Considerations for Calorimetry at a Super B Factory

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Coniderations for Calorimetry at a Super B Factory

William Wisniewski

SLAC

Presented by: W. Wisniewski                Session: Introductory

The study of B physics at $e^+e^-$ colliders running in the $\Upsilon$ region imposes significant performance requirements on calorimetry. The environment of a very high luminosity B factory further restricts calorimetry choices. Calorimeter design is discussed in light of these constraints. A solution using scintillating crystals is explored.

Note:
Considerations for Calorimetry at a Super B Factory

W. J. Wisniewski, SLAC
Introduction, Credits

• B physics requirements on calorimetry
  – Energy resolution, angular resolution
  – (BABAR Technical Design Report)

• Requirements imposed by backgrounds
  – Backgrounds seen currently
  – Extrapolations to higher luminosity
  – Challenge of continuous injection
  – (BABAR Note #533, SLAC-PUB-8970, S.Robertson)

• Scintillating Crystal Calorimeter
  – (BABAR Upgrade Report; SLAC-PUB-8970)
Caveats

• The super B factory work is still in its early stages. The effort continues with significant distractions provided by the wealth of current data provided by the two existing B Factories at KEK and SLAC.
• Detailed exploration of physics opportunities at a super B factory is beyond the scope of this talk.
Performance Requirements

• **Goals of a 10^{36} Asymmetric B Factory include:**
  ➡ search for effects of new physics on rare B (and D) decay rates and angular distributions
  ➡ search for deviations from predictions of CKM parameters in over-constrained tests of the unitarity triangle: sin2β ~1%; sin2α, γ ~several %
  ◆ this study is done in the ‘clean’ environment of e^+e^- interactions at ϒ(4s) and ϒ(5s), and is aimed to be complementary to and competitive with hadron machine efforts

• **What is needed for competitive B Physics?**
  – the calorimeter needs to perform comparably to current B factory calorimeters
  – look at characteristics of photons from generic and specific B decays
Photons from B Decays: Energy Spectra

- Energy Distributions:
  - photons from generic B’s
  - photons from $B \rightarrow \pi^0 \pi^0$
  - photons from $B \rightarrow \rho \pi$
- the calorimeter must deal with a broad spectrum efficiently: from low energy photons (~20MeV) from generic & tag B decays to high energy photons from $B \rightarrow \pi^0 \pi^0$ and electrons from bhabhas (~9GeV) and semileptonic decays
- higher energy photons and electrons require a deeper calorimeter: 16-17.5 $X_0$
Photons from B Decays

- Good low energy efficiency is needed for efficient $\pi^0$ and B reconstruction efficiency
- B’s move relatively slowly in the lab, so energy resolution dominates over angular resolution
- generic B decays contain ~5.5 photons: angular acceptance, segmentation
- forward direction is more important for acceptance than the backward direction (can leave lab angle not fully covered)
Segmentation

- Crystal size: fine segmentation for better photon separation (including background photons), position resolution
- Useful crystal transverse size is limited by its properties: Moliere radius (for CsI(Tl) ~3.8cm), readout expense
- Longitudinal size driven by energy resolution

\[
\frac{\sigma_E}{E} = \frac{1\%}{\sqrt[4]{E(\text{GeV})}} \oplus 1.2\%
\]

\[
\sigma_\theta = \frac{3\text{mr}}{\sqrt[2]{E(\text{GeV})}} \oplus 2\text{mr}
\]
Acceptance, Geometry

- should cover maximum solid angle with minimal interruptions for services, etc.
- ID and OD set by tracking/PID and magnet coil
- material in front of the calorimeter should be minimized
Crystal Performance Issues

- Light yield uniformity and resolution effects
- typical LY ~ 5.5-10K pe/MeV
- material between crystals
- spec contribute less than 0.5% to $\sigma_E/E$ up to 5 GeV: issues of readout device and location as well as crystal wrapping contribute here

<table>
<thead>
<tr>
<th>Material Thickness</th>
<th>$\sigma_E/E$ (%)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 $\mu$m</td>
<td>1.6</td>
<td>82</td>
</tr>
<tr>
<td>500 $\mu$m</td>
<td>2.1</td>
<td>79</td>
</tr>
<tr>
<td>800 $\mu$m</td>
<td>2.3</td>
<td>78</td>
</tr>
</tbody>
</table>
Crystal Performance Issues

- Radiation damage
  - light yield and light yield uniformity effects
  - source system, bhabhas, light pulser
  - design goal 10 yrs, 10krad, less than 20% ly loss

Readout & Electronics

- Spectral response of sensor; B field effects
- electronics noise goals: 150keV (20 MeV criterion)
Backgrounds Issues

• How can calorimeter be affected?
  – Integrated dose and consequent reduction in light yield (and uniformity?)
  – creation of false neutral clusters
  – inclusion of beam background photons during clustering into B decay photon shower
• examples from BABAR
Backgrounds Issues II

