The (i)TOP Detector for the Belle II Experiment

Alan Schwartz
University of Cincinnati

38th International Conf. on High Energy Physics
Chicago, Illinois USA
August 6, 2016

- overview
- optics
- mechanical & electronics
- first commissioning results
- expected performance
The Belle II Detector

CsI(Tl) EM calorimeter: waveform sampling electronics, pure CsI for end-caps

Time-of-Flight, Aerogel Cherenkov Counter → Time-of-Propagation counter (barrel), prox. focusing Aerogel RICH (forward)

Central Drift Chamber: smaller cell size, long lever arm

4 layers DS Si Vertex Detector →
2 layers PXD (DEPFET), 4 layers DSSD

RPC $\mu$ & $K_L$ counter: scintillator + Si-PM for end-caps
\( \pi \) and \( K \) have different \( \theta_c \) according to \( \cos \theta_c = \frac{1}{n \beta} \)

\[ \Rightarrow \text{different } \gamma \text{ hit positions and arrival times. For } p=3 \text{ GeV/c, } \Delta \theta_c = 0.65 \text{ degrees} \Rightarrow \Delta t = 68 \text{ ps per m} \]
Optical Components: synthetic fused silica (quartz)

Bars: medium to generate Cherenkov radiation. Two bars of dimensions $2 \times 45 \times 125 \text{ cm}^3$ are glued together to make a “long bar” of length 2.5 m.

Mirror: to focus Cherenkov photons onto PMTs, thus improving imaging. Dimensions are $2 \times 45 \times 10 \text{ cm}^3$. Mirrors are spherical with focal length of 3.25 m.

Prism: to expand the image of Cherenkov cone, improving resolution and reducing ambiguities. Dimensions are $2 \times 45 \times 10 \text{ cm}^3$; angle of tilted facet is 18.1 degrees.

Nominally 100-150 reflections off large top and bottom faces
Fabricating quartz bars: flatness is critical

Interferograms from metrology report:

S1 peak-to-peak: 5.3 µm (< 6.3 µm)
S2 peak-to-peak: 4.6 µm (< 6.3 µm)
Quality control: measuring prism tilted face

Angle of tilted face. Specification: 18.07 ± 0.04 deg. (±144 arcsecs)

\[
\theta = \tan^{-1} \left[ \frac{\alpha}{n_{qtz} \sqrt{1 + \alpha^2 - 1}} \right] \quad \text{for} \quad \alpha \equiv \frac{x}{d}
\]
Gluing Optics

3 types:
- bar to bar
- bar to prism
- bar to mirror

Alignment and Gluing:
- adjust surfaces positions using laser displacement sensor and micrometers
- adjust surfaces angles using autocollimator and micrometers
- insert shims, tape joint and repeat steps 1, 2
- apply epoxy (EPOTEK 301-2) to joint
Moving Optics to Quartz Bar Box (QBB)

Vacuum-based lifting jig is used to move fully glued optics to QBB assembly table:
Quartz Bar Box is built up around optics:

Fixing outer honeycomb panel to side rails with panel preloaded (to load buttons)

Sealing outer honeycomb panel to PEEK frame

Prism Enclosure: provides access for PMTs and readout electronics
Photon Detection: Hamamatsu PMTs

Hamamatsu SL-10 Multi-Channel-Plate PMTs:
- >5-year R&D effort at Nagoya University
- high gain to detect single photons
- excellent timing: TTS < 50 ps
- good QE: 28% on average
- good segmentation: 16 anodes/tube: 5.3 x 5.3 mm$^2$
- works in a 1.5 T magnetic field

- All PMTs tested; those with QE < 24% are rejected
- 32 tubes/module x 16 modules = 512 tubes needed (8192 channels)
- “Conventional” PMTs have lifetimes 0.3-1.8 C/cm$^2$ ⇒ will need to be changed @ ~20 ab$^{-1}$ (44% of tubes). Next generation (ALD) PMTs are satisfactory.
PMT Module Assembly

1. Vacuum chuck to align the PMT faces
2. RTV silicon rubber to hold the PMTs
3. Silicon rubber TSE3032 (before curing) to be filled between the PMTs and the wavelength cut filter

PMT module completed

PEEK parts

2 PMT modules mounted to prism with a “cookie” (+oil):
Front-end electronics

Front-end electronics based on a custom 8-channel waveform-sampling ASIC:

ASICS are mounted in “Carrier boards,” and 8 Carriers + controller/HV/connector boards = 1 boardstack:

FPGA firmware consists of 3 parts:

