Performance and Operation of the CsI(Tl) Crystal Calorimeter of the BaBar Detector

Calor 08
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The PEP–II $B$–Factory at SLAC

- Asymmetric $e^+e^-$ collider
  - 9 GeV $e^-$, 3.1 GeV $e^+ \Rightarrow 10.58$ GeV CM energy
  - $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$
  - Peak Luminosity: $12 \times 10^{33}$ cm$^{-2}$ s$^{-1}$ (April 2008)
  - Data taking period ended in April 2008
  - Total Luminosity recorded: 531.4 fb$^{-1}$
BaBar physics program: mainly $B$ physics, also $\tau$ and charm physics, and rare decay searches with high Luminosity.

Calorimeter main goal is the reconstruction of:
- Electrons
  - $J/\psi$ meson reconstruction for $\sin(2\beta)$: $B^0 \rightarrow J/\psi K_s (J/\psi \rightarrow e^+ e^-)$
  - For $B$ flavor tagging
- Photons from $\pi^0/\eta$ and radiative decays
Calorimeter Design

- 6580 CsI(Tl) Crystals
- **Barrel**: 48 $\theta$ rings
  - 120 crystals/ring
- **Endcap**: 8 $\theta$ rings
  - 80/100/120 per ring
- 90% coverage in CM frame
- 14 mrad non–projectivity in $\theta$
  - Fully covers Barrel/Endcap gap

- **Barrel**:
  - 280 Carbon Fiber modules
    - 7 along $\theta$ / 40 along $\phi$
    - 21 crystals / module
    - 7 crystals in $\theta$ / 3 crystals in $\phi$

- **Endcap**:
  - 20 Carbon Fiber modules
    - 8 crystals in $\theta$ / 4,5,6 in $\phi$
  - 300 $\mu$m thick Carbon Fiber tube walls to hold crystals
CsI(Tl) Crystals

- 0.1% Thallium doping
- Trapezoidal shape
- Length:
  - 16.0 $X_0$ (bwd) and 17.5 $X_0$ (fwd)
- Tyvek wrapping for reflection (2x 165µm)
- Al foil and Mylar wrapping for electrical isolation
- 2 PIN Si photodiodes (2x1 cm$^2$)
  - Epoxied to 2x2 cm$^2$ polystyrene plate at crystal rear
- 2 preamps in readout box above crystal

NIM article

Readout Electronics

Data Readout Chain

- 2 fold redundancy
- x1, x32 amplification
- 13 bit dynamic range

- x4, x256 amplification
- Choose best range diode
- 10 bit ADC, 2 bit range
- Data sent via optical fiber

- Untriggered Readout
- FEX and Filtering
- Correct for pedestal gain
- Convert to full E range
- Copy to trigger
- If accepted, read E and t
Calorimeter Performance

- Energy Resolution:
  \[ \frac{\sigma_E}{E} = \frac{\sigma_1}{4\sqrt{E}} \oplus \sigma_2 \]
  
  \[ \sigma_1 = (2.30 \pm 0.03 \pm 0.3)\% \]
  \[ \sigma_2 = (1.35 \pm 0.08 \pm 0.2)\% \]

- Angular Resolution:
  \[ \sigma(\theta) = \frac{\sigma_1}{\sqrt{E}} \oplus \sigma_2 \]
  
  \[ \sigma_1 = (4.16 \pm 0.04) \text{ mrad} \]
  \[ \sigma_2 = (0.00 \pm 0.00) \text{ mrad} \]
π^0 and η Response

- 2 photon invariant mass plots for hadronic events
  - E_γ > 30 MeV
  - E_π^0 > 300 MeV

π^0 mass = 134.9 MeV
π^0 width = 6.5 MeV

η-mass = 547.0 MeV
η-width = 15.5 MeV
Calibrations

- **Electronics Calibrations**
  - Linearize response of on-detector electronics by charge injection to preamp inputs
    - Determines pedestals and overall gain
    - Corrects for cross talk between crystals
  - Performed during beam down times and after hardware replacement:
    - ~2/month and requires ~1hr. with no beam.