- **BABAR** 2001

![Graph 1](image1.png)

- Composition of Calorimeter Background
  - Semi-inclusive
  - Luminosity
  - Non-collision terms
  - LER
  - HER
  - Multiple

![Graph 2](image2.png)

- Composition of Calorimeter Background
Backgrounds Issues III

- Take special runs to find the sources of backgrounds:
  - HER(\(e^\text{-}\)) only; LER only; both beams in/out of collision
  - look at occupancy above threshold (1MeV; 0.75MeV with digital filtering): gives handle on rad damage since typical energy is \(~1\text{MeV}\)
Backgrounds Issues IV

- Look at clusters: requires 10MeV seed to the multi-crystal shower; shower has energy greater than 20MeV
- use in analysis clusters >30MeV
- typically see one cluster per event due to backgrounds
- these are dominantly produced by HER and ‘luminosity’
Backgrounds Issues V

- Look at effect on $\pi^0$ candidate count and resolution: clear indication of extra candidates, but the jury is still out on the resolution

Caveats

- backgrounds are very machine dependent:
  - note the change with better signal processing and some machine improvements
  - there is a difference between PEP-II and KEK-B: head-on collisions vs crossing angle, factor ~3-10
Super B Factory

- Parameters based on using the PEP tunnel. A larger tunnel on the SLAC site would save on RF power and supplies, but require civil construction
- Particularly note that injection is continuous because of the very short beam lifetime
  - Trickle charge (1Hz) appears to broaden $\pi^0$ width; suspending readout around injection helps

<table>
<thead>
<tr>
<th>Parameter</th>
<th>High Energy Ring (HER)</th>
<th>Low Energy Ring (LER)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy (GeV)</td>
<td>9.0</td>
<td>3.1</td>
</tr>
<tr>
<td>Beam particle</td>
<td>$e^+$</td>
<td>$e^-$</td>
</tr>
<tr>
<td>Center of mass energy (GeV)</td>
<td>10.58</td>
<td>10.58</td>
</tr>
<tr>
<td>Circumference (m)</td>
<td>2200</td>
<td>2200</td>
</tr>
<tr>
<td>RF Frequency (MHz)</td>
<td>476</td>
<td>476</td>
</tr>
<tr>
<td>RF Voltage (MV)</td>
<td>50</td>
<td>30</td>
</tr>
<tr>
<td>Synch. Rad. Power (MW)</td>
<td>23</td>
<td>12</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>3492</td>
<td>3492</td>
</tr>
<tr>
<td>Total beam current (A)</td>
<td>6.6</td>
<td>19.2</td>
</tr>
<tr>
<td>$\beta_y/\xi$ (cm)</td>
<td>0.32/0.32</td>
<td>0.32/0.32</td>
</tr>
<tr>
<td>Emittance (y/x) (nm)</td>
<td>22/22</td>
<td>22/22</td>
</tr>
<tr>
<td>Momentum Compaction</td>
<td>0.001</td>
<td>0.0013</td>
</tr>
<tr>
<td>Bunch length (mm)</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Approx. AC power (MW)</td>
<td>50</td>
<td>27</td>
</tr>
<tr>
<td>Beam lifetime (min)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Injection particles per pulse</td>
<td>$7.3 \times 10^{10}$</td>
<td>$5.3 \times 10^{10}$</td>
</tr>
<tr>
<td>Continuous injection rate (Hz)</td>
<td>20</td>
<td>80</td>
</tr>
<tr>
<td>Beam-Beam tune shifts</td>
<td>0.14</td>
<td>0.14</td>
</tr>
<tr>
<td>Transverse beam size ($\mu$m)</td>
<td>8.4</td>
<td>8.4</td>
</tr>
<tr>
<td>Luminosity ($cm^{-2}s^{-1}$)</td>
<td>$10^{36}$</td>
<td>$10^{36}$</td>
</tr>
</tbody>
</table>
Background Extrapolations

- Background sensitivities to each source of lost beam particles will depend on the details of the machine optics and the IR and detector designs: more complete design and simulation is needed for a proper estimate of the backgrounds and dose. In *BABAR* sources are typically vacuum and luminosity sources; the large loss rates to Touschek, beam-beam, and dynamic aperture imply these will also contribute

