Simulation on the Charged Particle Response of the STAR Heavy Flavor Tracker Pixel Detector

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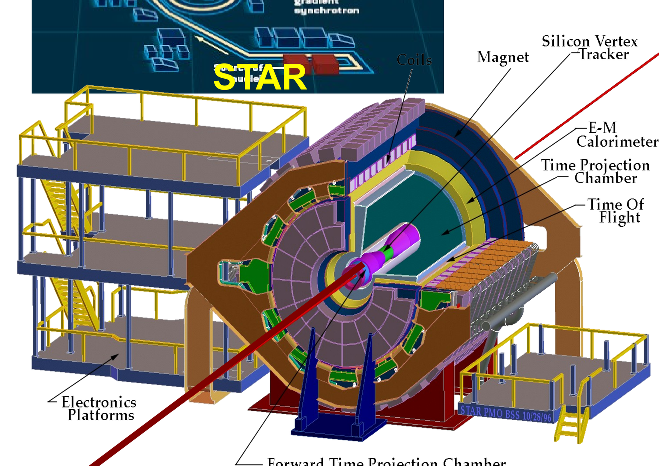
Abstract:

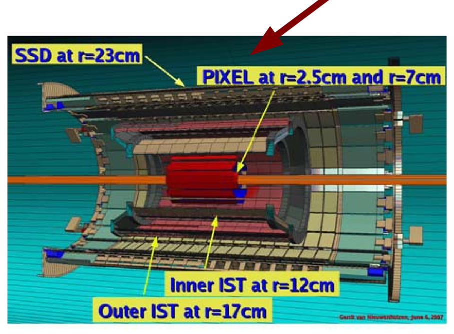
The main task of the STAR experiment, located at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory, is to study the quark-gluon plasma (QGP), which is expected to have been created a few microseconds after the "Big Bang." Heavy quarks are ideal tools for studying the properties of QGP. The Heavy Flavor Tracker (HFT) is the central part of the STAR future heavy flavor physics program and will enable STAR to directly measure heavy flavor mesons. The core of HFT is a pixel detector (PIXEL) using CMOS Active PIXEL Sensor.

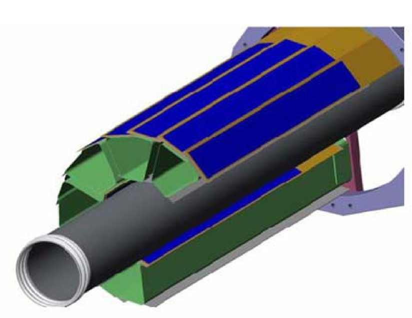
This poster will describe the development of a detailed simulation of the pixel detector response to charged particles and the corresponding fast simulation that dramatically enhances the simulation speed with little sacrifice in accuracy. The full simulation randomly generates ionized electrons along an incoming track and diffuses the electrons inside the pixel array until they are collected by the electronics or recombined inside a pixel. The main problem is that the full simulator is too slow and takes about one hour to process a single track. To significantly increase the speed while maintaining accuracy, we generate a grid inside a single pixel and create a map of probability distribution functions for a single ionized electron generated from a grid point to either be collected or recombined in any of the pixels. To complete a single track with comparable accuracy, the fast simulation drastically quickens the processing time from roughly one hour to about 5 seconds. We will also discuss the study of pixel detector position resolution using a simple clustering algorithm.

RHIC, STAR, and HFT:

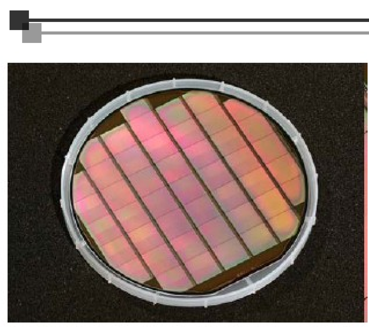
- The Relativistic Heavy Ion Collider (RHIC) is a particle accelerator located at Brookhaven National Laboratory in Long Island, New York.
- Heavy ions or protons are accelerated in opposing directions around the accelerator,.and they achieve speeds of up to 99.95% the speed of light.
- Maximum energy for heavy ion collisions: 200 GeV / nucleon.
- Currently 2 experiments running (STAR and PHENIX)
- The main task of the Solenoidal Tracker at RHIC (STAR) is to study the medium known as Quark-gluon plasma (QGP). It is expected to have been created a few microseconds after the "Big Bang."
- The heavy quarks are major probes to study QGP. They are produced immediately after collision and interact differently with the medium compared to light quarks. A detailed analysis of heavy quark production will provide key information for understanding the properties of the medium.
- The Heavy Flavor Tracker (HFT)[2] is the core of the future STAR heavy flavor physics program and will soon enable STAR to directly measure heavy flavor mesons.

