Time-of-Flight at CDF

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History

• An experimental TOF system installed in CDF at the end of Run-I:
  – Covered only 5% of the acceptance
  – Demonstrated feasibility
  – Identified potential problems

• Contributions to Run-II TOF system from several institutes:
  – Cantabria, FNAL, INFN, Korea, LBL, MIT, Penn, Tsukuba
Tracking chambers only detect stable, charged particles: $e^\pm, \mu^\pm, \pi^\pm, K^\pm, p/\bar{p}$

- $P_T$ measured by curvature in B field
- Extra information needed for particle ID:
  - Ionization of material
  - Cherenkov techniques
  - Time-of-Flight
  - Shower shapes
  - Transition radiation

These measure $\beta$ e/h separation
How well we can measure $\Delta t$ determines how well we can distinguish between the two particles.

$\Delta t = d \left( \frac{1}{v_1} - \frac{1}{v_2} \right)$

$t_1 = \frac{d}{v_1}$

$t_2 = \frac{d}{v_2}$
• Achievable resolution is of order 100 ps.
Measuring TOF

• Important issues:
  – Precision: K/π separation or cosmic veto?
  – Detector technology:
    • Scintillator + PMT
    • Resistive plate chambers
  – Segmentation: occupancy vs channel count
  – Cost per channel
Detecting charged particles

- Charged particles lose energy in material:

\[-\frac{dE}{dx} = K z^2 Z \frac{1}{A \beta^2} \left[ \frac{1}{2} \log \frac{2m_e c^2 \beta^2 \gamma^2 T_{\text{max}}}{I^2} - \beta^2 \right] \]

- Example:

1 MIP = 2 MeV/cm
Plastic Scintillator

- Ionization $\rightarrow$ excited molecular states

- $\pi$ electrons are loosely bound
- Ionization excites the $S_0$ electrons
- Light emitted when de-excitation occurs
- Emission spectra shifted to lower energies
- Absorption and emission spectra do not overlap $\rightarrow$ emitted light is not re-absorbed.
Properties of Plastic Scintillator

• Typical figures of merit:
  – Light yield (% compared with anthracene)
  – Emission spectrum
  – Bulk attenuation length
  – Rise time, decay times (short, long)
    \[ f(t) = \left(1 - e^{-t/\tau_r}\right)e^{-t/\tau_f} \]

• Bicron-408:
  – \( \tau_r = 0.9 \text{ ns}, \tau_f = 2.1 \text{ ns} \)
  – Bulk attenuation length, \( \lambda = 380 \text{ cm} \)
Examples from Bicron

Sci Emission Spectra

Lig  
Ris  
De  
Pu  
Wc  
Lig  
Bu  

At

Nc  
Nc  
Ra  
Nc

*Thienophen
Photomultiplier Tubes

- **Books** from vendors are fun to read:
Photomultiplier Tubes

- Typical dynode structure:
  - This kind won't work in a magnetic field.
  - Mesh dynode structure:
    - This kind will work in a magnetic field.
Photomultiplier Tubes

- **Window material:**
  - Borosilicate glass: transmits blue (not UV)

- **Photocathode:**
  - Bialkali metal (Sb-Rb-Cs): low work function
  - Also important: low dark current

- **Dynodes:**
  - Metal with secondary emissive material
    - Good (relatively inexpensive): Be-CuO-Cs
    - Better (more expensive): GaP: Cs
Quantum efficiency: 20% at 390 nm

Gain: $\mu = \alpha \cdot \delta_1 \cdot \delta_2 \cdots \delta_n$

$\delta_i = aE^k \sim 1 - 2$

With $n=19$, $\mu \sim 10^7$ at 2 kV and no B field

Gain greatly reduced in a magnetic field
Mesh PMT’s in Magnetic Fields

- Gain is reduced by $O(500)$, but not to zero

- Large tube-to-tube variation

![Graph showing relative anode output in magnetic fields with a peak at 1.4 Tesla]
Preamp for PMT

- We added a preamplifier with a gain of 15
- Differential output driver
- Gain switches to ~2 for big pulses
Photomultiplier tube properties

- Timing characteristics:
  - Pulse shape: Gaussian, few ns risetime
  - Transit time: ~ 15 ns
  - Transit time spread: ~ 300 ps

Timing resolution is roughly \( \frac{TTS}{\sqrt{n}} \)

That’s why we want \( n \) to be large.
Photomultiplier tube properties

Gain

$\Delta$ Transit time

Pulse rise time

Pulse width
• Scintillator dimensions is about 2x2 cm
• Sensitive area of photocathode is 27 mm
• Optical couplings made using glue or silicone pads
The CDF-II TOF System

Look for it here...
The CDF-II TOF System

The PMT goes in here.
Front-end Electronics

• Requirements:
  – Measure arrival time of pulse from PMT
  – Measure pulse height (or charge)
  – Do it every 132 ns (whimsical requirement)
  – Precision should be < 25 ps

• Limitations:
  – Only measures time of first pulse
  – Light from multiple pulses overlap (biases Q)
Front-end Electronics

- Fast components go to discriminator.
- Slow components used to measure charge.
Measuring Time

• Time measured using TAC with respect to a common stop signal:

Voltage proportional to time difference between START and STOP
Interface with ADMEM

- Use ADMEM boards to read out TOF:
  - CAFÉ cards measure charge
  - deCAF cards measure time (output of TAC)

9 channels
Typical Response

- Response of PMT from cosmic rays: 132 ns
Pulse Properties

• Pulse shape is a complicated mixture of:
  – Scintillation process
  – Light transport in the scintillator
  – Optics of PMT coupling
  – PMT response
  – Shaping from base
  – Preamplifier
  – Cables
  – Receiver and discriminator
Things we can’t measure directly

• Absolute gain:
  – Need calibrated light source (we do have a laser…)
  – Need magnetic field
  – Systematics from electronics (preamp, $Q_{\text{anode}} \rightarrow \text{ADC}$?)
  – Probably averages around $3 \times 10^4$

• Number of photons:
  – Don’t know PMT properties well enough
  – Don’t know the gain precisely
  – Systematics from electronics
  – Probably end up with few 100 p.e.

• Most effects are parameterized by the empirical model used for calibration.
Simulated pulses

- We can’t probe the electronics on CDF to see what the pulses really look like.
- Simulations can provide a qualitative description of most effects.
Simulated pulses

- Compare pulse shapes at east/west ends:

\[ z = -125.0 \text{ cm} \]

Attenuated far pulse

![Graph showing pulse shapes](image-url)
Timing Resolution

- Stated goal was “100 ps”.
- Actual model is:

\[ \sigma_t = \sigma_0 + \rho d \]

\[ \sim (100 \text{ ps}) + (0.4 \text{ ps/cm})d \]

- Resolutions measured after calibrations:

\[ \langle \sigma_t \rangle \sim (100 \text{ ps}) + (0.5 \text{ ps/cm})d \]

- Not the complete story, see next talk by Stephanie…
Summary

• Typical TOF detector
  – BC-408 scintillator
  – Mesh PMT’s
  – Properties poorly controlled – each channel is different

• Unique features
  – Hadron collider environment
  – Small bar cross section: not much light output

• DAQ interface
  – Looks like one of the calorimeters

• Performance
  – Generally meets timing precision requirements…