Monte Carlo Simulation of Silicon Vertex Detector for Bottom Collider Detector

Part I

Lee Roberts
Computing Department
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois

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ABSTRACT
A silicon vertex detector design for a Bottom Collider Detector incorporating segmented barrels and planar disks has been simulated using GEANT3 with PYTHIA-generated events. A Bottom Collider Detector is envisioned as a possible new experiment that addresses high statistics bottom physics at the TEVATRON Collider. Detector performance has been analyzed for the decay modes $B_d^0 \rightarrow \pi^+\pi^-$ and $B_d^0 \rightarrow \psi K^0_s (\psi \rightarrow e^+e^-)$. 
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I. Introduction

Monte Carlo simulation of detectors has become an essential design tool for future high energy physics experiments. Computer simulations can provide an efficient laboratory for testing and evaluating detector designs—detector efficiencies under varied geometrical configurations and cuts can be calculated long before any hardware need exist.

Computer simulations of detectors need not consume large amounts of computer time. Preliminary design stages should not require exact details for the evaluation of competing designs. In such cases, detector components can be described in large, macroscopic units—barrels, planes, etc. The amount of detail required in the answer should always guide the amount of detail present in the detector simulation. Specification and simulation of each individual detector element can be an unnecessary burden (and waste of computer resources) for rough detector designs.

This paper presents a computer simulation of one silicon vertex detector design for a Bottom Collider Detector (BCD). Since the silicon vertex detector is still in the preliminary design stages, the simulation was performed without detailed specification of the individual strips in the silicon detectors. GEANT3 [1] provided the detector specification and event simulation framework for the computer simulation. Bottom meson events were generated using the PYTHIA [2] event generator from the Lund suite of event generation programs. The present detector design has evolved from previous considerations of barrel vertex detectors and planar disk vertex detectors in an attempt to incorporate the best features of these simple designs.

Design of the silicon vertex detector has been a collaborative effort of many members of the Bottom Collider Study Group. Implementation of these designs in GEANT3 simulations and the computing effort has been largely performed by the author. Preliminary designs and simulation results have been vigorously discussed by attendees of the group meetings—with many important and worthwhile contributions resulting from these sessions.
II. Detector Geometry

A. Design specifications

The silicon vertex detector under consideration is logically segmented into two regions. The central region covers most of the interaction region with a combined geometry of equally-spaced silicon planes and two segmented barrels. The rapidity-spaced region covers the outer limits of the interaction region with silicon planes at equal density in pseudorapidity. All silicon elements lie outside the beryllium beam pipe. Figures 1 & 2 present GEANT3 pictures of the detector geometry.

The beryllium beam pipe has radius 1.3 cm and thickness 400 µm. All silicon elements are of 200 µm thickness and have a strip pitch of 50 µm. Each silicon disk has an inner radius of 1.5 cm and an outer radius of 10 cm. The detector consists of twenty-seven parallel silicon disks and two segmented silicon barrels. The total length of the vertex detector is approximately 210 cm.

The central region of the vertex detector contains seventeen silicon planes with an interdisk spacing of 5 cm. The silicon barrel segments are placed in the interdisk volumes and extend to the disk edges of the neighboring planes. The inner silicon barrel radius is 1.5 cm; the outer silicon barrel radius is 5.0 cm. The central region extends from the center...
of the interaction region to \( z = \pm 40 \text{ cm} \).

The rapidity-spaced region of the vertex detector consists of variably-spaced silicon planes. The rapidity-spaced region is abutted to the central region and covers the outer limits of the interaction region. Silicon planes are placed every one-third unit of pseudorapidity according to the following formula.

\[
\pm z = 25.0 \text{ cm} + \frac{1.5 \text{ cm}}{\tan(2 \tan^{-1}(e^{-\eta}))} \quad \eta = 3, 3\frac{1}{3}, \ldots, 4\frac{2}{3}
\]

Thus, the \( \eta = 3 \) planes are equivalenced to the outer planes of the central region; the nominal interaction point for the equal-pseudorapidity spacing lies approximately 15 cm inside the central region. Plane spacings are calculated based on the disk inner radius of 1.5 cm. Five rapidity-spaced planes extend from the ends of the central region to \( z \approx \pm 105 \text{ cm} \). Table 1 presents a summary of the detector specifications.

