COSMIC RAY DETECTION

IN THE CENTRAL OUTER TRACKER AT FERMILAB

By

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The Collider Detector at Fermilab (CDF)(Figure 1) is a general-purpose experiment for the study of proton antiproton collisions. Currently, the detector is undergoing substantial upgrades to take advantage of an order of magnitude increase in the number of particle collisions at higher energies and increased iterations. This total redesign of the system guarantees new results in the realm of high-energy physics, but to be accepted the validity of the detector must be proven. In order to verify the legitimacy of the particle tracking system, cosmic rays will be utilized. By observing cosmic rays using the Central Outer Tracker, and then comparing the results with previous experiments and a software simulation the new system can be validated. The purpose of my project is to modify the current software program to simulate and detect cosmic rays, generate results, and then modify the upgraded tracking hardware to allow for cosmic ray detection. Once this is accomplished the detector can begin actual data collection.

The CDF systems relevant to this project are the Central Outer Tracker (COT), and the triggering and electronics system. The COT is a three-meter long cylinder with an inner radius of 44cm and an outer radius of 132cm. Detection of charged particles generated by proton-antiproton collisions is achieved through the use of wires that generate an electrical current when a particle passing nearby ionizes the gas in the chamber. The wires are divided into sets of twelve, dubbed cells, and there are eight radial layers of cells called superlayers. Every other layer, starting with the second, is used for tracking, and so there are a total of 1344 cells and 16,128 wires used to detect created particles.

Particle collisions occur every 132 nanoseconds as a cloud of protons collides with a cloud of antiprotons in the geometrical center of the chamber. Charged particles created in the collision follow a curved path, due to an external magnetic field, outward through the chamber, and generate electrical pulses in the wires as they travel (Figure 2). The electrical data is sent to the eXtremely Fast Tracker (XFT) with the purpose of identifying the "interesting" physics events. To accomplish this in the 132 nanoseconds available before the next collision occurs, each COT superlayer is divided into groups composed of four cells. A programmable chip[1] is assigned to each group. These finder chips are arranged on two types of circuit boards. One set controls a section of the first and third superlayers, while a second set collect data for the second and fourth superlayers (Figure 3). The charged particle paths generate "hits" on twelve wires per layer, and a piece of hardware called the mezzanine card classifies the hits as prompt or delayed in relation to the 132ns time cycle. The resulting segment through each layer, called a mask, is compared to a database. Particles with radial momentum of less than 1.5 GeV/c are ignored to expedite the process. The two inner layers characterize masks as one out of twelve pixels in the cell. Pixels represent the position of the track segment in the given superlayer. The outer layers output data based on six pixels per cell, and also give slope information for the segment.

Finder output is sent to the Linker to form tracks from the segments detected (Figure 4). To locate tracks quickly, the COT is divided into 288 angular slices, each 1.25 degrees wide. A single programmable chip[1] compares the input pixel and slope data to a predefined set of patterns, and all of the patterns are searched over simultaneously. Each chip searches over a set of 2400 roads, where a road is a group of four pixels, one from each superlayer, corresponding to a valid track with momentum greater than 1.5 GeV/c. If no track is found, then the best track found using the innermost three layers is

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[1] Both the Finder and Linker chips use Flex10K programmable devices manufactured by Altera, Inc.

output. Twelve chips are placed on a linker board so that each board covers a 15-degree section of the chamber.

The simulation of the COT is realized through a Java program that follows the hardware as closely as possible. Utilizing Java's object oriented system each hardware component is constructed virtually and performs the same as its material counterpart. The program is used to evaluate the system and obtain expected performance ratings for the COT.

In order to find cosmic rays is it necessary to know something about them. Cosmic rays are high-energy muons that originate in space, and have an energy spectrum with a mean at 4 GeV that falls at $1/E^2$. Around 78 of these cosmic rays are expected to pass through a $0.6m^2$ area of the chamber each second. A constriction on the incident angle of the cosmics yields 25 per second that have a chance of being found.

