Commissioning and Initial Performance of the Belle II iTOP PID Subdetector

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University of Hawaii
Upgrading PID Performance

- PID ($\pi/K$) detectors
  - Inside current calorimeter
  - Use less material and allow more tracking volume
  → Available geometry defines form factor

Barrel PID Aerogel RICH

- New PID (Barrel)

- New PID (Endcap)

- Available geometry defines form factor

- E- 8.0GeV

- E+ 3.5GeV
**Concept:** Use best of both TOP (timing) and DIRC while fit in Belle PID envelope

- Use new, high-performance MCP-PMTs for sub-50ps single p.e. TTS
- Use simultaneous $T$, $\theta_c$ [measured-predicted] for maximum $K/\pi$ separation
- Optimize pixel size

**Image:**
- Side view of crystal
- BaBar DIRC

**Reference:**
NIM A623 (2010) 297-299
iTOP relativistic velocity

- Space-time correlations

These are cumulative distributions
Actual PID is event-by-event

• Test most probable distribution
Performance Requirements (TOP)

• Single photon timing for MCP-PMTs

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

\( \sigma \ll 10\text{ps} \)

(ideal waveform sampling)

NIM A602 (2009) 438

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

NOTE: this is single-photon timing, not event start-time “\( T_0 \)”
Mechanical constraints

• A highly constrained space
Quartz: procurement, verification

- **Bars:**
  1250 x 450 x 20 mm$^3$
  two bars per module

- **Mirrors:**
  100 x 450 x 20 mm$^3$

- **Prisms:**
  100 mm long, 456 x 20 mm$^2$
  at bar face expanding to 456 x 50 cm$^2$ at MCPPMTs

- **Material:** Corning 7980
  - DIN58927 class 0 material has no inclusions (inclusions ≤0.1 mm diameter are disregarded)
  - Grade F (or superior) material having index homogeneity of ≤5 ppm over the clear aperture of the blank; verified at 632.8 nm
  - Birefringence / Residual strain ≤1 nm/cm
Quartz gluing, Module Assembly

Optics: alignment, gluing, curing and aging (~2 weeks).

Enclosure: gluing CCDs and LEDs, integrating fiber mounts.

QBB: strong back flattening, button & enclosure gluing.

Put on a cart. PMT and front-end integration, performance check.

QBB assembly and gas sealing.

Move optics to QBB using the "lifting jig".
iTOP Readout

Waveform sampling ASIC

64 DAQ fiber transceivers

Subdetector Readout Module

ASICS

FPGA

or ADCs

On or in Detector

Clock, trigger, programming module (FTSW)

8k channels
1k 8-ch. ASICs
64 "board stacks"

Low-jitter clock

64 FINESS
16 COPPER

2x UT3 Trigger modules

64 SRM

Clock, trigger, programming module (FTSW)

Waveform sampling ASIC

TIPP 2017 Beijing
Readout Verification (pre-install, in-situ)

**Single photon timing**

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

**Trigger time (single photon)**

- < 10 ns

**Pulser testing**

- Event Time zero
  - < 100 ps
  - < 50 ps

**Trigger time (single photon)**

- < 10 ns

**Pulser testing**

- Laser timing: laser_pixel3_0_gain4_HV3201_18may2015

**Direct difference**

<table>
<thead>
<tr>
<th>Entries</th>
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<tbody>
<tr>
<td>Mean</td>
<td>0.001008</td>
</tr>
<tr>
<td>RMS</td>
<td>0.1819</td>
</tr>
<tr>
<td>χ² / ndf</td>
<td>55.51 / 12</td>
</tr>
<tr>
<td>Constant</td>
<td>7050 ± 35.9</td>
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<tr>
<td>Mean</td>
<td>-0.05767 ± 0.00028</td>
</tr>
<tr>
<td>Sigma</td>
<td>0.05758 ± 0.00030</td>
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</table>

**Ch. 0 Leading Edge timing**

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<tr>
<td>Mean</td>
<td>7.474e-005</td>
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<tr>
<td>RMS</td>
<td>0.02342</td>
</tr>
<tr>
<td>χ² / ndf</td>
<td>36.38 / 27</td>
</tr>
<tr>
<td>Constant</td>
<td>652.3 ± 12.2</td>
</tr>
<tr>
<td>Mean</td>
<td>-0.0001985 ± 0.0003319</td>
</tr>
<tr>
<td>Sigma</td>
<td>0.02236 ± 0.00026</td>
</tr>
</tbody>
</table>

**S011 C001 A0 Ch0 -- Slip 7, FB=111**
Installation (very tight fit)
Installation Complete (May 2016)
After installation – continued development

These studies used “raw waveform” readout; need Feature Extracted version (subsequent effort)
0, B-field Cosmic Ray Analysis data/MC nhit distribution

- Gaussian fit mean is used for nhit evaluation (in tight-cut condition)

Efficiency correction, artifact removal is tricky/difficult

Further studies were deferred for a couple months by PMT motion discovery (outcome of these studies)

Artifact contribution (Need improved FW)

1.5 T data (no eff. correction)

black : loose cut
red : tight cut

1.5 T MC

nHit distribution for slot05 (slot05 - slot1.3)
PMT Rotation Update (2 rotation issues)

- The PMT tube is made of Kovar and suffers \( \sim 1 \text{ kgf/PMT} \) in 1.5 T (maximum \( \sim 1.4 \text{ kgf/PMT} \) in \( \sim 1.1 \text{T} \)).

