Overview of the BTeV Pixel Detector

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1 Introduction

BTeV is a new Fermilab beauty and charm experiment designed to operate in the CZero region of the Tevatron collider. Critical to the success of BTeV is its pixel detector. The unique features of this pixel detector include its proximity to the beam, its operation with a beam crossing time of 132 ns, and the need for the detector information to be read out quickly enough to be used for the lowest level trigger. This talk presents an overview of the pixel detector design, giving the motivations for the technical choices made. The status of the current R&D on detector components is also reviewed. Additional Pixel 2002 talks on the BTeV pixel detector are given by Dave Christian[1], Mayling Wong[2], and Sergio Zimmermann[3].

Table 1 gives a selection of pixel detector parameters for the ALICE, ATLAS, BTeV, and CMS experiments. Comparing the progression of this table, which I have been updating for the last several years, has shown a convergence of specifications. Nevertheless, significant differences endure. The BTeV data-driven readout, horizontal and vertical position resolution better than 9 μm withing the $\pm$ 300 mr forward acceptance, and positioning in vacuum and as close as 6 mm from the circulating beams remain unique. These features are driven by the physics goals of the BTeV experiment. Table 2 demonstrates that the vertex trigger performance made possible by these features is requisite for a very large fraction of the B meson decay physics which is so central to the motivation for BTeV. For most of the physics quantities of interest listed in the table, the vertex trigger is essential.

The performance of the BTeV pixel detector may be summarized by looking at particular physics examples; e.g., the B_s meson decay $B_s \rightarrow D_s^- K^+$. For that decay, studies using GEANT3 simulations provide quantitative measures of performance. For example, the separation between the B_s decay point and the primary proton-antiproton interaction can be measured with an rms uncertainty of 138 μm. This, with the uncertainty in the decay vertex position, leads to an uncertainty of the B_s proper decay time of 46 fs. Even if the parameter x_s equals 25 (where the current lower limit on x_s is about 15), the corresponding relevant proper time is 400 fs. So, the detector resolution is more than adequate to make an excellent measurement of this parameter.

2 The BTeV Pixel Detector

The BTeV pixel detector (Fig. 1) sits inside a magnet with a $1.6T$ field. It is split into a right and left half, so that the detector can be moved out of the beam region when the beam collisions are first established and the beams are unstable. Each half of the detector is composed of thirty stations, each station containing a precision x-measuring and a y-measuring plane. The half-planes of a station are mounted on opposite sides of a support and cooling substrate. The two detector halves are L-shaped, and offset from each other along the beam direction so that a beam hole in the middle can be adjusted in size. The nominal hole allows active sensors to be positioned within 6 mm of the circulating beams.

The individual pixel elements are 50 μm by 400 μm, like the ATLAS pixel sensors from which their design derives. The pixel sensor elements are bump-bonded to readout chips which have 22 columns of 128 elements. Several readout chips (from four to eight arranged in a single line) are used to read out each sensor, with each sensor, its readout chips, and an attached flexible circuit corresponding to a sub-assembly module. We call this a multi-chip module. There are a total of nearly 23 million pixels in the full assembly, covering an active area of about 0.5 m^2. In order to minimize the material between the beams and the active pixel elements, the pixel half-detectors sit in vacuum, with only a thin rf shield between them and the beams.