4 boardstacks per module:
Installing Modules in the Magnet

Installing one of 16 modules into “Roman arch” configuration:

All 16 modules installed:
First commissioning results (data)

Test modules with cosmic rays, using simple scintillator paddle trigger:

(no tracking yet available, but will be very soon)

Both distributions are in reasonable agreement with MC simulations; other slots look similar
Expected Performance I

Monte Carlo simulation: $e^+e^- \rightarrow \bar{c}c$ (generic):

- $L(K/\pi) > 0.50$
- $L(p/\pi) > 0.50$
Expected Performance II

Monte Carlo simulation: $D^{*+} \rightarrow D^0 \pi^+, D^0 \rightarrow K^-\pi^+$:

### MC5 sample

<table>
<thead>
<tr>
<th>Cut</th>
<th>Efficiency (BGx1)</th>
<th>Fake Rate (BGx1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_PIDk &gt; 0.001$</td>
<td>98.2%</td>
<td>26.9%</td>
</tr>
<tr>
<td>$K_PIDk &gt; 0.110$</td>
<td>95%</td>
<td>10.9%</td>
</tr>
<tr>
<td>$K_PIDk &gt; 0.552$</td>
<td>90%</td>
<td>5.5%</td>
</tr>
<tr>
<td>$K_PIDk &gt; 0.835$</td>
<td>85%</td>
<td>3.4%</td>
</tr>
<tr>
<td>$pi_PIDpi &gt; 0.003$</td>
<td>99%</td>
<td>34.7%</td>
</tr>
<tr>
<td>$pi_PIDpi &gt; 0.344$</td>
<td>95%</td>
<td>12.1%</td>
</tr>
<tr>
<td>$pi_PIDpi &gt; 0.827$</td>
<td>90%</td>
<td>6.2%</td>
</tr>
<tr>
<td>$pi_PIDpi &gt; 0.959$</td>
<td>85%</td>
<td>4.0%</td>
</tr>
</tbody>
</table>

Monte Carlo simulation: $D^* \rightarrow D^0 \pi^+$, $D^0 \rightarrow K^-\pi^+$.
Summary

- A new type of particle identification detector has been built: a Time-of-Propagation counter with imaging. The construction took approximately 18 months.

- The detector is now fully installed in the Belle II solenoid. Electronics are cabled, and detector is being commissioned with cosmic rays.

- We are uncovering issues with interfacing to the data acquisition system, and issues with firmware running in the front-end readout boards. These are being debugged.

- We expect performance similar to or better than that achieved in Belle, but at much higher luminosity and background rates.

- The Belle II experiment is scheduled to take first commissioning data in 2017, and first real data in 2018. All detector systems are (more-or-less) on schedule.
Extra Slides
Mirror does two tasks:

- parallel rays get focused to a single point  
  $\Rightarrow$ removes bar thickness
- non-parallel rays are focused to different points  
  $\Rightarrow$ possibly allows to make a correction for chromatic dispersion.
Limiting issue: chromatic dispersion

\[ v = \frac{c}{n} \quad \text{phase velocity: } n = \sqrt{\frac{\epsilon \mu}{\epsilon_0 \mu_0}} \]

\[ n_g(\lambda) = n(\lambda) - \lambda \left( \frac{dn}{d\lambda} \right) \]

From \( \lambda = 300-500 \text{ nm} \):

- \( n_g \) ranges from 1.50-1.56; a 4% effect = 4x larger than the 1% difference of \( \pi/K \Delta t \)

- \( n \) ranges from 1.46-1.49 (Corning 7980 data sheet)

⇒ ultimate limit to performance of this type of detector (a long TOP counter)
Fabricating quartz bars: metrology report

Final metrology report:

