

The BTeV Pixel Detector and Trigger System

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BTeV is an approved forward collider experiment at the Fermilab Tevatron dedicated to the precision studies of CP violation, mixing, and rare decays of beauty and charm hadrons. The BTeV detector has been designed to achieve these goals. One of the unique features of BTeV is a state-of-the-art pixel detector system, designed to provide accurate measurements of the decay vertices of heavy flavor hadrons that can be used in the first trigger level. The pixel vertex detector and the trigger design are described. Recent results on some of the achievements in our R&D effort are presented.

1. Introduction

BTeV is an experiment expected to begin running at the C0 interaction region at Fermilab in the year 2007/2008. Its physics goals are to achieve unprecedented levels of sensitivity in the study of CP violation, mixing, and rare decays in the b and c systems [1]. In order to realize this, the detector will employ a state-of-the-art first level trigger (L1) that will look at every beam crossing to identify detached secondary vertices from charm and beauty hadron decays. The key element to this triggering approach is the pixel vertex detector. This provides high resolution space points near the interactions, which are used both online and offline to reconstruct tracks and associate them with their parent vertices. The pixel detector and the L1 vertex trigger are critical elements to the success of the BTeV experiment. The key goals of the pixel detector are excellent spatial resolution, ease of tracking pattern recognition, radiation hardness, material thinness, and readout of data fast enough for use in the lowest level BTeV trigger system. The goal of the L1 vertex trigger is to reject 99% of the light quark events while remaining $> 50\%$ efficient for all charged B hadron decays.

2. Pixel Detector Specifications

The baseline vertex detector consists of a regular array of 30 "stations" of "planar" silicon pixel detectors distributed along the interaction

region (Fig. 1) sitting inside a 1.6T dipole magnet. Each station contains one plane with the narrow pixel dimension vertical, and one with the narrow dimension horizontal. The stations are split, having a left half and a right half. Each half-station contains one (approximately) $5\text{ cm} \times 10\text{ cm}$ precision vertical-position-measuring half-plane, and a smaller, (approximately) $3.8\text{ cm} \times 7.3\text{ cm}$ horizontal-position-measuring half-plane. The left half-stations are positioned at regular intervals along the beam, and the right halves are similarly positioned, but midway between the left-half stations. This allows for possible overlap of half-planes with a variable-sized, small hole left for the beams to pass through.

The vertex detector contains nearly twenty-two million rectangular pixels, each $50\text{ }\mu\text{m} \times 400\text{ }\mu\text{m}$. Each sensor pixel is read out by a dedicated electronics cell. The sensor pixel and the readout cell are connected by a "bump bond." The basic building block of the detector is a hybrid assembly consisting of a sensor, a number of readout chips, and a flexible printed circuit (a high-density interconnect, HDI) which carries I/O signals and power. The sensors are sized to accept variable numbers of readout chips to make the required half-plane shape. Each readout chip is "flip-chip" mated to 22 columns of 128 rows of pixels on the sensors, corresponding to 2,816 active channels per readout chip. Each readout chip covers an active area approximately $0.64\text{ cm} \times 0.92\text{ cm}$. To avoid any dead space between adjoining read out

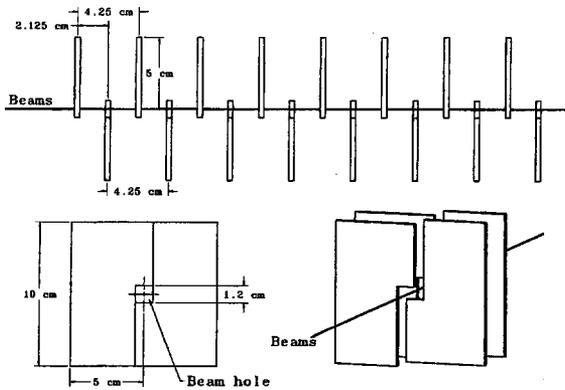


Figure 1. Schematic drawing of part of the pixel detector.

chips, the pixels on the sensors corresponding to the edge of the readout chip (first and last column) are extended to $600 \mu\text{m}$. These hybrid assemblies are supported by a movable carbon substrate that allows the pixel sensors to be positioned a safe distance away from the beam-line until stable conditions have been established in the Tevatron, at which point they are moved as close to the beam-line as radiation damage considerations will allow. This substrate also provides cooling for the readout electronics.