<table>
<thead>
<tr>
<th>beam pipe</th>
<th>radius</th>
<th>1.30 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>thickness</td>
<td>400 ( \mu )m</td>
</tr>
<tr>
<td>vertex detector</td>
<td>total length</td>
<td>210.00 cm</td>
</tr>
<tr>
<td></td>
<td>inner radius</td>
<td>1.50 cm</td>
</tr>
<tr>
<td></td>
<td>outer radius</td>
<td>10.00 cm</td>
</tr>
<tr>
<td>central region</td>
<td>total length</td>
<td>80.00 cm</td>
</tr>
<tr>
<td></td>
<td>interplane spacing</td>
<td>5.00 cm</td>
</tr>
<tr>
<td>silicon plane</td>
<td>inner radius</td>
<td>1.50 cm</td>
</tr>
<tr>
<td></td>
<td>outer radius</td>
<td>10.00 cm</td>
</tr>
<tr>
<td></td>
<td>thickness</td>
<td>200 ( \mu )m</td>
</tr>
<tr>
<td></td>
<td>strip pitch</td>
<td>50 ( \mu )m</td>
</tr>
<tr>
<td>silicon barrel</td>
<td>radius (inner)</td>
<td>1.50 cm</td>
</tr>
<tr>
<td></td>
<td>radius (outer)</td>
<td>5.00 cm</td>
</tr>
<tr>
<td></td>
<td>thickness</td>
<td>200 ( \mu )m</td>
</tr>
<tr>
<td></td>
<td>strip pitch</td>
<td>50 ( \mu )m</td>
</tr>
</tbody>
</table>

**Table 1** Summary of geometrical specifications for Bottom Collider Detector vertex detector.

All silicon detector elements are double-sided. The barrels have strips in \( z \) and \( \phi \) directions, while the planes have strips in the \( z \) and \( y \) directions. This silicon vertex detector design incorporates approximately one million detector channels.

This detector combines the features of the planar and barrel silicon geometries. Planes provide effective detector surfaces for particles traveling into the forward and backward regions, while barrels provide effective detector surfaces for radially-moving particles. The outer radius of the silicon planes has been chosen to be twice the interplane distance to guarantee two planar hits for all particles in the central detector region. The silicon
thickness has been adjusted to 200 µm to guarantee satisfaction of the cluster cut parameter for tracks incident on detectors up to 45° from normal incidence. Since the planes and barrels present relatively perpendicular surfaces to the particle tracks, this provides that all tracks that pass through the body of the detector will have two acceptable hits.

**Figure 2** Three-dimensional closeup of the BCD silicon vertex detector.

**B. GEANT3 implementation**

The GEANT3 implementation of the detector geometry is quite straightforward. All detector elements are placed within a mother volume, SPEC. The beam pipe, PIPE, is entered as a tube with the appropriate dimensions. Three silicon detector segments are defined, each as a tube in the GEANT3 terminology for the planes (DISK) and for the barrel segments (BARI and BARM). The detector is constructed by entering and positioning multiple copies of the detector segments into the mother volume. The GEANT3 geometry is optimized using subroutine GSORD along the beam axis.

Particle hits are recorded upon entry into each silicon detector element. For each hit, the space coordinates, the direction cosines, the total momentum and the total energy are stored. Silicon strips are simulated during the event analysis by transforming the recorded space coordinates into the central coordinate value for the "hit" strip and performing the analysis with these "digitized" coordinates. Similarly, cluster sizes of particle tracks in the silicon detectors are calculated from the track direction cosines and knowledge of the
detector geometry.

In addition, two additional detectors which lie outside the silicon detector elements are defined for convenience. These detectors, a barrel (D,B) and two endcaps (D,E), record the particle positions and momenta after passing (and multiple scattering) through the silicon detectors.

![Rapidity--production](image)
![Pseudorapidity--production](image)

**Figure 3** Production rapidities and pseudorapidities for bottom mesons in the PYTHIA event simulation.
III. Event simulation

A. Event generation

The Lund Monte Carlo for hadronic processes—PYTHIA 5.1—was used as the event generator for this simulation. Bottom meson events were generated for a $\bar{p}p$ collider with 2 TeV center-of-mass energy. Events were constrained to have two bottom quarks in the final state generated by either hadronic process $q + \bar{q} \rightarrow q_m + \bar{q}_m$ or $g + g \rightarrow q_m + \bar{q}_m$. The minimum invariant mass of the hard-scattering parton subsystem was set at 10.5 GeV; the minimum allowed transverse momentum was 0.0 GeV/c. Decays of secondary particles were prohibited in the PYTHIA event generation—all particle decays were handled by GEANT3. Generated events were stored in ISAJET [3] binary format for later processing by GEANT3 detector simulations.

