The iTOP Particle Identification Detector at Belle II

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Accelerators, Detectors, Computing Session

*Currently at Ultralytics
Belle-II Upgrade at Super KEKB

- B factory experiments (Belle & BaBar) have rich history of discoveries.
  - Belle II at Super KEKB will push luminosity by ~40x for precision New Physics searches.

- **K/π identification devices at Belle II:**
  - Endcap: proximity focusing aerogel RICH.
  - Barrel: time of propagation detector.
Time of Propagation (TOP) Concept

- TOP is a variant of detection of internally reflected Cherenkov (DIRC) device.
  - Light generated with angle $\cos \theta_c = \frac{1}{n(\lambda) \beta}$
  - Propagates to end of bar via TIR.
  - DIRC: primarily measures $x, y$ of each photon.
    - Can use $t$ to suppress background, and/or correct chromatic effects.
  - TOP: uses timing in place of $y$ coordinate.
    - Typical timing separation between $K/\pi$ of order 100 ps.
    - Requires precision timing.
Belle II Imaging TOP (iTOP) Detector

- Key elements:
  1. Quartz bars, mirror, prism.
     - Limited imaging relative to $x,t$ TOP.
  2. MCP-PMTs for fast timing.
  3. Integrated readout electronics.

\[ \sigma \sim 38 \text{ ps} \]
Quartz Optics

- Optics consists of three main elements:
  - Quartz bar, made of two pieces.
  - Focusing mirror in forward direction.
  - Expansion block / prism in backward direction.

- Strict requirements on optics in order to:
  - Preserve photon angles as they undergo TIR.
  - Retain high efficiency for photons as they propagate.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flatness</td>
<td>&lt; 6.3 μm</td>
</tr>
<tr>
<td>Perpendicularity</td>
<td>&lt; 20 arcsec</td>
</tr>
<tr>
<td>Parallelism</td>
<td>&lt; 4 arcsec</td>
</tr>
<tr>
<td>Roughness</td>
<td>&lt; 5 Å (RMS)</td>
</tr>
</tbody>
</table>

Expansion Block
Quartz Bar
Focusing Mirror
Quartz Optics – Status & Schedule

- QA of prisms and mirrors is being conducted at Cincinnati.
- Clean rooms have been set up at KEK to perform acceptance testing, gluing/assembly, and storage of assembled optics.
- Assembly procedures are well defined.
- Many test, assembly jigs available to streamline processing.
- Scheduled to complete 17 modules by Spring 2016.

After Cleaning
Reflectivity: 99.984 ± 0.004
Photodetectors

- Hamamatsu “SL10” MCP-PMT.
  - Developed as collaboration between Nagoya University and Hamamatsu.
  - Transit-time-spread (TTS) of ~40 ps.
  - 4x4 anode structure.
  - QE > 24% at 380 nm.
    - QE ~28% ave.
  - Nominal gain ~3-5x10^5.
    - Tradeoff between efficiency and lifetime.

Requirements:
- Excellent timing, O(100 ps).
- Operation in 1.5 T magnetic field.
- Lifetime suitable for Belle II operation.
MCP-PMT Lifetime, Production Status

- Lifetime of MCP-PMTs is a significant concern.
  - ALD shows significant improvement in lifetime over conventional.
  - R&D into lifetime improvement has been conducted, will provide further improvements for a subset of MCP-PMTs.
- Total of 569 MCP-PMTs will be produced for Belle II.
  - 514 already in-hand.
  - 283 are conventional MCP-PMTs, may need to be replaced at high integrated luminosity.
  - Conventional MCP-PMTs optimally placed for ease of access.
Readout Electronics

• Requirements:
  – Deadtimeless at L1 trigger rate: 30 kHz.
  – Trigger latency of ~5 μs sets buffer depth.
  – Typical occupancy dominated by background:
    • >3 MHz / PMT for worst case modules.
    • Corresponds to ~1-2% occupancy.
  – Preserve MCP-PMT’s excellent timing.

Utilizes “IRS” series ASICs from U. of Hawaii.
  – Samples at 2.7 GSa/s.
  – Deep analog storage (~12 μs).
  – Four front-end electronics modules (FEM) per iTOP:
    • 16 ASICs, 128 channels.
    • Supports 8 MCP-PMTs.
Prototype Test, LEPS @ SPring-8

8 GeV e

Laser (351 nm)

γ (< 2.4 GeV)

Pb target
(1.0 mm)

Back Compton scattering

Drift chambers

Dipole magnet
(0.7 T)

TOF counters

Trigger counters

SciFi trackers

e⁺ beam from the origin

δ-rays

momentum (GeV/c)

0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2

Nishimura - iTOP at Belle II

DPF - Aug. 5, 2015
Experience at LEPS led to significant improvements in electronics and mechanical designs to improve timing, raise efficiency, and reduce dead channel counts.