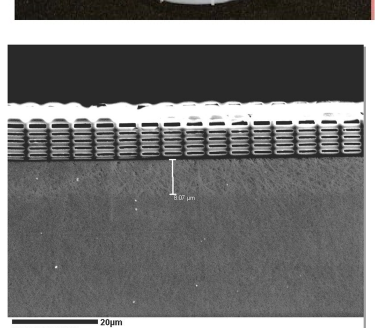






The CMOS Active Pixel Sensor:



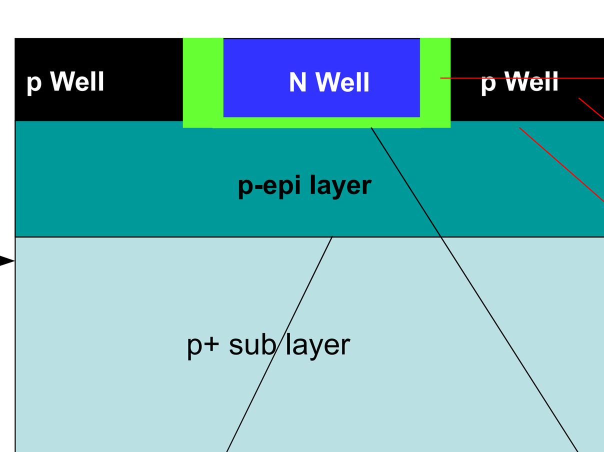


- The HFT is using the CMOS Active PIXEL Sensor (APS) technology for several reasons:
  - Capable of excellent spatial resolution
  - Good charge collection efficiency.
  - Satisfactory radiation tolerance.
- When a charged particle traverses the PIXEL sensor, it creates ionized electrons in the epi- and sub-layer, and these electrons can diffuse freely in these layers until they are collected by the n-well or recombined.
- The output electronics converts collected charge to voltage level before passing it to readout electronics, thus gaining the name "active pixel."

How the Full Simulation Works:

- The full simulation randomly generates ionized electrons along an incoming track and diffuses the electrons inside the pixel array until they are collected by the electronics or recombined inside a pixel.

Reference for detailed simulation comes from Shengdong LI's thesis[1]



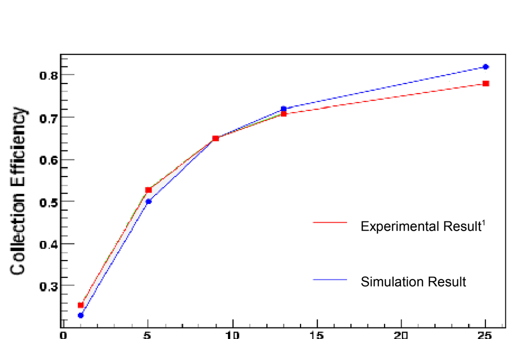
• When the electron fall into the depletion region between N-Well and P-Well or the N-well region, it will be fully collected into the readout electronics.
•Electrons in the p-well region will be neglected.

•When electron hits the p-epi and p well interface, the p-well/p-epi interface can be recognized as a boundary with total reflection for electrons in the epitaxial silicon because pWell are more heavily doped and electric field in the depletion region will reflect the electron away.

•when the p-epi electron hit p-epi/p+ substrate, because p+ substrate is more heavily doped, interface is recognized as a boundary with total reflection for electrons in the epitaxial silicon.
•when the p+ substrate electron hit p-epi/p+ substrate interface, the interface is totally transparent.