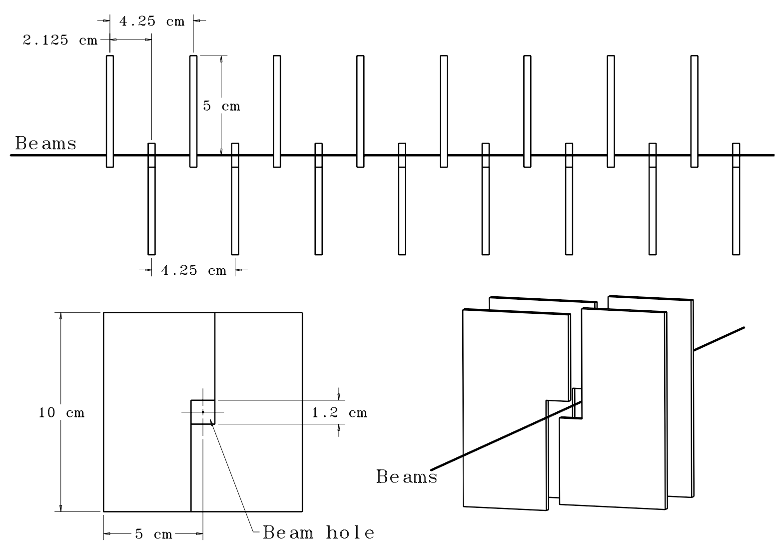

Figure 1: Layout of the BTeV pixel stations/planes.

The detectors themselves are also made thin to minimize the material traversed by the particles from the primary interactions. Table 3 gives the average amount of material in per cent of a radiation length (X_o) per plane seen by a particle at normal incidence. The total is 1.25 % per plane, or 2.5 % per station. The vertexing for the trigger depends on the first three stations traversed by charged particles, a sub-system that corresponds to a total of 7.5 % of a radiation length.

Having the pixel detector so close to the beams results in a very high dose of radiation. The damaging effects of this dose is dominated by the effects of the charged particle flux, approximately 10^7 charged particles per cm^2 per second in the hottest location at the nominal colliding beams luminosity of 2 x $10^{32} cm^{-2}s^{-1}$. For a nominal year of operation, this corresponds to 10^{14} particles per cm^2, a dose as intense as that planned for pixel detectors at the LHC. The BTeV radiation dose falls off quickly as one moves away from the beams, approximately with the radius to the 1.7 to 2.0 power. Thus, many of the sensors will operate with very different damage rates from one end to the other. In the face of this dose rate, BTeV will use $n^+/n/p$ type, low-resistivity silicon. No final decision has yet been made on the isolation of the individual pixel elements, p-stop or p-spray. The detector will be equipped with more than ten guard rings in order to allow the application of 600 volts or more, ensuring complete charge-depletion operation even after ten years of nominal operation. The operating temperature will be near -5^oC to minimize reverse annealing.

The BTeV readout chip is implemented in $0.25\mu m$ technology. All elements of this chip have been prototyped in small versions, and a full-sized chip is being submitted for fabrication. Each pixel cell in the readout chip has a 3-bit FADC using multiple comparators. The data-driven architecture [1] has in-cell sparcification using one settable threshold-control voltage per chip. A fast token-passing system is implemented, with 0.125-ns-per-pixel tokens running down all columns in parallel. This allows rapid readout of all cells above threshold. To get the data off the chip rapidly, a variable number of 140 $Mbit/s$ serial, point-to-point lines are used. For the chips closest to the beams, and therefore with the most data, six such serial lines are used, corresponding to 840 $Mbit/s$. The full bandwidth of the detector is actually 2 $Tbit/s$. This system allows negligible loss of data, even at triple the nominal luminosity.[3]

Each readout chip has a programmable interface, with 14 DACs to control bias currents and thresholds, and a wire-bonded ID. There are "kill" (disable) and inject (test) control bits for each pixel cell. All these configuration controls can be read back from the readout chip. There are four reset levels (2 hardware and 2 software). The readout is point-to-point, with no daisy-chain between chips. Thus, failure of one chip will not deter others from operation. The digital I/O is made via LVDS signals, and travel about 10 meters to "data combiner boards" which sit outside the analysis magnet. These boards receive row and column locations for the hit cells, an 8-bit time stamp, and 3-bit ADC information. They sort and format the data, adding elongated time stamps and chip address information to the data stream.