Figure 3 presents production rapidity and pseudorapidity distributions for the bottom mesons in the PYTHIA event simulation. Figure 4 presents the pseudorapidity distribution of decay products from $B^0 \rightarrow \pi^+\pi^-$ for all bottom mesons.

![Pseudorapidity distribution](image)

Figure 4 Pseudorapidity distribution for decay products from $B^0 \rightarrow \pi^+\pi^-$ for all PYTHIA-produced bottom mesons.

B. GEANT3 processing

A PYTHIA-generated bottom meson event was used as input for each GEANT3 event simulation. Each event was read in ISAJET format. Bottom mesons only were selected from among the full PYTHIA-generated event for entry into GEANT3. Our objective was
to determine whether reconstruction of bottom mesons would be possible using this vertex detector—one should first check that reconstruction is possible without any extraneous particles. (This also provides a substantial savings of computer resources.) Each bottom meson was decayed and the decay particles tracked through the vertex detector. Simulations were run using one of two decay modes: $B^0_d \rightarrow \pi^+\pi^-$ and $B^0_d \rightarrow \psi K^0_S (\psi \rightarrow e^+e^-)$. No magnetic field was present in the simulations, this being a preliminary design study. (Current Bottom Collider Detector designs include a 1.0–1.5 Tesla magnetic dipole field.)

Analysis of each event was performed in GEANT3 subroutine GUDUT. Analysis was performed using GEANT3’s knowledge of the particle decay. No pattern recognition was used; the GEANT3 particle decay chain was followed to identify descendants of each bottom meson. Both of the chosen decay modes allow a simple trigger—both provide two prompt, charged particles. Bottom meson events were accepted if both charged particle tracks had at least two (acceptable) hits in the silicon detectors.

Simulations were run which imposed a cluster size cut on the particle hits in the silicon detectors. The cluster size is defined to be the number of adjacent silicon strips which are fired by the passage of a single particle track. Large cluster sizes present possible problems with signal size, hit location and pattern recognition. Hits with cluster sizes greater than four strips were rejected in this class of simulations.

Vertex fitting of bottom meson decays was performed using the CERN VERTEX subroutine. This subroutine requires straight-line track parameters as inputs and provides fitted vertex locations and adjusted track parameters as output. Particle tracks were defined by the first two (valid) hits on the track. Since GEANT3 provides a vertex coordinate for its particle decays, comparison of the actual and fitted vertex coordinates was quite simple. Cuts on the vertex resolution were imposed on the quantity $S/\Delta S$, where $S$ represents the distance of flight of the bottom meson and $\Delta S$ represents the three-dimensional distance between the reconstructed decay vertex and the true (Monte Carlo) decay vertex. $S/\Delta S > 5$ was the imposed cut.

Measurement of the effect of multiple scattering by the beryllium beam pipe and the silicon detectors was provided by the calculation of the bottom meson invariant masses after the decay products had traversed the silicon. The outer, non-physical detectors were used to provide exact measurements of the particles’ positions and momenta after passing
through the silicon. These momentum measurements allowed calculation of the bottom meson invariant masses.

Accepted rapidity and pseudorapidity of the bottom mesons, angles of incidence of particles on the silicon detectors and cluster sizes for hits are among the other parameters calculated during the simulations.

IV. Results

Simulations were performed using two interaction region models. A simple, random distribution of events in \( z, -2.5 \text{ cm} < z < +2.5 \text{ cm} \), was used as the initial model. This distribution covers one period of the central region of the vertex detector. Use of this distribution allowed us to concentrate on the behavior of the central region of the vertex detector.

A realistic model of the interaction region incorporating a normal (Gaussian) distribution of events with \( \sigma = 35 \text{ cm} \) and mean \( \bar{z} = 0 \) was used for all following plots. This model corresponds to the current \( \bar{p}p \) Tevatron beam.

Vertex detector acceptance as a function of the applied cuts can be seen in Table 2 below. Results are shown for both interaction region models and for both of the decay modes \( B_d^0 \rightarrow \pi^+\pi^- \) and \( B_d^0 \rightarrow \psi K_s^0 \). Application of cuts is cumulative down through the rows of the table.

