BTeV
Pixel Detector and Silicon Forward Tracker

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OUTLINE

- BTeV Overview
- Technical Design
- R&D Status
- Conclusion
What is BTeV?

At the Tevatron $p\bar{p}$ collider, at Fermilab:

- Forward spectrometer.
- Beauty and charm physics:
  - Measure: CP violation, mixing
  - Search for rare and forbidden phenomena.
  - Precision measurements on SM parameters
  - Exhaustive search for physics beyond SM

BTeV is a part of broad program to address fundamental questions in flavor physics.

Details at: http://www-btev.fnal.gov
### BTeV Physics Requirements

A range of physics, most requiring precision tracking near the beam and vertex triggering; e.g., in B decays.

<table>
<thead>
<tr>
<th>Physics Quantity</th>
<th>Decay Mode</th>
<th>Vertex Trigger</th>
<th>K/π sep</th>
<th>γ det</th>
<th>Decay time σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>sin(2α)</td>
<td>$B^0 \to \rho \pi \to \pi^+\pi^-\pi^0$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
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<tr>
<td>sin(2α)</td>
<td>$B^0 \to \pi^+\pi^- \land B_s \to K^+K^-$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>cos(2α)</td>
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<td>✓</td>
<td>✓</td>
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<tr>
<td>sign(sin(2α))</td>
<td>$B^0 \to \rho \pi \land B^0 \to \pi^+\pi^-$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>sin(γ)</td>
<td>$B_s \to D_s K^-$</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>sin(γ)</td>
<td>$B^0 \to D^0 K^-$</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>sin(γ)</td>
<td>$B \to K \pi$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>sin(2χ)</td>
<td>$B_s \to J/\psi\eta', J/\psi\eta$</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>sin(2β)</td>
<td>$B^0 \to J/\psi K_s$</td>
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<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>cos(2β)</td>
<td>$B^0 \to J/\psi K^* \land B_s \to J/\psi\phi$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>$x_s$</td>
<td>$B_s \to D_s \pi^-$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>$\Delta\Gamma$ for $B_s$</td>
<td>$B_s \to J/\psi\eta', K^+K^-, D_s\pi^-$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
Key Features of BTeV

- Precision vertex detector based on fast, rad-hard pixel arrays placed near beam
- High efficiency Level 1 detached vertex trigger using pixel information
- Excellent particle ID including photon and $p_0$ detection
- Fast, high capacity DAQ
BTeV Tracking System

- **Coverage:**
  - Aperture 300 mr
  - Momentum acceptance 1- >100 GeV/c
- **Spatial resolution for vertex detector:**
  - Better than 9 µm
- **Angular resolution:**
  - Better than 0.1 mr
- **Momentum resolution:**
  - 1% at 100 GeV/c
- **Can handle huge data rate and survive high radiation dosage**

- **Two Tracking Systems**
  - **Pixel Vertex Detector**
    - Precise vertex detection and crude momentum measurement capability
    - Fast info available for use in L1 vertex trigger
  - **Forward Tracker**
    - Precise momentum measurement, Ks/Λ detection, project tracks into RICH, EMCAL, Muon chambers
    - Combination of Silicon strips near the beam and Straw Chambers at large radius
Pixel Vertex Detector

Reasons for Pixel Detector:
• Superior signal to noise
• Radiation Hard
• Excellent spatial resolution: 5-10 microns depending on angle, etc
• Pattern recognition power
• Very low occupancy

Special features:
• Info used directly in the L1 trigger.
• Pulse height is measured on every channel with a 3 bit FADC.
• It is inside a dipole and gives a crude standalone momentum measurement.
• Sitting close to beam and in vacuum
• 30 stations and 23 million pixels in total
Pixel Detector

- Pixel Sensor bump-bonded to Readout chip
- Fine segmentation
  - Large number of channels
  - Electronics in the active tracking volume
  - High power density
  - Material budget
- Basic building block – Multichip Module (MCM)
  - Large amount of data
  - Large number of HDI and cables
- Assemble modules on substrate to form pixel half station
## BTeV Pixel Vertex Detector Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pixel Size</strong></td>
<td>50 x 400 µm²</td>
</tr>
<tr>
<td><strong>Outer plane dimension</strong></td>
<td>10 cm x 10 cm</td>
</tr>
<tr>
<td><strong>Central square hole (adjustable)</strong></td>
<td>Nominal setting: 12mm x 12mm</td>
</tr>
<tr>
<td><strong>Total number of planes</strong></td>
<td>60</td>
</tr>
<tr>
<td><strong>Total number of stations</strong></td>
<td>30</td>
</tr>
<tr>
<td><strong>Total number of pixels</strong></td>
<td>23 million</td>
</tr>
<tr>
<td><strong>Total Silicon active area</strong></td>
<td>0.5 m²</td>
</tr>
<tr>
<td><strong>Separation of stations</strong></td>
<td>4.25 cm</td>
</tr>
<tr>
<td><strong>Pixel plane orientations (per station)</strong></td>
<td>One with narrow pixel dimension vertical and the other with narrow dimension horizontal</td>
</tr>
</tbody>
</table>
Pixel stations mounted by brackets to C-fiber support
Readout Chip → High Density Interconnect (HDI) → Flex cables → Feedthrough Board → 10 m twisted pair → Pixel Data Combiner Board (PDCB) → Trigger processor
Detector assembled in 2 halves
Each half moves horizontally (by actuators)
Detector placed inside vacuum vessel
Detector shielded from beams by thin Al rf foil
Signal fed through via PCB (feedthrough boards)
Physics Performance of Pixel Detector