The readout chip interconnections are made via flexible circuits wire-bonded to the chips. The measured performance of prototypes is very satisfactory, even for the more complicated four-layer circuits fabricated by CERN for our earlier FPIX1 readout chips. A simpler version will suffice for our new readout chips, FPIX2.[3]

Given the good progress on the electronic components of the BTeV pixel system, attention has been focused recently on the very significant mechanical and cooling issues of the detector. The baseline support and cooling design uses a ”fuzzy carbon” on glassy-carbon cooling-tubes design.[4] However, we are also looking at pocofoam[5] and pyrolitic graphite based supports. Signals will be routed from inside the vacuum to the outside via large printed-circuit boards which are sealed at the vacuum periphery. The final vacuum level is achieved using a cryo-panel operating at liquid nitrogen temperatures and providing excellent water pumping. The use of cryo-pumping has been tested on a 5% mock-up of the full system, using quite similar materials to those of the final version.[2]

3 Use of the Pixel Detector in the BTeV Trigger

The pixel detector in BTeV will be used to identify events in which there is likely to be the decay of particles containing heavy quarks. The selection algorithm depends on the short, but finite lifetimes of such particles, and the fact that the particles are produced with large momenta as observed in the laboratory. The decay products from these particles typically will not point back to the primary interaction point. The decay particles will have an impact parameter, b, as shown in Fig. 2. Thus, it is possible to enrich the sample of accepted data by demanding that there are, say, two such decay-particle tracks in recorded beam crossings, each with a significant detachment relative to the resolution (uncertainty) in the detachment measurement.

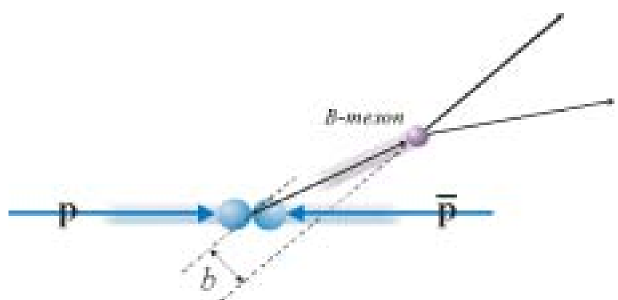

Figure 2: Schematic diagram of tracks used in the BTeV vertexing trigger algorithm.

The trigger system must determine the proton-antiproton interaction point (the primary vertex) event by event since the beams interact over a very long region (30 *cm* rms). However, using the same detector to determine the primary vertex and the track projections relative to that vertex removes the need to have the absolute location of the beam relative to the detector reproducible, or even known in advance. Also, if one chooses only tracks with momenta larger than, say 2.5 GeV/c, multiple scattering of the tracks will not generate large, false impact parameters. One can also demand that the impact parameters be less than, say, 0.2 cm to avoid accepting interactions with decays of much longer-lived particles such as K_s and Λ. The geometry of the pixel detector is also useful in choosing only those decay tracks headed in the direction of the rest of the detector, and therefore is most efficient for interactions with heavy-particle decays which can be well analysed in the rest of the experiment apparatus.

Using the requirements in the above algorithm for interesting interactions, we can test our ability to reject uninteresting data (so-called "minimum bias" beam crossings), and to predict the efficiency of the trigger for events which would be used in a final physics analysis. BTeV has studied these issues for a variety of B decay channels, with two simulation packages: GEANT3 and MCFast. In the first, a full detector simulation is done. In the second, the simulation is parameterized, to take much less computer time to run. Table 4 gives a sample of efficiencies for our current optimized trigger algorithm. It shows that we can achieve a rejection factor of 100 (1% efficiency) for beam crossings without heavy quarks (at Poisson-distributed nominal luminosity) while maintaining an efficiency greater than 50% for beam crossings with at least one all-charged B-decay mode present.

4 Test Beam Results and Other R&D

Measurements of the radiation hardness of the sensor and readout chip prototypes have been very encouraging. These measurements have been done primarily at the Indiana University Cyclotron Facility, using 200 MeV protons, each proton causing similar damage as the nominal 1 MeV neutron. Thus, we speak of our measurements at 14, 43, and 87 $Mrad$. The noise and threshold distributions are little affected (See Fig. 3.), even up to 87 $Mrad$.