Fig. 2 shows a conceptual design for the aluminum vacuum vessel for the pixel detector. The vessel is a rectangular box with a length of ~ 165 cm and a height of ~ 60 cm. Particles within the 300 mrad acceptance of the spectrometer traverse only the pixel stations and the 0.75 mm thick exit window. The carbon substrate will be attached to a support frame made out of carbon fibers. Its position will be controlled by motors located just outside the vacuum vessel.

The major components of the pixel detector system are the sensor, readout chip, sensor-readout-chip connection (bump bonding), high-density interconnection between the pixel readout chips and the system control elements, and the mechanical support and cooling system. We have been designing and purchasing these components, assembling units and testing them in beams and

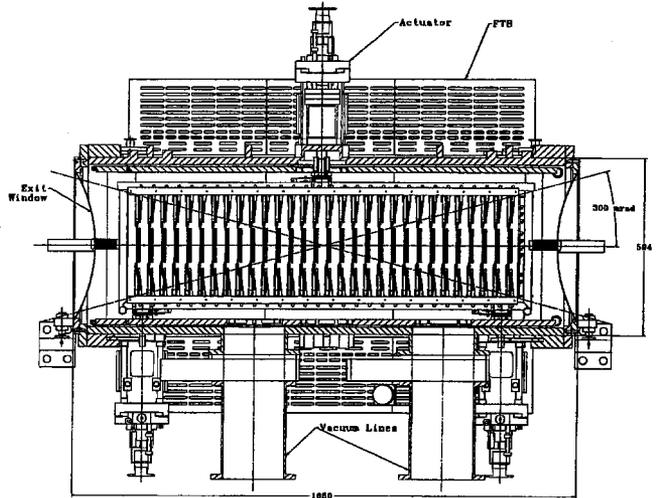


Figure 2. Side view of the vacuum vessel and support structure for the pixel detector.

in vacuum, and exposing them to intense radiation.

We have also performed detailed simulation studies to understand the various design issues for the components as well as system aspects.

3. Spatial Resolution

BTeV test beam studies, performed with prototype sensors and readout having pixel sizes of $50 \mu\text{m}$ by $400 \mu\text{m}$, have demonstrated a spatial resolution between 5 and $9 \mu\text{m}$ in the narrow dimension, depending on the track angle of incidence [2] (see Fig. 3). The solid line shows the resolution function (Gaussian) used for the Monte Carlo studies presented in the BTeV proposal. (The MC simulations also included non-Gaussian tails in the resolution distributions as measured in the test beam.) The figure shows both the resolution obtained using 8-bit charge information directly, and also the resolution obtained by degrading the pulse height to 2-bits of information. This result confirms the prediction of our simulations: that excellent resolution can be obtained using charge sharing, even with very coarse digitization. Based on these results, it has been decided that the BTeV readout chip will have a 3-bit FADC in each pixel cell. This will provide excellent spatial

resolution. In addition, the actual pulse heights may be used to indicate the presence of δ -rays or γ conversions.

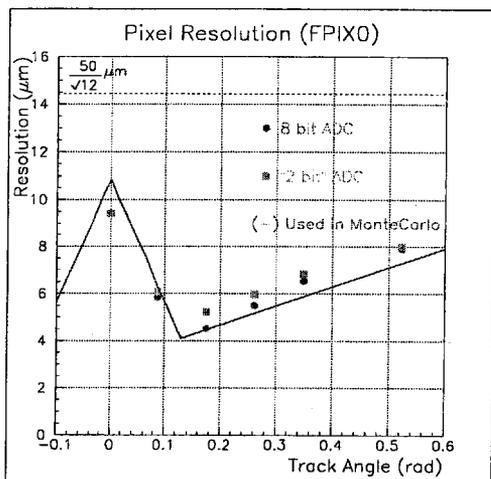


Figure 3. Resolution as a function of the angle of the incident beam for both 2-bit and 8-bit ADC readouts. The lines are piecewise linear fits of the resolution as used in simulations.

The single hit resolution is made possible by the choice of pixel size and a relatively low threshold for readout (approximately 2500 input electrons equivalent compared to about 24000 electrons for a minimum ionizing track at normal incidence for the devices tested). Relatively low dispersion of the thresholds across the chip and low noise in each pixel make the low readout threshold possible. Given the 132 ns beam crossing interval of the Tevatron, time slewing in the chips will not be a problem. While the above performance is for unirradiated devices, we anticipate operation at about -5°C to minimize effects of radiation damage during the lifetime of the detectors. Mounting stability and the necessary pixel alignment, using actual tracks in the final location, will be important to avoid serious degradation of this good resolution.