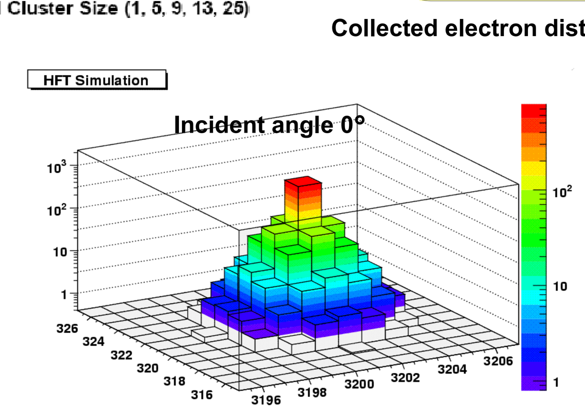
• When electrons hit the n-well/p-epi depletion region, has very little chance to be reflected but pass through. Consequently, the n-well/p-epi interface can be recognized as a boundary with total absorption.

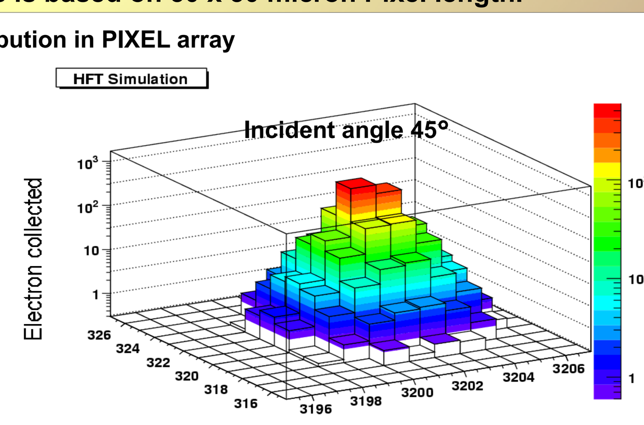
Preliminary Full Simulation Tests:



- PIXEL cluster size: the number of PIXEL summed with the hit PIXEL as center (e.g. 5 x 5 PIXEL array is a cluster of 25 PIXELs)
- Collection efficiency: the number of electrons collected within the PIXEL cluster divided by the total number of electrons collected by the whole PIXEL array.
- The simulation is in good agreement with the experimental results
- A processing time of 1 hr per track is not desirable.
- This analysis is based on 30 x 30 micron Pixel length.

Collected electron distribution in PIXEL array

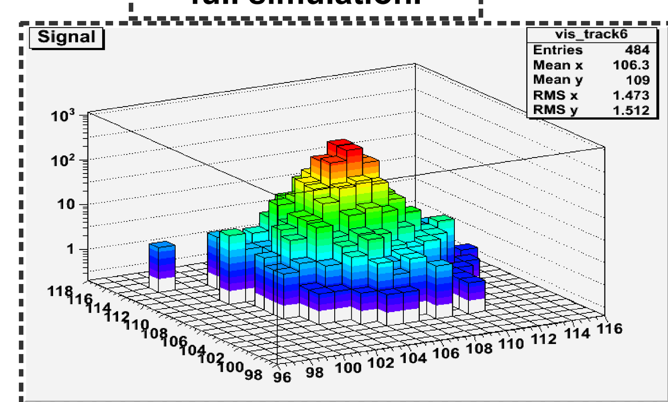




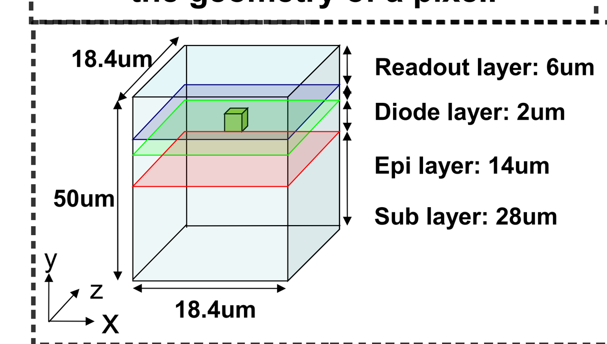
Pixel ID

How the Fast Simulation Works:

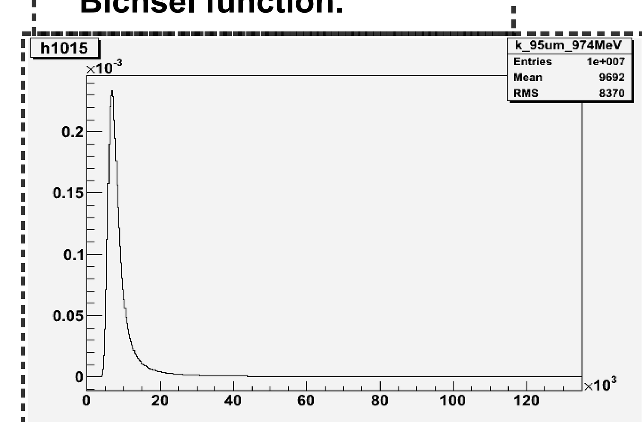
- Generate a Look-Up Table from the full simulation.