The first objective of this project was to determine whether the tracking system could find cosmic rays. The main complication arising in cosmic ray tracking is their origin. Whereas the triggering system is designed to find tracks originating at the geometrical center of the chamber, cosmic rays enter from the exterior of the system and typically do not pass through the center of the chamber. This translates to a large impact parameter, or the distance of closest approach to the central axis of the chamber. The response of the Finder and Linker systems to this new data was not known, and so at first cosmic rays were simulated using the unmodified simulation. Results revealed that the Finder system output a sufficient number of pixels for track finding, and therefore a new masks database was not needed. The Linker system, as expected, only found cosmic rays that passed very close to the center of the chamber. To remedy this a new roads database was required that included tracks that did not pass through the center of the chamber. This was further complicated by the limitation of only being able to use 2400 roads per linker. At the time each linker chip also used the same roads, and it was desirable to leave it that way. The database ended up allowing tracks to enter in the chamber up to 15 degrees off vertical while passing within ten centimeters of the radial center of the chamber. The database also only includes very high-energy roads, but it turns out low momentum tracks are found anyway with an impact parameter that makes up for the curvature of the track (figure 5). Using this new roads database the simulation was successful in finding cosmic rays.

With the simulation giving promising results the time came to add another feature that would be present during the cosmic ray run. Normally the tracking system and Tevatron collider operate on a 132 nanosecond time cycle, but at the time of the test the system will be running in a 396 nanosecond time cycle. For proton-antiproton collisions this merely means less data, but for the cosmic rays it translates to a drop in detection. The loss occurs because 240 nanoseconds into the time cycle the electronics system stops looking for wire hits. This makes sense for regular collisions because the maximum time it takes for the gas to ionize and create a current on the wire is around 220 nanoseconds. Cosmic rays pass through the chamber at random times, and those that do so 240 nanoseconds into the time cycle have no chance of being found.

When the simulation was determined to be satisfactory studies on efficiencies became possible. Using a flat momentum distribution from 1.5 to 100GeV, impact parameters from –10 to 10cm, and a 30° distribution of incident angles cosmic rays were simulated. The simulation finds low momentum tracks although all of the linker roads are high momentum. This occurs because of the different impact parameters built into the roads database (figure 6). Low momentum tracks are actually found more often than high momentum ones (figure 7). This is still an unexplained effect. The impact parameter has little effect on the efficiency of the tracking system (figure 8). The major effect is the time that the cosmic ray enters the chamber (figure 9). A cosmic ray that occurs after 60 nanoseconds into the 396 nanosecond time cycle will not be found. This is because after 66ns. the mezzanine cards classify all wire hits as delayed, and there are no finder masks that contain all delayed hits. The efficiency for cosmic ray finding is 11%. This translates to two to three cosmic rays found per second by the tracking hardware.

There is still much to be done with this project. A simulation with no magnetic field still needs to be completed. The linker roads database must be converted into a format the programmable logic devices can interpret, and then they must be downloaded onto the linker boards. This will be tested using simulated data that passes through from a prototype finder board to a linker board. If all goes well the system will find tracks, and then it can be implemented at Fermilab.

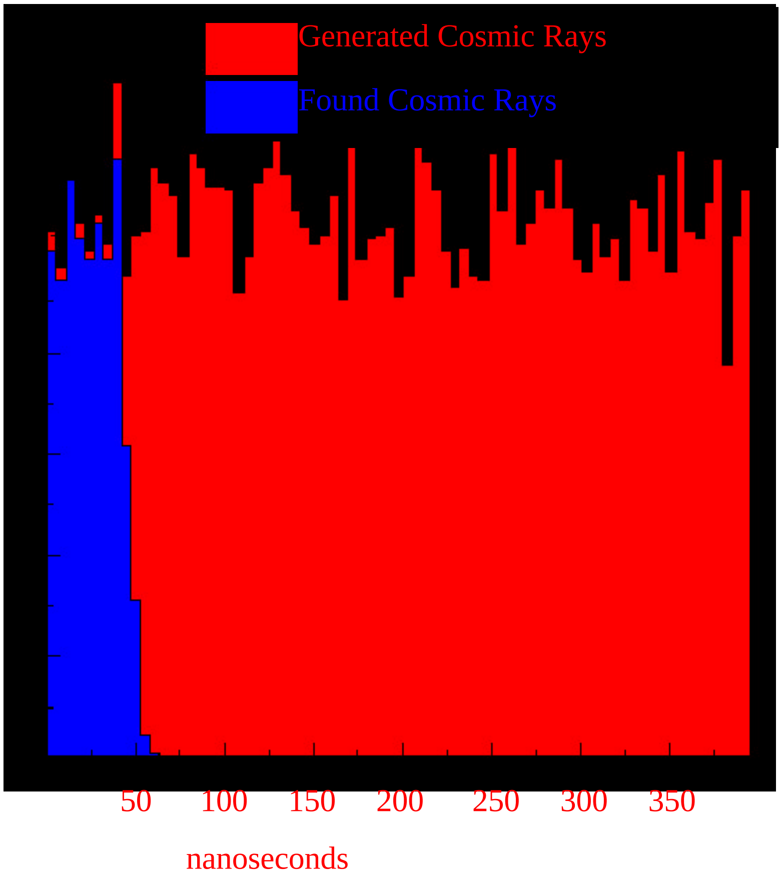

Figure 9: Efficiency based on the time offset of the cosmic ray.