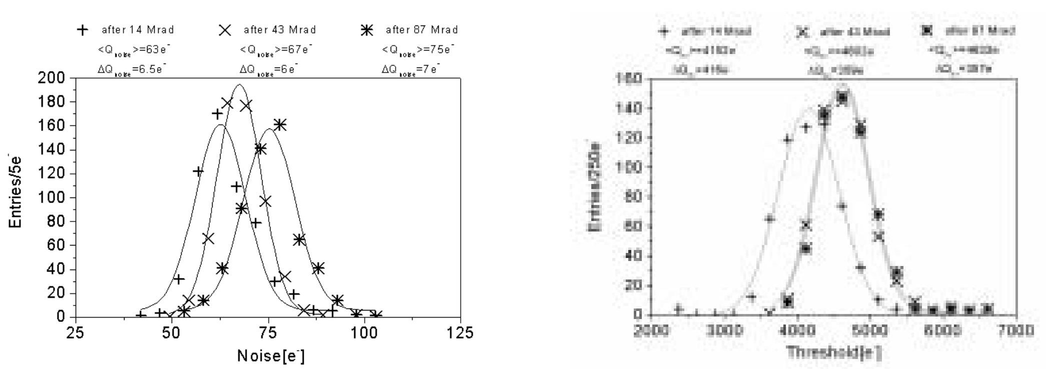

Figure 3: Noise and threshold distributions of BTeV prototype 0.25-μm-technology readout chip after irradiations to 14, 43, and 87 $Mrad$.

A full test beam effort was mounted in 1999, using a 227 GeV/c pion beam at Fermilab.[6] The tests focused on measuring the spatial resolution of a prototype pixel detector as a function of the angle of incidence of the pion, and as functions of such parameters as the sensor bias, readout threshold, and number of bits of ADC obtained for each pixel's signal. The test results agreed well with the predictions of the BTeV pixel detector simulation package. The resolution results, along with simulation predictions, are shown in Fig. 4. The achievable resolution is better than 9 μm at all angles out to 30 degrees. It was these results which led BTeV to select a three-bit ADC for each pixel cell, for example.

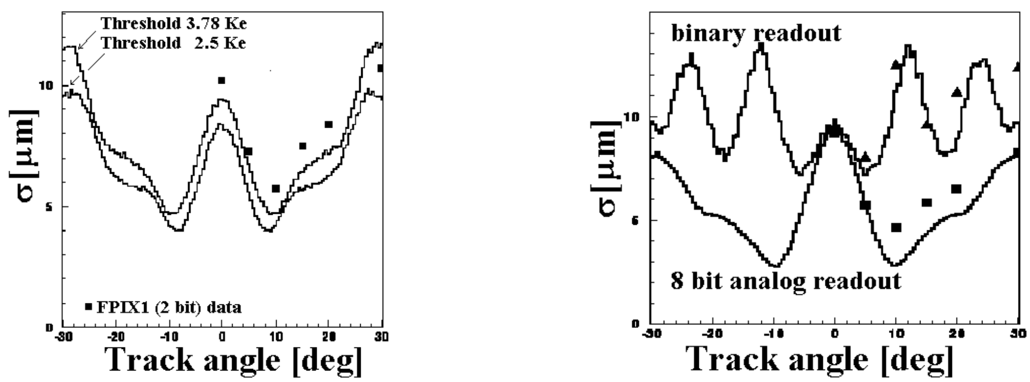

Figure 4: Spatial resolution dependence on particle angle, relative to normal incidence, for two thresholds (right) and number of ADC bits of pulse-height information (left). The curves are from simulations, the points from test-beam data.

