Because of the extreme temperature and/or pressure conditions necessary to deconfine the quarks of the lead nuclei, it should be relatively easy for up, down and strange quarks to be produced. From the initial, high energy interaction, heavier quarks will be created. These quarks are unstable and so will decay into lighter quarks on a time scale which is larger than the lifetime of the Quark Gluon Plasma. Therefore, the relative number of up, down, and strange quarks can be used to measure the temperature of the plasma. The creation of particles made of charm or bottom quarks, such as \( J/\psi \) particles and \( \Upsilon \) particles can be used to measure the degree of quark deconfinement [4].

There are several reasons why researchers are trying to create and observe Quark Matter. The first is to test our understanding of the fundamental properties of matter;
separating quarks from each other will help challenge the Standard Theory of Strong Interaction. Also, Quark Gluon Plasma should be able to tell us more about the universe as it existed almost immediately after the Big Bang; for most of the first second after the Big Bang, all the matter in existence is believed to have been in the form of Quark Matter [1].

To create and observe Quark Matter, the LHC will collide two streams of lead ions into each other at relativistic velocities. The average nucleon in these lead ions will have a kinetic energy of 5.5 TeV. Occasionally when the ion streams hit each other, two lead nuclei will collide to create a “fireball” of Quark Gluon Plasma by deconfining quarks from the protons and neutrons that they make up. The ALICE detector will record and analyze the particles that are thrown out of the Quark Gluon Plasma as it cools back to normal matter. The central ALICE detectors are arranged cylindrically around the collision site. The innermost detector is the ITS which will detect and record the positions of particles as they pass through the detecting elements. By monitoring their decay path, it will distinguish particles made out of different types of quarks [5].

The SPDs are the innermost two layers of the ITS. Each SPD is made of a pixelized silicon wafer. Readout chips are “bump bonded” with drops of solder to the pixels. The cross section of the two SPD layers is shown in Figure 1:
Figure 1: Schematic cross section of the SPDS. From [6]

In this figure, the collision of the lead ions occurs in the central, open circle. The blue and red formations represent the carbon fiber support structure of the SPDs as well as cooling systems. Each of the thin green lines is one of the individual SPDs. The radius from the center of the detector to the first layer of SPDs is 39 millimeters; the radius to the second layer is 76 millimeters. Each pixel is a rectangle measuring 50 microns by 425 microns. The long dimension of each pixel is in the z direction, along the length of the detector’s cylinder; each pixel’s shorter dimension is set up along $\Phi$ of the cylinder.

Particles thrown off by the collisions must pass through the 300 micron silicon wafer. As charged particles pass through this silicon, some of the silicon atoms will be
ionized. Due to an electric field applied to the detector, the freed electrons will drift to the metal pixel on the silicon’s surface. When enough charge is collected on a pixel, it turns on and is fired. Because each pixel is either on or off, the information from the SPDs will only provide whether or not a charged particle passed through a specific pixel. From the position of a fired pixel, the location of the original charged particle’s path can be determined.

A test beam for the SPDs was performed in two different segments. These runs were carried out in July and September of 2001 at CERN. For the test, the detector was orthogonal to the beam. In the actual ALICE detector, the beam and SPDs will be perpendicular to each other only in the first layer; therefore the test beam results can only be applied to Layer One of the SPDs and not Layer Two.

The test was performed with $150\,\frac{\text{GeV}}{c}$ pions, varying bias voltages, and prototype SPDs that were 300µm thick; the test took place at 300K [7]. The efficiency of the SPDs versus the bias voltage is graphed in Figure 2:

![Figure 2: Online Efficiency vs. Bias Voltage from the SPD test beam. From [7]](image-url)
One of the important measurements gathered from the test beam results is the number of clusters formed of different sizes. A cluster is a group of adjacent pixels that all fire. A graph of cluster size versus number of clusters for the test beam is shown in Figure 3:

![Cluster number and size from SPD test beam. From [7]](image)

**Background on the Dubna Model**

ALICE is an incredibly complex apparatus. Once it is online and taking data, it will generate an unprecedented amount of data. During a heavy ion run, the ALICE detector can record up to 1.5 gigabytes of data each second. Over a typical month of a run, there will be $10^6$ seconds in which data will be taken. That amounts to an incredible 1.25 to 1.5 petabytes of data for one month of the experiment [4].

To help ensure that everything will go smoothly once ALICE becomes operational, computer simulations are being written for the various individual detectors. These simulations must first reproduce data taken from test beams if they are available. This is the only way to determine whether or not the simulations are accurate.

There are two simulations designed for the SPDs. However, comparing these simulations to the test beam has revealed a problem. Neither the Bari-Salerno (Ba/Sa)
and Dubna model reproduce the test beam measurements; therefore, the physics in the models needs to be improved.