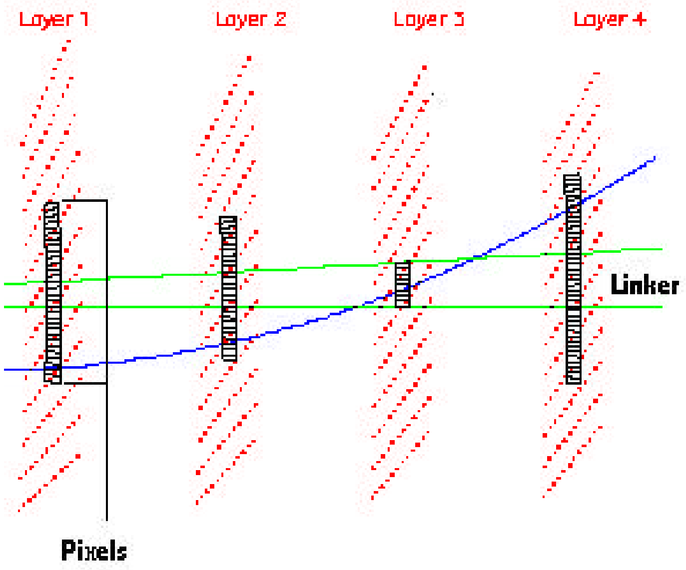

Figure 5: Charged Particle Passing Through a Linker

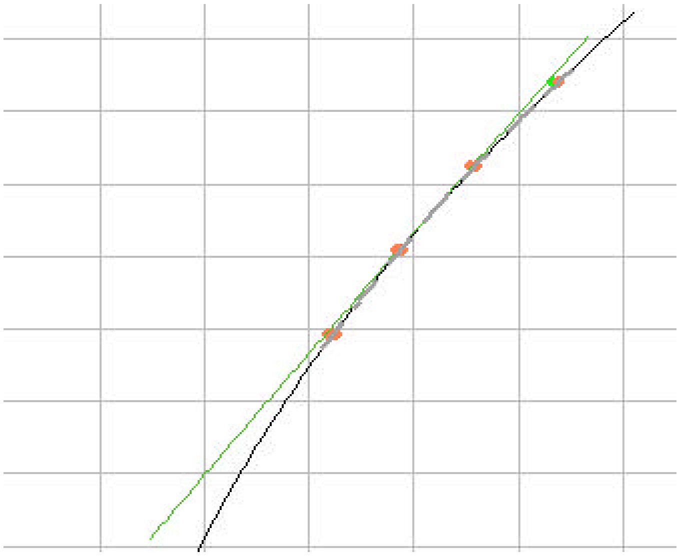

Figure 6: A high momentum road with a different impact parameter (green) finds A low momentum cosmic ray (black).

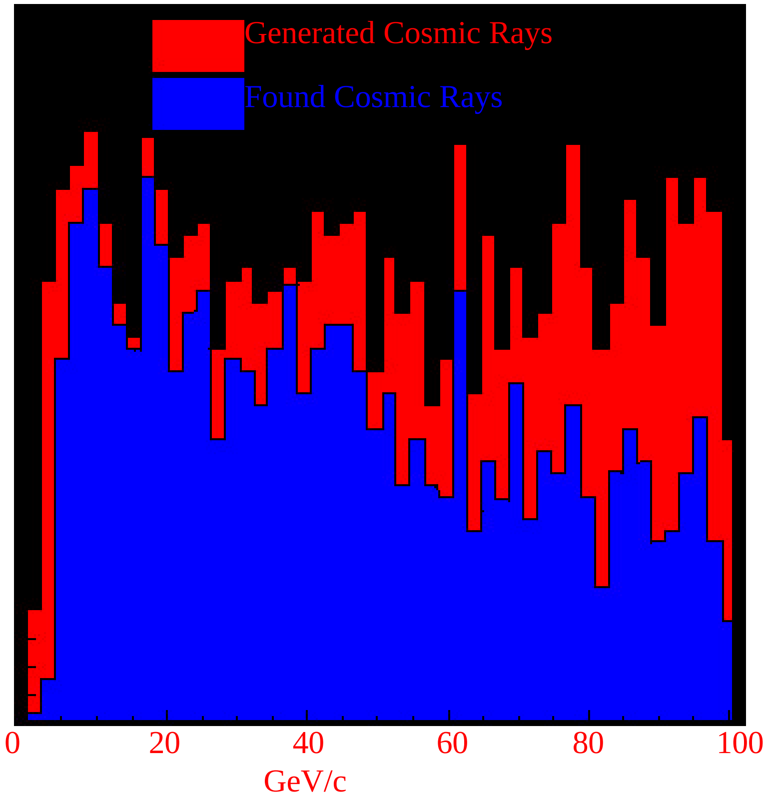

Figure 7: Efficiency based on the momentum of the cosmic ray.