We have also worked to minimize the multiple

scattering due to the material in all the components of the system. In addition to making the components of the detector proper as thin as possible, the pixel detector will sit in a vacuum with only a $\sim 150\mu\text{m}$ thick aluminum rf shield between the beam and the detectors. The total radiation length for each pixel plane is 1.25%.

4. Radiation Hardness

To minimize the extrapolation error, the pixel detector will be placed as close as 6mm from the colliding beams, and hence will be exposed to a significant level of irradiation. At our maximum projected luminosity, it is expected that the innermost pixel detector will receive a fluence of 1×10^{14} minimum ionizing particles/cm²/year. This significant radiation environment means that all components of the pixel system have to be radiation hardened.

The silicon sensors are based on $n^+/n/p^+$ technology as developed by LHC experiments. Following the conclusion from the CERN RD48 collaboration, we will also use oxygenated silicon wafers of low resistivity as the starting material for the sensors[3]. The pixel readout chips are manufactured with deep sub-micron ($0.25\mu\text{m}$) CMOS technology, an inherently radiation-tolerant process, once enclosed-geometry transistors and appropriate guard ring designs are used [4].

Irradiation tests have been performed up to 0.6×10^{15} 200 MeV protons per cm² on our sensors (about 20 MRad) and up to 2×10^{15} 200 MeV protons per cm² (equivalent to 87 MRad) on our readout chips. These tests show acceptable operation of sensors based on current and capacitance curves vs applied bias voltage in terms of leakage current, required depletion voltage, and breakdown voltage[5]. Fig. 4 shows the dependence of the full depletion voltage on the proton irradiation fluence for a few p-stop sensors made from standard and oxygenated wafers. At a fluence of 4×10^{14} p cm⁻², the full depletion voltage is still rather low, even lower than the value before irradiation. This result, together with the fact that the breakdown voltage is still high compared to the full depletion voltage after irradiation, means

that the BTeV pixel detector can be fully depleted without excessively high bias voltage even after a few years of operation.

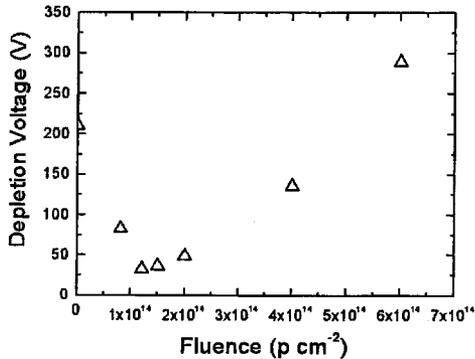


Figure 4. Full depletion voltage as a function of the fluences of the proton irradiation for prototype BTeV pixel sensors.

Our irradiation tests show that heavy radiation dosage does not seriously affect noise, and threshold dispersion[6]. Fig.5 shows the effect of radiation on amplifier noise.

These irradiation results will be augmented with charge collection and other tests in a test beam at the Fermilab Meson Test Beam Facility as soon as it is available. In addition, the measured rates of single event upset are low enough to be handled easily. No evidence of more serious single event effects has been seen[7].

5. Readout Speed

The use of the pixel detector data in the first level trigger means that the BTeV pixel readout chip must be capable of reading out all hit information from every $p\bar{p}$ interaction. Furthermore, the pixel readout chip should be optimized for the 132 ns time between crossings planned for the Tevatron collider.

Our pixel readout is data-driven. That is, the readout occurs as soon as data is ready on the readout chip. The token passing from row to row,

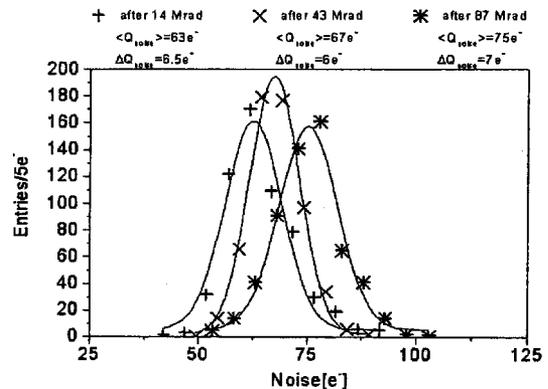


Figure 5. Measured noise in the 576 pixel cells of preFPiX2Tb chip after 14, 43, and 87 Mrad of proton irradiation.

which is an important part of the potential readout speed, is very fast (0.125 ns per row), and this starts in parallel in all columns. The readout rate allows us to move all the data off chip with negligible loss of data, even if the amount of data is three times that projected for our nominal luminosity of $2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$. Data output is serialized, but uses a number of parallel readout paths selectable for each readout chip. The bandwidth of each serial path is 140 Mbps. The chips located closest to the beam are read out using 6 serial paths (840 Mbps total). Other chips are read out using 1, 2, or 4 serial paths. Most of the readout chips in the pixel system require only 1 serial output path. The readout bandwidth summed over the entire pixel detector is approximately 2 Tbps (terabits per second). The data coming off the chip is already highly sparsified, since only pixels above threshold are read out. Sorting out the data and assembling events is done external to the detector in large buffer memories.