In the Dubna model, data from a MonteCarlo file is used to create digits and clusters. A digit is a pixel that has been fired by hits from particles passing through it [8]. One of the key factors of the Dubna model is that it takes diffusion of the ionized electrons’ charge into account. As charged particles pass through the silicon of the SPDs, they deposit electric charge along their track. This charge is then diffused to the surface of the silicon and will be collected by the pixels. The charge diffuses through the silicon because of a voltage applied across the silicon. The Dubna model takes this diffusion into account by analytically solving for the effects of diffusion. The model then divides the charge distributed along the track into portions that will diffuse to different pixels and treats the pixels.

Both the Ba/Sa model and the Dubna model create the wrong size of clusters. They both consistently predict smaller clusters than are seen in the test beam. In the x dimension, the Dubna model predicted that almost all of the clusters would be of a single pixel, but the test beam showed that only half of the clusters were a single pixel in size. A comparison of the cluster sizes from the test beam and the original simulations is shown in Figure 4:
The main purposes of my REU project were to correct this discrepancy in the Dubna model and standardize the model with the existing code for ALICE simulations.

Early Work

At the start of the program, I made several attempts to find the solution to the problem of the inaccurate cluster size predictions. I performed research to find information on the derivation of the Bethe-Bloch Equation and also investigated the effects of multiple scattering.

The Bethe-Bloch Equation gives \( \frac{dE}{dx} \); this is the change in energy over the change in distance of a charged particle moving through matter. This energy is lost as the particle inelastically collides with the electrons of the matter that it is passing through. It is readily available in the fully derived form:
\[-\frac{dE}{dx} = \frac{4\pi e^4 z^2}{mv^2}NZ\log\frac{2mv^2}{I_\psi} + \psi(1) - R\psi(1 + iz^2 \hbar \nu)\]

In this equation $\psi$ is the logarithmic derivative of the gamma-function; $R\psi$ is the real portion of that function. $I_\psi$ is the average ionization potential, is typically defined as $10 \times Z$, and is given in electron volts [10].

However, this form was derived from an integral of $\frac{d^2 E}{dx db}$ where $b$ is the distance between the charged particle and one of the electrons in the material. The quantities $b$ and $db$ are illustrated in Figure 5:

![Figure 5: Illustration of $b$, $db$, $x$, and $dx$ for alternate Bethe-Bloch equation. From [11]](image)

The Bethe-Bloch equation before the integration performed to solve for $\frac{dE}{dx}$ is:

\[
\frac{d^2 E}{dx db} = \frac{2\pi N A}{2r_e^2 m_e c^2 z^2} \frac{h}{\beta^2 b \rho}
\]

By applying boundary conditions, the minimum and maximum values of $b$ can be found; they are given by these equations:

\[
b_{\text{min}} = \frac{h}{2\gamma m_e \beta c}
\]
\[
b_{\text{max}} = \frac{\gamma h \beta c}{l} \quad [11]
\]
The value of $b_{\text{max}}$ is of importance to the Dubna model because if it is large enough then it may account for clusters that are not currently being predicted. Including $b_{\text{max}}$ in the Dubna model would have potentially helped portray the fact that charged particles passing through matter will not travel in straight lines but will spread out from the track. This might have been useful in adjusting the size of clusters. By substituting in the appropriate values for silicon and the properties of particles thrown off by an ALICE collision, $b_{\text{max}}$ was found:

$$b_{\text{max}} = \frac{\gamma \hbar \beta c}{l} = \frac{\frac{1}{\sqrt{1 - (0.99)^2}}(4.136 \times 10^{-15})(0.99[2.998 \times 10^8])}{10(14)}$$

$$b_{\text{max}} = 6.22 \times 10^{-8} \text{ m} = 6.22 \times 10^{-2} \mu\text{m}$$

However, because the calculated value for $b_{\text{max}}$ is orders of magnitude smaller than the pixels of the SPDs, it will not make a difference if it is added to the simulation.

Next, the possible effects caused by multiple scattering were examined. An article in the Physical Review from 1996 was found on the scattering of electrons as they pass through matter. In this article an equation was given for the amount of deflection from its path that an electron will experience as it travels through matter. The various parameters for this equation are shown in Figure 6:
The particle travels in the s plane through a thickness $x$ of a material, and it experiences a certain deviation due to scattering off of the atoms of that material. The value of the deviation, $s_{\text{plane}}^{\text{rms}}$, is given by this equation:

$$s_{\text{plane}}^{\text{rms}} = \frac{1}{\sqrt{3}} x \theta_o$$

In the equation, $x$ is the thickness of the material being passed through, and $\theta_o$ is given by this equation:

$$\theta_o = \frac{13.6\text{MeV}}{\beta cp} z \sqrt{\frac{x}{X_o}} [1 + 0.038 \ln\left(\frac{x}{X_o}\right)]$$