<table>
<thead>
<tr>
<th>cuts</th>
<th>( B_d^0 \rightarrow \pi^+\pi^- )</th>
<th>( B_d^0 \rightarrow \psi K_s^0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>geometry cut</td>
<td>0.965</td>
<td>0.978</td>
</tr>
<tr>
<td>cluster cut</td>
<td>0.950</td>
<td>0.965</td>
</tr>
<tr>
<td>vertex cut</td>
<td>0.637</td>
<td>0.610</td>
</tr>
</tbody>
</table>

Table 2a Vertex Detector Acceptance—simple interaction region with random \( z, -2.5 \text{ cm} < z < +2.5 \text{ cm} \).

<table>
<thead>
<tr>
<th>cuts</th>
<th>( B_d^0 \rightarrow \pi^+\pi^- )</th>
<th>( B_d^0 \rightarrow \psi K_s^0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>geometry cut</td>
<td>0.796</td>
<td>0.808</td>
</tr>
<tr>
<td>cluster cut</td>
<td>0.774</td>
<td>0.791</td>
</tr>
<tr>
<td>vertex cut</td>
<td>0.527</td>
<td>0.509</td>
</tr>
</tbody>
</table>

Table 2b Vertex Detector Acceptance—realistic interaction region with normal (Gaussian) distribution, \( \sigma = 35 \text{ cm} \).
A. Separation / Delta Separation

Figure 5 presents the Separation / Delta Separation plots for the decay mode $B_d^0 \rightarrow \pi^+\pi^-$ for the cases without and with the cluster cuts. Imposition of the cluster cuts causes the barrel hits to be ignored for particles with an angle of incidence greater than 45° upon the barrels. Such tracks are fitted using hits from the planes only, thus requiring the hits to be more separated and yielding more accurate vertex reconstructions. All plots throughout the rest of the paper will have imposed cluster cuts.

![Separation / Delta Separation](image)

**Figure 5a** Separation / Delta Separation for the decay mode $B_d^0 \rightarrow \pi^+\pi^-$ with no cluster cuts. Mean $S/\Delta S = 14.56$.

![Separation / Delta Separation](image)

**Figure 5b** Separation / Delta Separation for the decay mode $B_d^0 \rightarrow \pi^+\pi^-$ with cluster cuts imposed (cluster size > 4 rejected). Mean $S/\Delta S = 16.96$. 

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Separation / Delta Separation can be used as a measure of the accuracy of vertex resolution and reconstruction. A vertex cut of $S/\Delta S > 5$ has been imposed on the plots throughout the rest of the paper. Figure 6 presents a scatterplot of $S$ vs. $\Delta S$; events occurring above the dashed line are cut. Note the difference in the $S$ and $\Delta S$ projections of this scatterplot. Due to the finite resolution of the silicon strips, the reconstructed vertex location has some inherent error—the most likely value of $\Delta S$ is clearly non-zero. However, the separation, which is the distance travelled by the bottom meson before its decay, peaks at (or very near) zero. Improved detector acceptance requires increased accuracy in event reconstruction. Simulations with 25 $\mu m$ silicon strips have been performed, yielding an improvement in overall event acceptance of approximately 2% due to the improved reconstruction accuracy (smaller values of $\Delta S$).

![Separation vs. Delta Separation](image)

**Figure 6** Separation vs. Delta Separation for the decay mode $B_d^0 \rightarrow \pi^+\pi^-$. Events occurring above the dashed line fail the vertex cut.

### B. Rapidity and Pseudorapidity

Figure 7 presents accepted distributions of rapidity and pseudorapidity for bottom mesons in the BCD silicon vertex detector. All cuts (geometry, cluster size $\cal B$ vertex) have been imposed on these distributions. The distributions are for the decay mode $B_d^0 \rightarrow \pi^+\pi^-$; the distributions for the decay mode $B_d^0 \rightarrow \psi K^0_S$ are virtually identical.

Comparison with Figure 3 shows that bottom mesons with highest rapidity are lost—decay products escape along the beam pipe. The depletion of events at low rapidity
results from the vertex cut. Low-momentum bottom mesons are lost because their vertex reconstruction error is large relative to their distance of flight. Figure 6 clearly shows the loss of bottom meson events with short flight distances (separations) in the region above the dashed line of the $S/\Delta S$ vertex cut.

![Rapidity---accepted](image1)

![Pseudorapidity---accepted](image2)

Figure 7 Accepted rapidities and pseudorapidities for bottom mesons in the BCD silicon vertex detector. All cuts (geometry, cluster size & vertex) have been applied. Results are for the decay mode $B^+_d \rightarrow \pi^+ \pi^-$. 