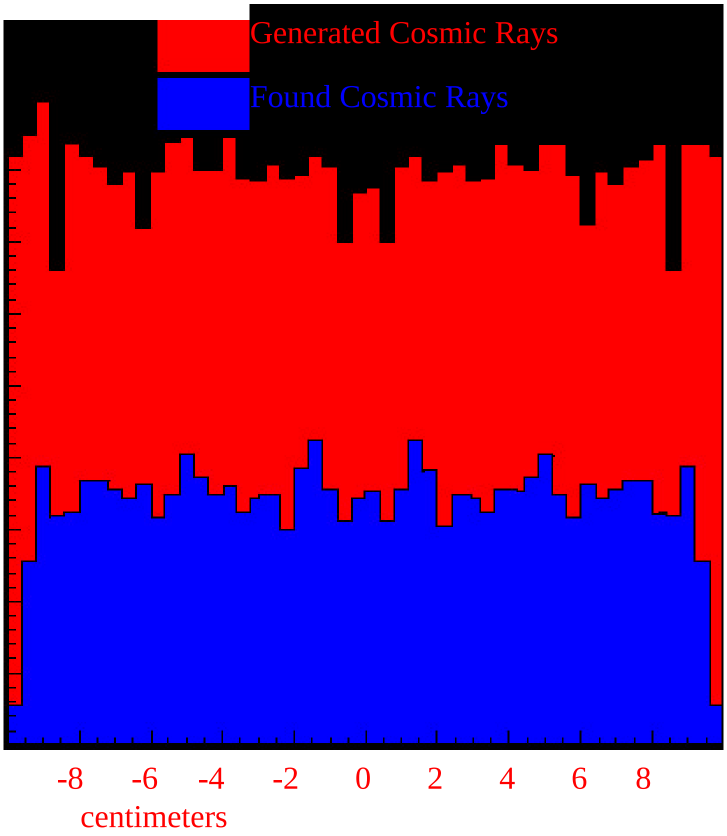

Figure 8: Efficiency based on the impact parameter of the cosmic ray.