In addition to the quantitative results like those above, a high track density test was done by placing a thin carbon target just upstream of a telescope of pixel detectors and looking at events with interactions in the target. Fig. 5 shows such an event, this one with seven tracks well within 1 cm^2. The density of tracks here is an order of magnitude more than expected in the BTeV pixel detector. Nevertheless, it is easy to reconstruct the individual tracks from the information in the pixel detector. This good pattern recognition capability is essential to the on-line trigger.

A new test beam run is scheduled for this autumn. We will use the previous generation of pixel prototypes to define the incident beam trajectories. Studies will focus on charge collection in more recent p-stop and p-spray sensor designs, for both irradiated and non-irradiated detectors. We will also study multi-chip modules; e.g., the charge collection in the region between readout chips and for modules with a large variation of irradiation from one edge to the other.

We are about to submit for fabrication a full-size (22 column by 128 row) FPIX2 readout chip. The readout chips from this submission are planned for use in beam tests and for tests of assemblies of multi-chip modules and larger system efforts of the future. Additional work is planned on substrate options, using the cryo-pump

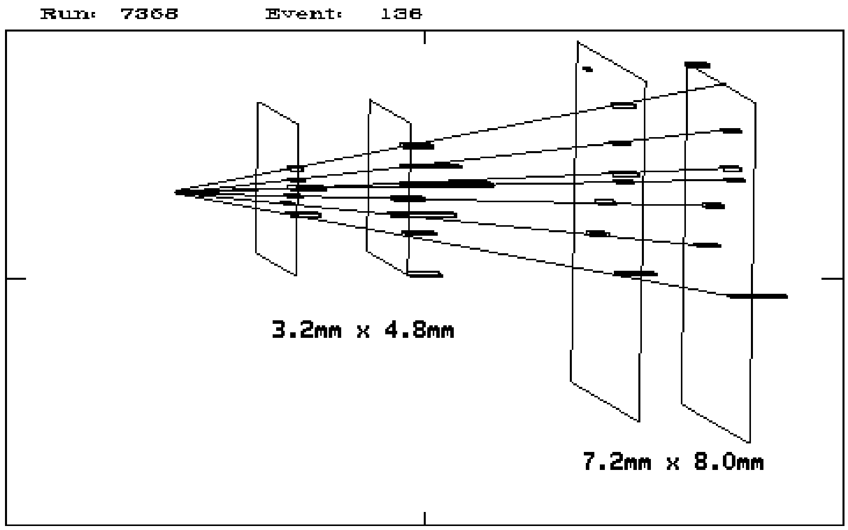

Figure 5: Multi-particle production in a carbon target just, upstream of a small pixel detector telescope in the BTeV test beam studies of 1999.

reservoir to cool the detectors to their -5^o C operating temperature, rf shielding techniques involving screens and wires in place of the aluminum shield planned so far, and simulation effort to better understand charge collection in p-stop and p-spray sensors. We anticipate making a final choice of sensor type during the coming year, as well as moving toward a test of a system on the scale of 10% of the full BTeV pixel detector.

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References

[1] D.C. Christian, presentation given at the *Pixel 2002* conference, in these proceedings.

[2] M.L. Wong, presentation given at the *Pixel 2002* conference, in these proceedings.

[3] S. Zimmermann, presentation given at the *Pixel 2002* conference, in these proceedings.

[4] Tim Knowles, Energy Science Laboratories, Incorporated, San Diego, CA 92121.

[5] PocoFoam^{TM} Products Group, Poco Graphite, Inc., Decatur, Texas 76234 and Mer Corp., Tucson, Arizona 85706.

[6] J. A. Appel *et al.*, "Performance of prototype BTeV silicon pixel detectors in a high energy pion beam," Nucl. Instrum. Meth. A **485**, 411 (2002) [arXiv:hep-ex/0108014].