- **Single crystal calibrations**
  - Light yields and crystal uniformities change through radiation damage
  - Radioactive Source $\Rightarrow$ Low energy crystal response
  - Bhabha $\Rightarrow$ High energy crystal response
  - Lightpulser

- **Cluster energy calibrations**
  - Relate $E_{\text{cluster}}$ to energy of incident $e^\pm/\gamma$
  - Deposited $E$ depends on leakage that is a function of $(\theta, \phi)$ and the detector material
  - $\pi^0 \rightarrow \gamma\gamma \Rightarrow 70 \text{ MeV} < E_{\gamma} < 2 \text{ GeV}$
  - $e^+e^- \rightarrow \mu^+\mu^-\gamma \Rightarrow 400 \text{ MeV} < E_{\gamma} < 6 \text{ GeV}$
  - See Jörg Marks’ talk for details on the cluster calibrations
Bhabha Calibration

- Used for single crystal calibration at high energies: 3–9 GeV (~ monthly)
  - Deposited cluster energy is constrained to equal prediction of GEANT based MC
- Solve linear equations so that $c_i$ minimizes:

$$\chi^2 = \sum_k \frac{\left( \sum_i (c_i E_i^k) - E_{dep}^k \right)^2}{\sigma^k}$$

$i$ – crystal index, $k$ – cluster index
$c_i$ – calibration constant
$E_i^k$ – raw energy in crystal $i$
$E_{dep}^k$ – deposited cluster energy from MC
$\sigma^k$ – error
Radioactive Source Calibration

- Radioactive source used to set the low energy response for each crystal
  - n irradiated Fluorinert circulates through piping at front face of crystals
  - 6.13 MeV photon from $^{19}$F+n $\rightarrow$ $^{16}$N+α, $^{16}$N $\rightarrow$ β+$^{16}$O$^*$ $\rightarrow$ $^{16}$O + γ
  - $^{16}$N: $\tau_{1/2}$ ~ 7s
- 15–30 minute runs taken every 4±1 weeks with no beam in machine
- Resolution of constants: 0.33 %
- 2 failed generators over 10 year data taking period 2003, 2007 (red arrows)
Lightpulser Monitoring

- Daily lightpulser calibrations cover complete readout path from diodes to DAQ system
  - Time required for calibration: ~few minutes
- Xe lamp spectrum matched to emission freq. of CsI(Tl) scintillation
  - Allows monitoring of relative change in crystal response between calibrations
  - Also for diagnostics on electronics read out
Radiation Monitoring

- Radiation induced optical losses produce non uniform change in light yield along crystal length which degrade energy resolution.
- 116 p–channel MOSFET transistors arranged at the front face of crystals
  - **Barrel**: 56 / **Endcap**: 60 RadFETs
- Map integrated dose absorbed by different regions of calorimeter.
  - Radiative Bhabhas
  - Scattered beam particles interactions with residual gas in vacuum chamber
    - $E \sim$few MeV
Hardware Monitoring

- Hardware is monitored in real time using EPICS
- Monitoring takes place for 100’s of parameters
  - Temperature of electronics and crystals
  - I/V of electronics power supplies
  - Temperature and flow rates of chillers
- Readings archived in database
- Alarms are immediately passed to shifters and EMC On–Call Expert
  - Depending on severity, problems can be remedied within minutes

Barrel Crystal Temperatures
Temperature regulation needed to maintain integrity of crystal ↔ diode glue joints and LY of crystals. (~20±1°C)

Electronics and Crystal Cooling maintained by a set of chillers
- 3 independent Fluorinert chillers: 1 barrel, 1 endcap, and 1 spare that can be switched on to either barrel/endcap circuit or both
- Deionized Water chiller for barrel on–detector electronics
- Backup chiller system (BCS) can replace both water and Flourinert chillers in emergencies
Data Monitoring–1

- Live Data Monitoring
  - During data taking human checks made ~15 min.
  - Checks are made on occupancies, energy–time structure, energy/multiplicity profiles
  - Automated comparisons made between previous runs
  - 3 permanently dead crystals and typically 6–12 total masked/dead channels
  - Hardware intervention required for >70 crystals dead/masked out
Data Monitoring–2