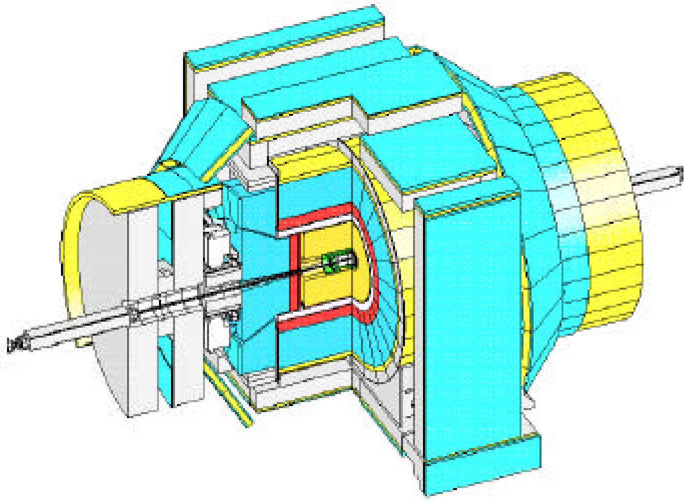

Figure 1: Cut Away View of Detector

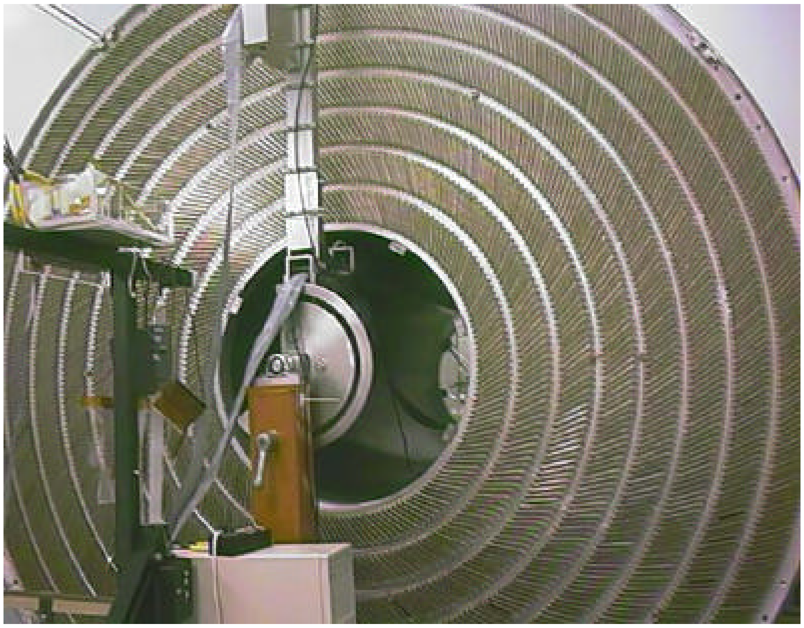

Figure 2: Central Outer Tracker

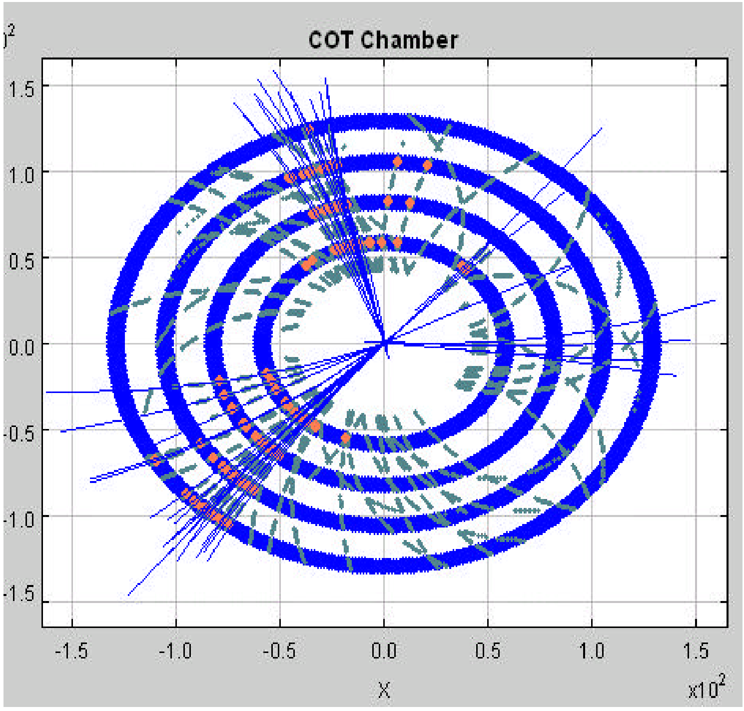

Figure 3: R-ϕ View of Typical Top Quark Event. Hits and Charged Tracks Shown

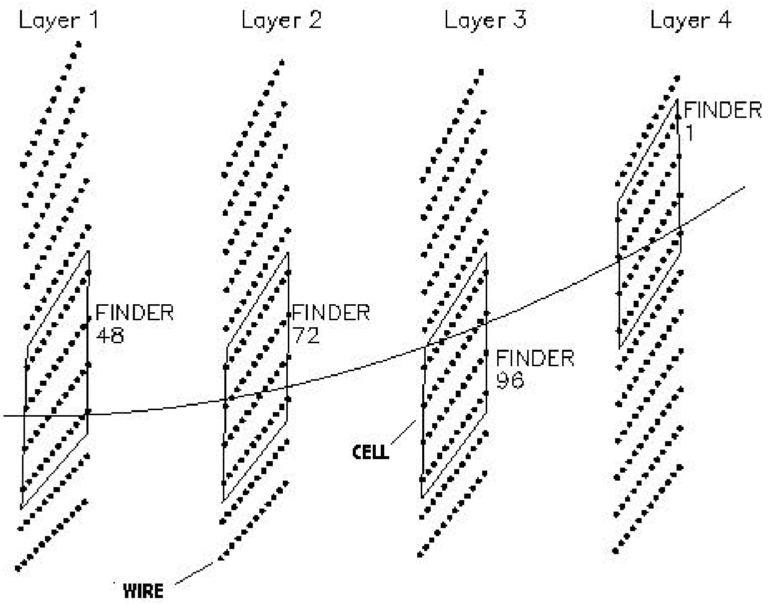

Figure 4: Charged Particle Passing Through Finders in COT Axial Layers