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C. Invariant Mass

Figure 8 presents the invariant mass distributions for the decay modes $B_d^0 \rightarrow \pi^+\pi^-$ and $B_d^0 \rightarrow \psi K_s^0$. The bottom meson invariant mass is calculated using the exact values of the particle momenta in the non-physical detectors outside the silicon vertex detectors. The particle four-momenta have been multiple-scattered by the silicon detector elements. No other measurement errors are considered.

**Figure 8a**  Bottom meson invariant mass for the decay mode $B_d^0 \rightarrow \pi^+\pi^-$. All cuts (geometry, cluster size $\mathcal{B}$ vertex) are included.

**Figure 8b**  Bottom meson invariant mass for the decay mode $B_d^0 \rightarrow \psi K_s^0$. All cuts (geometry, cluster size $\mathcal{B}$ vertex) are included.
D. Angle of Incidence

Figure 9 presents the angle of incidence (degrees from normal) of particles on the silicon vertex detectors for the decay mode $B^0_d \rightarrow \pi^+\pi^-$. The angle of incidence plots are similar for all cases studied. Only hits for accepted (all cuts) bottom mesons are shown.

Note that this plot includes the multiplicity of hits in the detectors for each particle track. The peak at small angles of incidence results primarily from the silicon planes. Previous studies of the barrel geometry show that the distribution of angles of incidence upon the barrels is much flatter than in the planar geometry; furthermore, the distribution for the barrel geometry increases with angle of incidence, peaking near parallel incidence.

Figure 9  Angle of incidence (degrees from normal) on the silicon vertex detectors for decay products of bottom mesons.
E. $Z$ Cluster Size

Figure 10 presents the $z$ cluster size for the barrel vertex detectors for the decay mode $B_d^0 \rightarrow \pi^+\pi^-$. The $z$ cluster size plots are similar for all cases studied. All cuts (geometry, cluster size & vertex) are included.

![Z Cluster Size](image)

**Figure 10** $z$ cluster size for the barrel vertex detectors for decay products of bottom mesons.

This simulation does not analyze the effects of multiple particles with large cluster sizes and the ability to distinguish signals in the barrel silicon detectors.

Tracks with large $z$ cluster sizes are reconstructed from planar hits—their barrel hits are removed by the cluster size cut. The $z$ cluster sizes of such tracks provide some measure of the amount of silicon traversed by these accepted tracks. Other particles in the event will have similar effects upon the vertex detector. Pattern recognition for the silicon must be concerned with the effects of many low-angle particles and overlapping signals. A cluster size cut for pattern recognition will undoubtedly need to be much larger than the small value of four strips chosen for this simulation. One might hope that the effect of pattern recognition and rejection of noise would approximate the cluster cut of four strips chosen in this clean environment.
V. Conclusions

The Bottom Collider Detector silicon vertex detector design and simulation results presented in this paper represent the combined ideas and efforts of many individuals since the Workshop on High Sensitivity Beauty Physics at Fermilab, held at Fermilab from November 11–14, 1987. Silicon vertex detector simulations, initiated during the Workshop, explored the barrel and planar detector geometries using a point interaction region. Inadequacies of both models led to a combined barrel & planar geometry. Study of this combined model yielded better understanding of the detector parameters, in particular, correlated parameters such as interplane spacing and plane (outer) radius and such as silicon thickness, strip pitch and cluster size cut. Finally, study of a more realistic interaction region and the desire to increase acceptance in rapidity required the addition of the rapidity-spaced planar silicon detectors.

Understanding of the interrelations of detector parameters and their effects on event acceptances is the primary result of these simulations. Discussion will continue regarding the most suitable interplane spacing, plane radii, barrel radii, detector length, etc. Such discussions must include consideration of cost, hardware feasibility and effects on design of the outer detector components.

Further simulations of Bottom Collider Detector silicon vertex detectors should include more realistic geometry, magnetic fields and full event tracking. We must evaluate the effects of the multiplicity of particles in the full event upon the vertex detector—can we recognize the bottom mesons? Can the individual track signals be distinguished? We should eventually aim for Monte Carlo simulation of pattern recognition and event reconstruction to fully verify the detector design.

Acknowledgements

I wish to thank the many members of the Bottom Collider Study Group for their innumerable comments, questions and suggestions regarding the design and simulation of the silicon vertex detector. In particular, I wish to thank Paul Karchin, who has provided most of the detector design parameters and has performed a substantial role in the interpretation of the simulation results and the direction of the detector simulations.
References