Experiment Property	ALICE Pb-Pb Collider	ATLAS $p-p$ Collider	BTeV $p-\overline{p}$ Collider	CMS $p-p$ Collider
Pixel Size	50 x 425 $(\mu m)^2$	50 x 300/400 $(\mu m)^2$	50 x 400 $(\mu m)^2$	150 x 150 $(\mu m)^2$
Size of Largest Subassembly	1.7 x 7.1 $(cm)^2$	1.6 x 6.1 $(cm)^2$	0.9 x 7.6 $(cm)^2$	1.7 x 6.6 $(cm)^2$
Min.dist. to beam	41 mm	50 mm (B) 98 mm	6 mm	41 mm, barr. 60 mm, disk
Number of Pixels	$\sim 10x10^6$	$80x10^6$	$23x10^6$	$35x10^6$
Total Active Area	$0.26m^2$	$1.5m^2$	$0.5m^2$	$\sim 0.8m^2$
Material Xo per plane	$\sim 1\%$	1.80% (B) 1.62%	1.25%	1.65% 2.3%
Special Features	90 tracks/$(cm)^2$	4-bit TOT ADC	Level 1 Trig. 3-bit FADC	4 T Field

Table 1: Specifications of future pixel detectors.

Physics Quantity	Decay Mode	Vertex Trigger	K/π Sep.	γ det.	Decay time σ
$sin(2\alpha)$	$B^o \to \rho\pi \to \pi^+\pi^-\pi^o$	X	X	X	
$sin(2\alpha)$	$B^o \to \pi^+\pi^-, B_s \to K^+K^-$	X	X		X
$cos(2\alpha)$	$B^o \to \rho\pi \to \pi^+\pi^-\pi^o$	X	X	X	
sign($sin(2\alpha)$)	$B^o \to \rho\pi$ and $B^o \to \pi^+\pi^-$	X	X	X	
$sin(2\beta)$	$B^o \to J/\psi K_s$				
$cos(2\beta)$	$B^o \to J/\psi K^*$ and $B_s \to J/\psi\phi$		X		
$sin(\gamma)$	$B_s \to D_s^- K^+$	X	X		X
$sin(\gamma)$	$B^- \to D^o K^-$	X	X		
$sin(\gamma)$	$B \to K\pi$	X	X	X	
$sin(2\chi)$	$B_s \to J/\psi\eta', J/\psi\eta$		X	X	X
x_s	$B_s \to D_s^+\pi^-$	X	X		X
$\Delta\Gamma$ for B_s	$B_s \to J/\psi\eta, K^+K^-, D_s^+\pi^-$	X	X	X	X

Table 2: A range of physics parameters to be measured by BTeV, most requiring precision tracking near the beam and vertex triggering.

Item	Thickness, X per plane (μ)	X_o (mm)	Coverage	X/X_o per plane (%)
Sensor	250	93.6	1.46	0.39
Readout Chip	200	93.6	1.47	0.31
Bump and Wire Bonds	20	10.0	0.02	0.004
HDI and Components				0.19
Adhesive				0.02
Substrate and Cooling	675			0.17
rf Shielding (Al)	150	89.0	1.00	0.16
TOTAL				1.25

Table 3: Estimated material in the BTeV pixel detector. X_o is the radiation length of the relevant material. Coverage refers to the fractional coverage of the active area by each material. Fractions greater than one account for overlaps of sensors and readout chips.

Process	Efficiency (%)	Monte Carlo
Minimum Bias	1	BTeV GEANT
$B_s \to D_s^- \ K^+$	74	BTeV GEANT
$B^o \to D^{*+}\rho^-$	64	BTeV GEANT
$B^o \to \rho^o\pi^o$	56	BTeV GEANT
$B^o \to J\psi K_s$	50	BTeV GEANT
$B_s \to J\psi K^{*o}$	68	MCFast
$B^- \to D^o K^-$	70	MCFast
$B^- \to K_s\pi^-$	27	MCFast
$B^o \to$ 2-body $(\pi\pi, K\pi, KK)$	63	MCFast

Table 4: Level 1 trigger efficiencies.