<table>
<thead>
<tr>
<th>Tolerance</th>
<th>Specification</th>
<th>Measurement</th>
<th>Pass</th>
<th>Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1 Datum A Flatness</td>
<td>≤ 6.3µm</td>
<td>5.31</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>S1 Local Flatness over 200mm Area</td>
<td>≤ 1.8µm</td>
<td>Max 0.564</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>S2 Flatness</td>
<td>≤ 6.3µm</td>
<td>4.6</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>S2 Local Flatness over 200mm Area</td>
<td>≤ 1.8µm</td>
<td>Max 1.01</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>S3 Datum B Flatness</td>
<td>≤ 6.3µm</td>
<td>0.48</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>S4 Flatness</td>
<td>≤ 6.3µm</td>
<td>0.47</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>S5 Datum C Flatness</td>
<td>≤ 25µm</td>
<td>2.47</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>S6 Flatness</td>
<td>≤ 25µm</td>
<td>2.753</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>S1 Parallel S2</td>
<td>≤ 4 arcsec</td>
<td>1.2</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>S1 Perpendicular S3</td>
<td>≤ 20 arcsec</td>
<td>4.0</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>S1 Perpendicular S4</td>
<td>≤ 20 arcsec</td>
<td>5.0</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>S1 Perpendicular S5</td>
<td>≤ 1 arcmin</td>
<td>0.083</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>S1 Perpendicular S6</td>
<td>≤ 1 arcmin</td>
<td>0.083</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>S3 Parallel S4</td>
<td>≤ 60µm (10 arcsec)</td>
<td>4.8 arcsec</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>S3 Perpendicular S5</td>
<td>≤ 20 arcsec</td>
<td>8.0</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>S3 Perpendicular S6</td>
<td>≤ 20 arcsec</td>
<td>6.0</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>S5 Parallel S6</td>
<td>≤ 20 arcsec</td>
<td>10.0</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Surface Roughness S1</td>
<td>≤ 5 Å rms</td>
<td>4.1</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Surface Roughness S2</td>
<td>≤ 5 Å rms</td>
<td>4.4</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Surface Roughness S3</td>
<td>≤ 5 Å rms</td>
<td>4.2</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Surface Roughness S4</td>
<td>≤ 5 Å rms</td>
<td>3.65</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Surface Roughness S5</td>
<td>≤ 25 Å rms</td>
<td>9.52</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Surface Roughness S6</td>
<td>≤ 25 Å rms</td>
<td>9.05</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>1250 ±0.50mm</td>
<td>1250.3</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Width</td>
<td>450 ±0.15</td>
<td>450.10</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Thickness</td>
<td>20 ±0.10</td>
<td>20.055</td>
<td>x</td>
<td></td>
</tr>
</tbody>
</table>
**Testing Bars** *(transmission, internal reflection)*

**Step a:**
Measurement of bulk transmission of bars and coefficient of total internal reflection. \((R_0, R_1)\) calculated via Fresnel equations.

\[
I_0 (1 - R_0) \tau (1 - R_1) = I_1
\]

**Step b:**
Measurement of coefficient of total internal reflection of bars [SLAC-PUB-9735 (2003)]

\[
(I_1 - R_1) = (I_0 - R_0) \cdot \alpha^N \cdot \exp \left( -\frac{L}{\Lambda} \cdot \sqrt{1 + \left( N h / L \right)^2} \right)
\]

\(N\) is the number of reflections inside bar, \(\Lambda\) is the attenuation length of quartz (>1000m @ \(\lambda=530\) nm), \(L\) is bar length (125 cm), \(h\) is bar height (2.0 cm). \(R_0\) and \(R_1\) are measured or calc. via Fresnel eqs.
Gluing buttons to honeycomb panels

Button heights must match quartz profile:

Module 01-02

Module 03-
Measuring button heights *(must match quartz profile)*
Test PMT channels with laser, record single photon hit times, calculate time difference w/r/t reference pulse, plot residuals w/r/t known time difference:

| Entries | 92580 |
| Mean    | 0.001008 |
| RMS     | 0.1819 |
| $\chi^2$/ndf | 55.51/12 |
| Constant | 7050 ± 35.9 |
| Mean    | -0.05767 ± 0.00028 |
| Sigma   | 0.05758 ± 0.00030 |

~31ps TDC+phase
SL-10 TTS ~35ps
IRSX electronics: ~33ps

Testing all boards, excellent yield:

$\langle \sigma \rangle = 71 \text{ ps}$
### Super-KEKB and Detector schedule

**Calendar year**

<table>
<thead>
<tr>
<th>Japan FY</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
<th>2019</th>
</tr>
</thead>
<tbody>
<tr>
<td>JFY2016</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MR renovation for phase 2, including installation of QCS and Belle II</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Damping Ring installation &amp; startup</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VXD installation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DR commissioning</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summer shutdown (power saving)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Previous schedule**

- **phase 1**
  - w/o QCS
  - w/o Belle II

- **phase 2**
  - w/ QCS
  - w/ Belle II (no VXD)

- **phase 3**
  - w/ full Belle II

**New schedule based on JFY2016 budget**

- **phase 1**
  - w/o QCS
  - w/o Belle II

- **phase 2**
  - w/ QCS
  - w/ Belle II (no VXD)

- **phase 3**
  - w/ full Belle II

- **VXD installation**
- **DR commissioning**
- **Summer shutdown (power saving)**
- **HER start**
- **LER start**