An example: \( B_s \rightarrow D_s \ K^+ \)

Primary-secondary vertex separation

Distribution in \( L/\sigma \) of Reconstructed \( B_s \)

\[ \sigma = 138 \mu \]

Mean = 44

BTeV Geant3 simulation

Note \( x_s = 25 \rightarrow 400 \) fsec mixing period

\[ \tau_{\text{proper (reconstructed)}} - \tau_{\text{proper (generated)}} \]

\[ \sigma = 46 \) fsec
Forward Silicon Tracker

Major Requirements

- **Material Budget**
  - $< 0.5\% \ X_0$ (averaged over a 30 cm radius circle around the beam pipe)

- **Noise hit rate**
  - $< 10^{-4}$ per strip per BC

- **Read out bandwidth**
  - Fast & data-driven (no trigger available)

- **Radiation Tolerance**
  - From ~1 Mrad up to ~5 Mrad (10 years)
Radiation Dose in Forward Si Tracker

- Max. fluence expected: $1.6 \times 10^{13}$ particles/cm$^2$/yr at $L = 2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$
- Radiation level decreases rapidly with increasing distance away from beam
- Possible to use p+ on n sensors; benefit from experience of LHC RD – HV operation using multiple guard rings
Baseline Silicon Tracker Design

- 7 stations
  - 3 in dipole fringe field
  - 3 before RICH
  - 1 after RICH
- Coverage from beam pipe to ±13.5cm from the beam
- Each station has 3 planes of 300 µm thick SMD with 100 µm pitch
- Each detector is 7x7 cm²
## Forward Silicon Tracker

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensors</td>
<td>~ 7 x 7 cm(^2) p-on-n type</td>
</tr>
<tr>
<td>Pitch</td>
<td>100 (\mu)m</td>
</tr>
<tr>
<td>Thickness</td>
<td>300 (\mu)m</td>
</tr>
<tr>
<td>Sensor configuration</td>
<td>4 ladders of 4 sensors</td>
</tr>
<tr>
<td>Coverage</td>
<td>27 x 27 cm(^2)</td>
</tr>
<tr>
<td>Central Hole</td>
<td>5.4 x 5.4 cm(^2) (7 x 7 cm(^2) in last station)</td>
</tr>
<tr>
<td>Total stations</td>
<td>7</td>
</tr>
<tr>
<td>Z positions (cm)</td>
<td>99, 142, 200, 292, 336, 386, 729</td>
</tr>
<tr>
<td>Views per station</td>
<td>3 (X, U, V)</td>
</tr>
<tr>
<td>Readout</td>
<td>Sparsified binary</td>
</tr>
<tr>
<td>Total active area</td>
<td>~ 1.5 m(^2)</td>
</tr>
<tr>
<td>Channels per station</td>
<td>~ 5600</td>
</tr>
<tr>
<td>Total channels</td>
<td>~ 127600</td>
</tr>
</tbody>
</table>
Mechanical Support & Cooling

- Light weight carbon frame holding the 4 ladders forming the plane
- Opening along a diameter allow wrapping around beam pipe
- Cooling ducts on backside
Forward Silicon Strip Tracker: crucial to cover the small angle region near the beam. The straw detector could not cope with the high occupancy. Based on three views with 100µm Strips. 3 views can be stacked to form a station. Reference pins guarantee a very precise relative alignment.
R&D Status: Features of BTeV Pixel Detector

• Data driven readout, for use of the pixel detector in at first (lowest) level detached vertex trigger

• High radiation dosage – radiation hard components

• Large output bandwidth needed (~ 30 GB/s on average)

• Better than 9 μm spatial resolution within 300 mrad $\theta_x$, $\theta_y$

• Situated in vacuum, within 6 mm of beams

• Designed for 132 nsec crossing times
BTeV Radiation Background
(L=2\cdot10^{32} \text{ cm}^{-2} \text{ s}^{-1}), \text{ charged hadrons}
Pixels, \ Z = (55 – 60) \text{ cm}
Pixel Readout Chip

- RD effort started in 1997
  - Tailored towards requirement of Tevatron (132ns BCO) and
  - Fast data-driven readout and large bandwidth to get all hit info to trigger (BTeV)

- Two generations of prototype chips (FPIX0 & FPIX1) have been designed and tested, without and with sensors including in a test beam (1999)

- Move to DSM with radiation tolerant design in 1999; 3 test chips have been designed and tested (incl. Irradiation up to $2 \times 10^{15}$ p/cm$^2$). Each with increasing complexity.