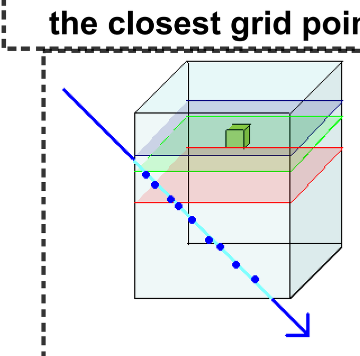
- Create a grid system based on the geometry of a pixel.



- The number of electrons generated for a single track depends on the Bichsel function.[3]



- Randomly generate electrons along the track and determine the closest grid point.

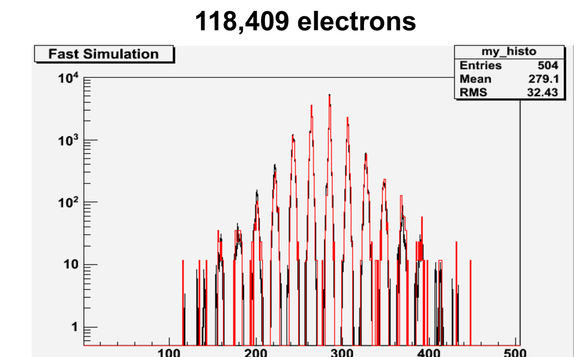


- Count each electron that was collected by randomly sampling the Look-Up Table.
- Create a histogram output signal.
- Result: Track simulation that is just as accurate as the full simulation but takes 5 seconds to process as opposed to 1 hour.

Full Simulation Versus Fast Simulation:

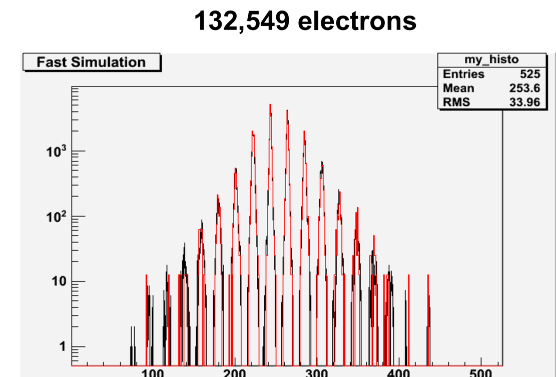
- These plots are a one dimensional representation of a signal within the two dimensional Pixel array.
- A single track was run in both the full simulation and the fast simulation to generate a signal.

118,409 electrons



Track: (0.001104,0.00185) → (-0.00612,0.0009)

132,549 electrons



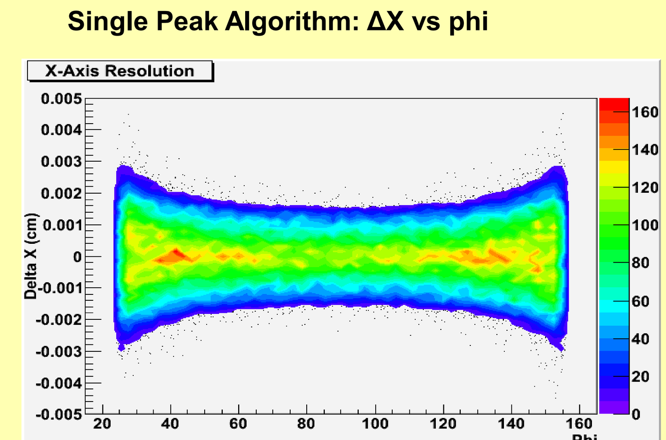
Track: (-0.0092,0.0001) → (0.001472,-0.0011)

- The red represents the signal generated by the full simulation, and the black represents the signal generated by the fast simulation.