<table>
<thead>
<tr>
<th></th>
<th>HER</th>
<th>LER</th>
<th>SuperHER</th>
<th>SuperLER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam current (A)</td>
<td>0.7</td>
<td>1.4</td>
<td>5.5</td>
<td>20.5</td>
</tr>
<tr>
<td>Beam lifetime $\tau_b$ (min)</td>
<td>550</td>
<td>150</td>
<td>4.2</td>
<td>3.2</td>
</tr>
<tr>
<td>Beam loss rate $I_b/\tau_b$ (A/min)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Luminosity</td>
<td></td>
<td></td>
<td>0.37</td>
<td>0.35</td>
</tr>
<tr>
<td>Vacuum (Brem/Coulomb)</td>
<td></td>
<td></td>
<td>0.06</td>
<td>0.68</td>
</tr>
<tr>
<td>Touschek</td>
<td>0.06</td>
<td>2.28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam-beam tune shift</td>
<td></td>
<td></td>
<td>0.55</td>
<td>2.05</td>
</tr>
<tr>
<td>Dynamic aperture</td>
<td></td>
<td></td>
<td>0.28</td>
<td>1.03</td>
</tr>
<tr>
<td>Total</td>
<td>$1.3 \times 10^{-3}$</td>
<td>$9.3 \times 10^{-3}$</td>
<td>1.32</td>
<td>6.39</td>
</tr>
</tbody>
</table>
Background Extrapolations II

- Background estimates scaled from measured rates in light of the expected loss rates are suspect due to beam optics differences, aperture limits, and collimation: good to ~10x.
- Estimates obtained scaling the beam currents yield lower backgrounds. Touschek is similar to vacuum sources; no estimate for dynamic aperture and beam beam sources.
- Scaled energy deposition yields ~1-200 GeV in 1.85µs, up a factor of 100
Strawman Detector

- Compact detector option:
  - eliminate gaseous tracker: assume that backgrounds from factory operation are too high. Use fast, compact detector, silicon, in a 3T B field.
  - crystal choices (discussed later) are expensive: shrink the volume. Scale BABAR by Moliere radius ratio
  - DIRC PID is fine at shrunken radius; R&D forward
Crystal Calorimeter Candidates

- need good light output for energy resolution
- need a rad hard crystal
- need a fast crystal to reduce backgrounds (& need to be clever)

<table>
<thead>
<tr>
<th>Crystal</th>
<th>CsI(Tl)</th>
<th>CsI</th>
<th>BGO</th>
<th>BaF₂</th>
<th>PbWO₄</th>
<th>CeF₃</th>
<th>YAP</th>
<th>GSO</th>
<th>LSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>τ decay(ns)</td>
<td>680, 16</td>
<td>300</td>
<td>.6, 5, 10-30</td>
<td>27</td>
<td>56, 47</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>χ₀(cm)</td>
<td>3340</td>
<td>620</td>
<td>15</td>
<td>600</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R_moliere (cm)</td>
<td>1.86</td>
<td>1.86</td>
<td>1.12</td>
<td>2.03</td>
<td>0.89</td>
<td>1.66</td>
<td>2.63</td>
<td>1.39</td>
<td>1.14</td>
</tr>
<tr>
<td>λ_nuclear (cm)</td>
<td>3.8</td>
<td>3.8</td>
<td>2.3</td>
<td>3.4</td>
<td>2.2</td>
<td>2.6</td>
<td>2.8</td>
<td>2.4</td>
<td>2.3</td>
</tr>
<tr>
<td>LY (γ/MeV)</td>
<td>56000, 2500</td>
<td>8200</td>
<td>1400f, 100</td>
<td>3500</td>
<td>16200</td>
<td>12500, 27000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>64:36%</td>
<td>9950s</td>
<td>1250</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>λ_peak (nm)</td>
<td>550</td>
<td>315</td>
<td>480</td>
<td>220f</td>
<td>420-500</td>
<td>310-340</td>
<td>390</td>
<td>440</td>
<td>420</td>
</tr>
<tr>
<td>Rad Hard (Mrad)</td>
<td>.01</td>
<td>.01 - .1</td>
<td>1 - 1</td>
<td>1</td>
<td>100</td>
<td>1</td>
<td>10</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>ρ (g/cm³)</td>
<td>4.51</td>
<td>4.51</td>
<td>7.13</td>
<td>4.89</td>
<td>8.28</td>
<td>6.16</td>
<td>5.35</td>
<td>6.70</td>
<td>7.40</td>
</tr>
<tr>
<td>n₀</td>
<td>1.79</td>
<td>1.95</td>
<td>2.15</td>
<td>1.56</td>
<td>2.20</td>
<td>1.68</td>
<td>1.94</td>
<td>1.85</td>
<td>1.82</td>
</tr>
<tr>
<td>Cost ($/cc)</td>
<td>3.2</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>8</td>
<td>3</td>
<td>?</td>
<td>&gt; 15</td>
<td>&gt; 7</td>
</tr>
</tbody>
</table>
Segmented Calorimeter?

- Photosensors must be immune to the high magnetic field and quite compact: PDs for crystals with high light output, APDs?
- Can we reduce cost by longitudinally segmenting the calorimeter: better event identification, spatial resolution, ability to reduce backgrounds? Use rad hard compact crystal in front, cheaper, less rad hard crystal in back?
Summary

- Physics requirements for a super B factory calorimeter have been briefly discussed.
- A flavor for the potential beam backgrounds at a super B factory have been extrapolated from PEP-II experience.
- A strawman detector and its candidate calorimeter have been discussed.
- R&D needs to proceed to identify the best calorimeter material.