- Some limitations observed:
  - Electronics $\sigma_t$ limited to $\sim 90$ ps.
  - Low channel trigger efficiency ($\sim 82\%$).
  - Dead channels.
- However, narrowest peaks in MC are $O(100 \text{ ps})$ due to chromatic broadening.
- MC/data show excellent agreement.
Front-End Electronics Development

Prototype

- IRS3B ASIC
- 1x Spartan6 FPGA.
  - Bussed ASIC control.
- Feature extraction in dedicated downstream module (or offline).

Intermediate

- IRS3C ASIC
  - Improved dynamic range.
- 1x Spartan6 FPGA.
  - Bussed ASIC control.
- Feature extraction in dedicated downstream module (or offline).

Production

- IRSX ASIC
  - DLL improves time stability.
  - Added gain for trigger path.
- 4+1 Zynq SoCs.
  - Point-to-point ASIC control.
- Feature extraction in front-end (or offline).
- Same HV/MCP-PMT coupling as intermediate.
Production Electronics

- Electronics now in full production:
  - Efficiency ~100% at nominal gain.
  - Electronics timing resolution < 50 ps.
  - Dead channels significantly reduced (none on any accepted modules so far).
  - Well-defined pipeline between collaborating institutes for assembly, testing, QA, integration.
Reconstruction & Performance

- Software to perform $K/\pi$ separation is now implemented into the Belle II Analysis Software Framework (bASF2).
- Includes all required physical processes:
  - Optical: dispersion, surface roughness, reflectivity.
  - MCP-PMT: QE, CE, TTS.
  - Other: electronics $\sigma_t$, event $t_0$.
- Further verification (and system testing) this fall/winter with joint PID/CDC test.
Summary

• Barrel K/π PID at Belle II will be provided by imaging time of propagation detector.
• Performance relies on excellent performance of optics, MCP-PMTs, and readout electronics.
• This performance has been demonstrated with prototype modules, which showed excellent data/MC agreement.
• Production underway, incorporates further improvements from lessons learned during beam, bench tests.
• Fully assembled bars to be installed into Belle II next year.
BACKUP
Feature Extraction Steps

1. Subtract storage cell pedestal (avg. ~2000 ADC +/- 100’s counts)
2. Linearity correction (optional)
3. Individual sample time offset correction

Three sets of calibration constants required:

- **Sample pedestal values**
  - (262144 samples/ASIC)

- **Sample time widths**
  - (128 values per ASIC)

- **Timewalk correction**
  - (~20 values per ASIC)

**Waveform Pedestal Correction**

**Pulse Time Vs Sample Array Bin #**
(used to measure Sample-DTs)

**Pulse Time Vs Height**
(timewalk correction)
Performance Requirements

• Impact of electronics timing

\[ \sigma \approx 38.4 \text{ps} \]

To include T0, clock distrib, timebase ctrl

\[ \sigma \leq 100 \text{ps} \rightarrow 1\% \text{ impact} \]

\[ \sigma \approx 50 \text{ps target} \]

NOTE: this is single-photon timing, not event start-time “T0”
MCP-PMT Socket Seating

Unable to control depth of insertion:

→ Sockets not protected
→ Discharges
→ Had to lower some HV (wanted to run at +100V over nom.)
Temporal Broadening

- Cherenkov ring opening angle $\beta$ dependent
- Propagation velocity is wavelength dependent

- Detected photons wavelength spread
  $\rightarrow$ propagation time dispersion
- Longer photon propagation length
  $\rightarrow$ Improves projected ring image difference
  But broadens time distribution

Light propagation velocity inside quartz

Wavelength filter
Prototype Modules @ LEPS, SPring-8

- e+ beam from the origin
- δ-rays
- momentum (GeV/c)

Side view

- Small and large trigger
- SciFi tracker x/y
- Timing
- Rate monitor
- TOF
- Triggered the 2 GeV/c e+ beam with the four trigger counters
  (two 40 x 40 mm² and two 5 x 5 mm²)
  - γ rate: ~30 kHz
  - Trigger rate: ~10 Hz
  - DAQ rate: ~5 – 10 Hz

DC2  DC3

~140

Floor
MCP-PMTs run at lower gain than bench:

- Trigger efficiency lower (~82%).
- Timing resolution worse.

- Narrowest peaks in MC are $O(100 \text{ ps})$ due to chromatic broadening.
- MC/data show excellent agreement.
Prototype Modules – Normal Incidence

Data ring image for $\cos\theta = 0.00$

Simulated ring image for $\cos\theta = 0.00$
Prototype Modules – Inclined Angle

Data ring image for $\cos \theta = 0.43$

Simulated ring image for $\cos \theta = 0.43$
Narrowest Peaks in Spring-8 LEPs Beam Test MC

Normal Incidence
1st peak width:

No dispersion: 6-8ps
With dispersion: 90-100ps
+TTS/T0 jitter: 110-120ps
+ electronics: 120-150ps
Data/MC Photon Yield Comparison

Number of hits in basf2 simulation for $\cos \theta = 0.43$