- Event reconstruction monitoring
  - Done offline and run by run
    - Typical runs 45–55 minutes in length (Each blue dot represents a single run)
    - Above data from Nov 2005 through Aug. 2006
  - $E/p$ of Bhabha’s, $\pi^0$ mass and width, occupancy multiplicities
  - Daily checks
Operational Performance

- For the last several years the EMC has been in a stable operation and maintenance mode
  - Result of first years hard work and automation of monitoring
- Typical maintenance activities:
  - On detector electronics (access required for repair)
    - ADB board (12 crystals) or IOB board (72 crystals) replacement
      - Typically O(3) boards replaced per access
      - Requires Detector access (~4+ hrs) so planned with PEP down time.
      - Can mask channels out of data taking if no access can be made (~5 min)
      - Water leaks from cooling lines
  - Off detector electronics (no access required)
    - Power supplies are unstable and tend to trip, cause data taking to stop
    - Power cycling, reseating, swapping with spares are normal (few minutes)
    - DAQ Read–Out Modules replacement ~1/month (few minutes)
- 1 major intervention
  - BaBar installed upgrade to muon system in Fall 2006 which required uncabling and removal of most of the front end calorimeter electronics for a period of 3 months.
    - 280 electronics boards remove/changed and all cabling rerouted
    - Not a single channel lost.
Summary

- 10 years of operation completed in April 2008
- High efficiency and excellent data quality for the past several years.
- High luminosity achieved by PEP–II did not adversely affect EMC performance
- SuperB has plans to reuse barrel crystals and support structure for their electromagnetic calorimeter.
Calorimeter Crystals

- Distribution of crystals by vendor inside the barrel

\[ \theta \text{ index} \rightarrow \]

\[ \phi \text{ index} \uparrow \]

- Crismatec
- Ronik
- Karkhov
- Shanghai
- Hilger
- Beijing
Calorimeter Design

- 6580 CsI(Tl) crystals – 0.1% Thallium doping
- **Barrel**: 48 rings along $\theta$ and 120 crystals/ring
- **Endcap**: 8 rings along $\theta$ with 80/100/120 crystals/ring
- Angular coverage
  - Polar angle: $-0.785 < \cos(\theta) < 0.962$
  - Azimuthal: $360^\circ$
- Crystals are non-projective in $\theta$ by 15mrad to minimize unmeasured energy loss due to inactive material between crystals.
  - Barrel $\leftrightarrow$ Endcap gap fully covered by non-projectivity

$90\%$ coverage in CM frame
Calorimeter Support Structure

- **Barrel:**
  - 280 carbon fiber modules → 7 along $\theta$; 40 along $\phi$
  - Per module: 7 crystals in $\theta$, 3 crystals along $\phi$
- **Endcap:**
  - 20 carbon fiber modules → 8 crystals along $\theta$; 4/5/6 along $\phi$
CsI(Tl) Crystal Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation Length</td>
<td>1.85 cm</td>
</tr>
<tr>
<td>Molière Radius</td>
<td>3.8 cm</td>
</tr>
<tr>
<td>Density</td>
<td>4.53 g/cm³</td>
</tr>
<tr>
<td>Light Yield</td>
<td>50,000 γ/MeV</td>
</tr>
<tr>
<td>Ligh Yield Temp. Coeff.</td>
<td>0.28%/°C</td>
</tr>
<tr>
<td>Peak Emission (λ&lt;sub&gt;max&lt;/sub&gt;)</td>
<td>565 nm</td>
</tr>
<tr>
<td>Refractive Index (λ&lt;sub&gt;max&lt;/sub&gt;)</td>
<td>1.80</td>
</tr>
<tr>
<td>Signal Decay Time</td>
<td>680 ns (64%)</td>
</tr>
<tr>
<td></td>
<td>3.34 µs (36%)</td>
</tr>
</tbody>
</table>
Electronics Calibration

- Calibrate gains by injecting known charge into preamps
- Different capacitors used to cover entire ranges (x1/4/32/256)
- Fit all 4 ranges simultaneously

Good Channel

Problem Channel
Radioactive Source Calibration

- **Left Plot:**
  - Relative light yield change over lifetime of BaBar.
  - Yellow bands represent periods of no collisions