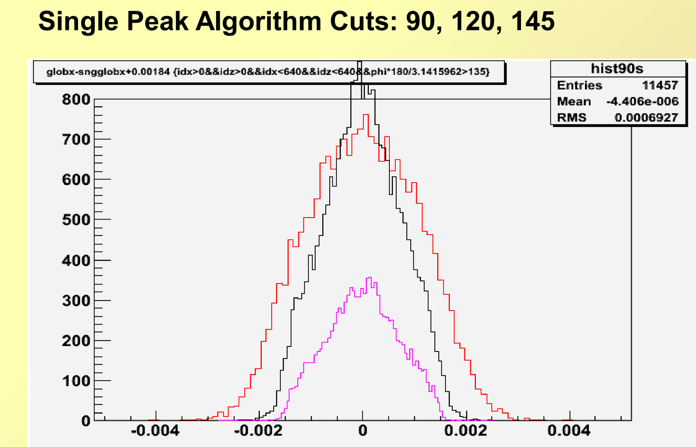
Single- and Double-Peak Cluster Algorithm:

- The algorithm takes the difference between the reconstructed point and the actual point the charged particle passes through (**ΔX**).
- This **ΔX** is taken as a function of the azimuthal angle (**phi**) of the track incident upon the pixel array.
- Single-Peak cluster algorithm: The center of the Pixel with the most electrons collected in the signal will be reconstructed as the point which the track passes through.
- Double-Peak cluster algorithm: The average center of the two Pixels with the most electrons collected in the signal will be reconstructed as the point which the track passes through.
- The Double-Peak algorithm is the current method of electronic readout.

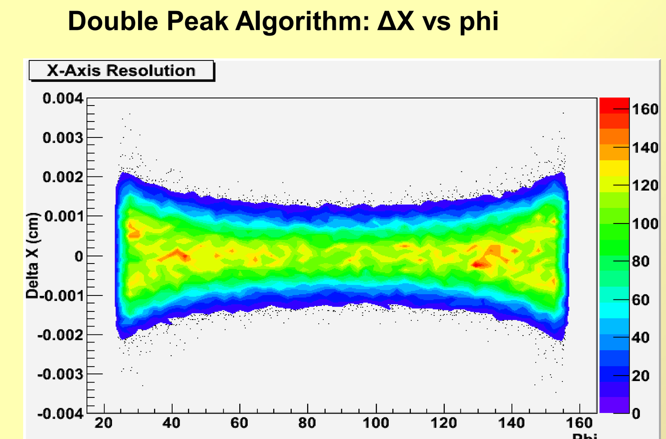
Single Peak Algorithm: ΔX vs phi



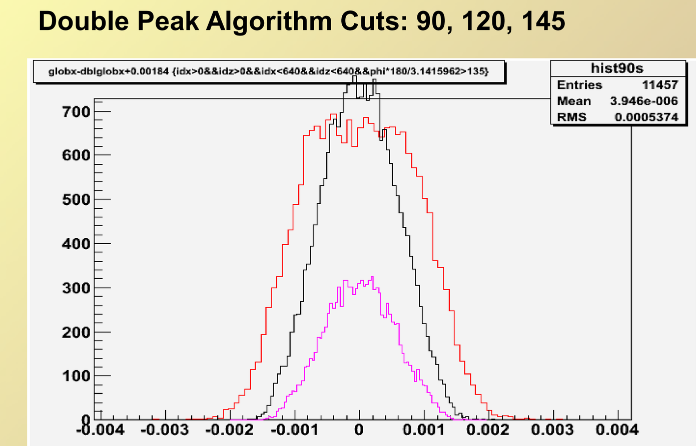
Single Peak Algorithm Cuts: 90, 120, 145



Double Peak Algorithm: ΔX vs phi



Double Peak Algorithm Cuts: 90, 120, 145



- Pink = 90 degrees ± 15 degrees
- Black = 120 degrees ± 15 degrees
- Red = 145 degrees ± 10 degrees
- The resolution is around 10 microns.
- A pixel is about 18 microns in length.

Acknowledgments:

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- Xin Li, mentor and developer of the full simulation
- Collaborators from STAR HFT project.

References:
1 S. Li. *Modeling, Design, and Analysis of Monolithic Charged-particle Image Sensors.* 2007.

2 S. Kleinfelder *et al.*, Nucl. Instr. And Meth. **A565**, 32(2003).

3 H. Bichsel, *Review in Modern Physics*, vol.60, pp. 663, (1988).