Here, $X_o$ is the radiation length of the material being passed through; substituting $\theta_o$ into the equation for $s_{\text{plane}}^{\text{rms}}$ yields:

$$s_{\text{plane}}^{\text{rms}} = \frac{1}{\sqrt{3}} x \frac{13.6\text{MeV}}{\beta cp} z \left( \sqrt{\frac{x}{X_o}} \right) [1 + 0.038 \ln\left(\frac{x}{X_o}\right)]$$

When the appropriate values for the ALICE experiment and SPDs are substituted into the equation:
\[ s_{\text{plane}}^{\text{rms}} = \frac{1}{\sqrt{3}} (7.5 \times 10^{-7} \text{ m}) \left( \frac{13.6 \text{ MeV}}{1 \text{ (500 MeV)}} \right) \left( \ln \left( \frac{7.5 \times 10^{-7} \text{ m}}{9.36 \times 10^{-2} \text{ m}} \right) \right) + 0.038 \ln \left( \frac{7.5 \times 10^{-7} \text{ m}}{9.36 \times 10^{-2} \text{ m}} \right) \]

\[ s_{\text{plane}}^{\text{rms}} = 2.887 \times 10^{-8} \text{ m} = 2.887 \times 10^{-2} \mu\text{m} \]

Like the value found for \( b_{\text{max}} \), this value is orders of magnitude smaller than the size of a pixel and so its inclusion in the Dubna model would not solve the cluster problem.

**Later Work**

After the attempts to find a solution to the problems in the physics behind the Dubna model failed, work began on the code itself. The first task to deal with for standardizing the Dubna model to the preexisting ALICE simulation code was to add the concept of summable digits (s-digits) to the model.

S-digits are included in the simulations for ALICE to speed the simulation time. They can quickly be formulated and manipulated because they do not include such factors as electronic noise or coupling. Coupling accounts for the fact that when a pixel is fired nearby pixels are likely to have been hit as well. Coupling is not the same effect as a cluster. A cluster is formed from the data taken in the process of an actual experiment; however, coupling is merely in the code of the simulation to make it more realistic. It is necessary because the data from the MonteCarlo will not automatically take into account this property.

Through adding new functions to the Dubna model, s-digits were added. These functions were modeled after functions found in the Ba/Sa simulation code. In the process of adding these functions, the existing sections of the Dubna model were altered to take the new additions into account. For example, the function SDigitiseModule was
added to the Dubna model. This function calls HitToDigit, a preexisting section of the Dubna model, which takes a hit in the system and creates a digit.

HitToDigit was altered to take into account the fact that now s-digits as well as digits were to be formed in the code. The biggest change in HitToDigit was the removal of the call to the ChargeToSignal function. By moving this call to a new function DigitiseModule, HitToDigit, which was renamed HitToSDigit, could be used in the process of creating both s-digits and digits. SDigitiseModule also calls another new function, WriteSDigits, which was modeled after code in the Ba/Sa model and in turn calls other functions in the simulation package to write the s-digits out to a file.

A class called AliITSpList is used to both collect the charge on each pixel and set up the format for S-Digits. In the original version of the Dubna model, similar functions to AliITSpList were being performed by an array. This method was somewhat unwieldy because it required multiple declarations with array items to make sure that the list was set up properly. After the AliITSpList class was added, the process was much more streamlined; however, changes needed to be made to the Dubna code to take the new class AliITSpList into account, and part of my work on the Dubna model involved making these changes.

After the process of making the necessary changes to the code to include s-digits in the Dubna model and to compensate for the changes made to other parts of the ALICE code, I compiled the code and dealt with the errors that the compiler found. After these messages and some syntax errors were taken care of, a macro was written to call the Dubna code and that was run. Next, this macro needed debugging because of errors that
occurred at runtime. Many of these were caused by syntactical mistakes in the Dubna code such as passing a row number as the column number and vice versa.

Considerations caused by the network and difficulty accessing the code resulted in a change of pace and a pause in working on the code after debugging the macro. I began looking for an analytical solution to the charge deposited along the track of the particle passing through the silicon. This would have been done by solving the following integral:

\[
q = \int_{z_0}^{z_1} \int_{x_0}^{x_1} q_0 \left( \frac{3}{\pi^2 (\sqrt{2Dt} + \sigma_0)^3} \right) \left( \frac{(z-z_i)^2 + (x-x_i)^2}{(\sqrt{2Dt} + \sigma_0)^2} \right) e^{-\frac{(z-z_i)^2 + (x-x_i)^2}{2(\sqrt{2Dt} + \sigma_0)^2}} \, dz \, dx \, dt
\]

In this integral, D is the diffusion coefficient of the material, t is time, \( \sigma_0 \) is a constant to increase the sigma diffusion, and \((x_i, z_i)\) is the coordinate where the charge was liberated [13]. The solution to this integral was searched for using Mathematica and integral tables. However, because this integral was neither solved with Mathematica nor was an appropriate form found, a numerical solution was coded into the Dubna model.