- Full-sized FPIX2 submitted last week. All function blocks have been designed and tested.
Radiation Hardness of RO Chip

Measurements at 14, 43, and 87 Mrad by 200 MeV p’s

Noise Distribution

Threshold Distribution
Readout: Pre-FPIX2 LVDS Drivers

- Good quality of the 140Mbit/s eye-pattern of Pre-FPIX2 LVDS drivers.
- 50 foot ribbon cable.

<table>
<thead>
<tr>
<th></th>
<th>Chip 1</th>
<th>Chip 2</th>
<th>Chip 3</th>
<th>Chip 4</th>
<th>Chip 5</th>
<th>Chip 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hits (approx.)</td>
<td>6400</td>
<td>4250</td>
<td>1700</td>
<td>800</td>
<td>450</td>
<td>350</td>
</tr>
<tr>
<td># Serializers</td>
<td>6</td>
<td>6</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Efficiency @ nom.\text{L}</td>
<td>99.7%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Efficienct @ 3\times nom.\text{L}</td>
<td>98.0%</td>
<td>99.6%</td>
<td>99.6%</td>
<td>99.9%</td>
<td>100%</td>
<td>99.7%</td>
</tr>
</tbody>
</table>
Sensor Technology

• $n^+/n/p^+$ configuration that allows the sensors to operate partially depleted after type inversion
• Sensor thickness: 250 $\mu$m
• Low resistivity material: 1.0-1.5 $\Omega$ cm
• Investigations:
  – P-STOP and P-SPRAY electrode isolation techniques
  – Oxygenated vs non-oxygenated wafers
  – Various guard ring configurations
Irradiation Tests

We irradiated p-stop and p-spray sensors

- More tests are planned for the new BTeV TESLA p-spray (low res).
- We can see that, as expected, the type inversion occurs at lower dose for the high-resistivity p-spray (ATLAS) than for the low resistivity p-stop sensors.
BTeV TESLA p-spray sensors

15 oxygenated wafers delivered in July
Acceptance Criteria:
Breakdown Voltage > 300V
Leakage current : < 50 nA/cm$^2$
Vacuum System

- Internal Mechanical Design review identified this as a major concern

- 5% model built
  - 6 substrates with dummy modules and cables (10% of total)
  - “Cables” clamped to aluminum plate
  - 5% of total surface area

- Cooling Al panel to $-160^\circ\text{C}$ resulted in vacuum pressure $\sim 10^{-9}$ torr (regardless of substrate temperature)

- Cryopanel allows detector to reside in single vacuum chamber

- Additional pumping by turbo-pumps
1999 Test Beam Results

Pixel Resolution

- FPIX0 p-stop (8 bit)
- FPIX0 p-spray (8 bit)
- FPIX1 p-stop (2 bit)
- (-) Used in Monte Carlo

Run: 7358  Event: 136
R&D efforts

- Beam test
  - Study charge collection of p-stop and p-spray detectors before and after irradiation
  - Study operation of multichip module, including study of non-uniformly irradiated modules
- Large scale module assembly and testing
- Prototype substrates including testing the idea of using cryo-pumping cooling for detector cooling
- Study of EMI effects and rf shielding
- Aim at a 10% test of final system
Silicon Tracker R&D

- Study detectors developed from CMS which has $V_{bd}$ around 800V
- Identical setup in Milano and Tennesse using test stations from IDE to characterize the sensors
- Study performance of long strips assembled in daisy chain configuration
- Will soon test 6x11cm$^2$ sensors of 300 µm thick from Hamamatsu for CMS and study performance after uneven irradiation
Silicon Strip Readout Chip

- Require large readout bandwidth
- Long strip means large input capacitance (20pF)
- FE basic scheme designed by Pavia group
- Target technology: 0.25 µm CMOS
- Recently Fermilab ASIC group has joined the effort
- First submission early next year
- Shared the same readout architecture with pixel readout
- HDI will be developed by CD/ESE engineers
Conclusion

The BTeV Silicon tracking system has two elements: **Pixel vertex detector and forward silicon tracker.**

For both systems:

- **Baseline technical design exists**
- **Good progress has been made in the R&D activities**
- **A core team of people (physicists and engineers)**
- **Prepare Technical Design Report**