6. BTeV Trigger

BTeV will operate at a luminosity of $2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ corresponding to about 2 interactions per 7.6 MHz beam crossing rate, yielding 2×10^{11}

b -pairs/ 10^7 seconds with a b to background event ratio of $\sim 0.5 \times 10^{-3}$. Average event sizes will be ~ 200 KB after zero-suppression of data is performed on-the-fly by front-end detector electronics. Since every beam crossing will be processed, this translates to an extremely high data rate of ~ 1.5 TB/sec from a total of over 20×10^6 data channels.

To handle this high rate, BTeV will employ a three-level hierarchical trigger architecture. Sparisified data from all subsystems will be sent via optical links to L1 buffers. Data from the pixel detector and muon detector will also be sent to the L1 trigger processor. The L1 vertex trigger processor will perform pattern recognition, track, and vertex reconstruction on the pixel data for every interaction. A L1 vertex trigger is generated if there are at least 2 tracks satisfying the following criteria: $p_T^2 \geq 0.25(\text{GeV}/c)^2$, $b/\sigma \geq n$, and $b \leq 2\text{mm}$ where b is the impact parameter, σ is the error in b , and n is a preset value ranging from 4-7.

Our studies indicate that the L1 vertex trigger is able to reject 99% of all minimum-bias events while accepting $\sim 60 - 70\%$ of the B -events that would survive our offline analysis cuts[8].

Results from the L1 vertex trigger are combined with results from an independent Level 1 dimuon trigger based only on the muon system. A Global L1 (GL1) trigger selects the beam crossings that pass a L1 trigger. The dimuon trigger has a rejection factor of 600 and is useful both for calibrating the vertex trigger and for physics. Data that survive the selection criteria in L1 are assigned to a Level 2/3 processor for further analysis. In turn, data that survive Level 2 will be analyzed by Level 3 algorithms that decide whether or not the data should be recorded on archival media.

Level 2 and 3 will be implemented with a cluster of commodity CPU nodes. Level 2 will further reduce the data rate by a factor of ~ 10 . Level 3 will reduce the number of accepted crossings by at least an additional factor of ~ 2 . Furthermore, Level 3 will be able to compress the data for accepted beam crossings by a factor of ~ 4 . We expect the data rate out of Level 3 to be ~ 200 MB/sec.

7. Conclusion

The BTeV pixel detector and trigger systems are the most crucial elements in the BTeV experiment. While they are technically challenging, we have made great progress towards identifying a viable solution for individual components for the pixel detector. The pixel detector mechanical design is progressing rapidly and we hope to have a detailed technical design next year. The L1 vertex trigger has been designed to make use of the information provided by the pixel data. We are currently working on optimizing a high-level version of the vertex trigger algorithm and testing a prototype board for understanding various aspects of the L1 vertex trigger hardware.

REFERENCES

1. G.Y. Drobychev et al., Update to BTeV Proposal, March 2002, P. Kasper, Physics Reach of BTeV, these proceedings.
2. J.A. Appel et al., Performance of prototype BTeV silicon pixel detectors in a high energy pion beam, FERMILAB-Pub-01/229E, to be published in *Nucl. Instrum. Meth. A*.
3. F. Lemeilleur et al., 3rd RD48 Status Report, CERN/LHCC 2000-009.
4. P. Jarron et al., 3rd RD49 Status Report Study of the Radiation Tolerance of ICs for LHC, CERN/LHCC 2000-03 (13 January 2000); D.C. Christian et al., FPIX2: A Radiation-hard Pixel Readout chip for BTeV, FERMILAB-Conf-00/316E.
5. M.R. Coluccia et al., IV and CV curves for irradiated prototype BTeV silicon pixel sensors, FERMILAB-Conf-02/148E.
6. G. Chiodini et al., Radiation tolerance of prototype BTeV pixel detector readout chips, FERMILAB-Conf-02/147E.
7. G. Chiodini et al., Single event effects in the pixel readout chip for BTeV, FERMILAB-Conf-01/369E.
8. M.H.L.S. Wang, BTeV Level 1 Vertex Trigger, FERMILAB-Conf-01/336E.