The final step of my REU project was to adjust the code to form histograms from the updated Dubna model so that histograms would be output in the correct format. These histograms also include the test beam data as well as the original Dubna results and the Ba/Sa predictions. Their purpose is to allow the four sets of information to be compared.
Results

After the Dubna model was run, the histograms were used to evaluate it. First a set of 50 events was used to test the histograms and perform a preliminary test of the new Dubna model. The result of this run is seen in Figure 7:

![Figure 7: Preliminary comparison of clusters in the x and z dimensions formed by the test beam, the new Dubna model, the old Dubna model, and the Ba/Sa model. Solid Black = new Dubna; Red Dots = Test Beam; Blue, Dash = Ba/Sa model; Green, Dot-Dash = Original Dubna.](image)

These preliminary histograms seemed to show that the new Dubna version conforms to the test beam data much more closely than both the old version of the Dubna model and the Ba/Sa model. After this, a data run was performed for the new version of the Dubna model with one thousand events. Unfortunately, that run revealed that the changes to the Dubna model had overcompensated for the problem of cluster size. As Figure 8 shows, the Dubna model now predicted cluster sizes that were too large:
Figure 8: Comparison of clusters in the x and z dimensions formed by the test beam, the new Dubna model, the old Dubna model, and the Ba/Sa model. Solid Black = new Dubna; Red Dots = Test Beam; Blue, Dash = Ba/Sa model; Green, Dot-Dash = Original Dubna.

However, despite the fact that the clusters were too large, the new Dubna model still agreed more closely with the test beam than the original. In the x-dimension, the original Dubna model predicted that almost all of the clusters would be of a single pixel as compared to the test beam for which only half of the clusters were a single pixel in size. The new Dubna model predicts that approximately thirty percent of the clusters have one pixel in them. This means it differs from the test beam by twenty percent instead of almost fifty percent.

After this test run, the diffusion coefficient parameter was altered from the value first used in the simulation to try to more closely follow the test beam conditions. The diffusion coefficient parameter is given by this formula:

\[ \sigma_D^2 = 2 \frac{kT}{eV} d l \]

The portion of this equation that can be altered in the Dubna model is the coefficient of:

\[ 2 \frac{kT}{eV} d \]
In the formula, \( k \) is Boltzman’s constant, \( T \) is the temperature, \( e \) is the elementary charge, \( V \) is the voltage applied to the detector, and \( d \) is the detector’s thickness [13]. The test beam was performed on 300 micron detectors at 300K with a bias voltage of 80V; that makes the factor of \( \frac{2kT}{eV}d \) equal to:

\[
2 \frac{kT}{eV}d = 2 \frac{(1.381 \times 10^{-23} \text{ J})(300K)}{(1.602 \times 10^{-19} \text{ C})(80V)} \times (6.463 \times 10^{-4})(300 \mu m) = 0.193892 \mu m
\]

However, for the first test run of the new version of the Dubna model, the voltage bias was set at 50V. This makes \( \frac{2kT}{eV}d \) equal to:

\[
2 \frac{kT}{eV}d = 2 \frac{(1.381 \times 10^{-23} \text{ J})(300K)}{(1.602 \times 10^{-19} \text{ C})(50V)} \times (1.034 \times 10^{-3})(300 \mu m) = 0.3102 \mu m
\]

This factor from the Dubna model is forty percent larger than the value of the test beam for the test beam. Another test run of the Dubna model was performed using the more appropriate values resulting in the histogram shown in Figure 9:

Figure 9: Comparison of clusters in the x and z dimensions formed by the test beam, the new Dubna model with adjusted diffusion coefficient, the old Dubna model, and the Ba/Sa model. Solid Black = new Dubna; Red Dots = Test Beam; Blue, Dash = Ba/Sa model; Green, Dot-Dash = Original Dubna.
After making the adjustments to the diffusion coefficient parameter, there were slight changes to the histogram showing the Dubna model was now slightly closer to the test beam results.

Conclusions

My REU project was devoted to work on the Dubna model for the simulation of the SPDs to make it conform to the test beam. The results of this work can be seen in the histograms generated with the updated Dubna model. The project was marginally successful because though the changes overcompensated for the problem, the new Dubna model is closer to the test beam’s results than the original had been. More work needs to be done to try to continue to improve the Dubna model.

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References


[4] Discussion with B. Nilsen