Study of physics impact of decoupled PMTs (Modest effect)

**Rotation of PMT module**
- Large effect on photon transmittance due to bubbles of the optical oil on the Si cookie
- Has been fixed in situ by shimming

**Rotation of PMT**
- Effect only for photons of larger incident angles than \( \sim 43^\circ \) if the peel-off surface is clear.
- Will be fixed if necessary after phase 2

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### PMT Production

<table>
<thead>
<tr>
<th>Year</th>
<th>2017</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
</tr>
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<tbody>
<tr>
<td>Month</td>
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<td>4</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>4</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>4</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>4</td>
<td>7</td>
<td>1</td>
</tr>
</tbody>
</table>

**Global schedule**

- Phase 2
- Physics run

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**Plan in place to replace \( \sim 50\% \) of PMTs**
Start-up Schedule/Commissioning

Integrate DAQ (now)  
Global Cosmic Ray Run (with B-field)  
Phase II startup (early 2018)

Configuration / Command/Acquisition

Timing alignment  
Global Commissioning

Trigger Development (refine)

30kHz L1 Buffer Mgmt (tuning)

Low amplitude Feature Extraction  
FE Tuning
Timebase Calibration

- Took a while to get new FW release, SW work continued

/image/path/to/figure1.png

FIG. 1: Example of calculation on Slot.01 ASIC.00. (a) is the shape of time difference ($\Delta T$) of the double pulses in channel.7 from the raw data, (b) is the time difference after correction, (c) is the project of $\Delta T$ after correction and a fit performed to the distribution to show the mean and the resolution of $\Delta T$, (d) shows how the $\chi^2$ values change in the iterations of calculation.

/image/path/to/figure2.png

FIG. 2: Summary of calculation results of the 64 ASICs of Slot.01. Plot (a) is means of the time difference of double pulses, and (b) is the time resolution.
Channel-by-channel Timing alignment

- Global timing alignment – laser studies
Standard CFD algorithm works well, though performance degrades at low PMT (mandated to mitigate aging effects).
Low PMT Gain Operation

- Current feature extraction uses constant fraction discrimination to extract signal timing.
- Resolution deteriorates at small signal amplitudes.
- Using laser data from Hawaii test setup.
- TProfile to get waveform template.
- Fit with central Gaussian and exponential tail.

Rising Edge Resolution CFD vs. Amplitude

- Use template fitter to improve resolution at small amplitudes/high noise.

Significant improvement at low pulse heights

Necessary to maximize MCP lifetime.

Studying how best to implement (Zynq: PS is too slow(?), PL option).
Summary

Belle II TOP Detector coming online

• Present:
   Production Firmware debugging
   DAQ integration and initial timing alignment

• Global Cosmic Ray Campaign:
   Detector alignment
   Magnetic field tracking

• First collisions (early 2018):
   Verify detector alignment
   Initial PID release
Back-up slides
30kHz L1, high occupancy emulation

30kHz L1 trigger, 10 MHz background photons/PMT, multi-hit, multi-event buffering

At 400 SSTin Cycles (~19us per single photon hit), can run at 50kHz, so plenty of margin
Gain and Efficiency

Laser efficiency ASIC 3, ch 6

<table>
<thead>
<tr>
<th>Laser on -- no trigger</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>RMS</td>
</tr>
<tr>
<td>$\chi^2$/ndf</td>
</tr>
<tr>
<td>Constant $3.632e+004 \pm 1.219e+002$</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>Sigma</td>
</tr>
</tbody>
</table>

Gain vs. Gain [10^5]

Laser efficiency ASIC 3, ch 3 (gain = 4x), HV3051

<table>
<thead>
<tr>
<th>Laser on -- triggered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>RMS</td>
</tr>
</tbody>
</table>

Trig. Efficiency = 100.0 %

Extr. Mean Gain = 2.6 x 10^5

Trigger Efficiency vs. Extr. Gain

- Ch. 5
- Ch. 6
- Ch. 7

Trig. Efficiency = 70.6 %

Extr. Mean Gain = 1.1 x 10^5

Fit Extracted Gain [10^5]
PMT Replacement

- The 224 conventional MCP-PMTs in the 7 slots have to be replaced due to the QE degradation by the beam background.
- In 2015 the time of the replacement was estimated as the 2020 summer shutdown.
  → Revisit the estimation.
- Need additional mass production of the MCP-PMTs for the replacement.
  → Discuss the production plan.

\[ 1 - \varepsilon_\pi \text{ (slot16)} \]
\[ 1 - \varepsilon_\pi \text{ (slot10)} \]

“1x BG”
**PERFORMANCE SUMMARIES**

### Laser Efficiency

<table>
<thead>
<tr>
<th>hEff</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>8193</td>
<td>87.31</td>
<td>6.615</td>
</tr>
</tbody>
</table>

**Laser Gain**

- **Entries**: 8193
- **Mean**: 2.07
- **RMS**: 0.5103
Single photon timing

- All installed channels
- 1 entry per channel
- Limited statistics

Note: CAMAC TDC and phototube TTS contributions included: actual resolution is better

<table>
<thead>
<tr>
<th>hLaser</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Entries</td>
<td>8192</td>
</tr>
<tr>
<td>Mean</td>
<td>70.8</td>
</tr>
<tr>
<td>RMS</td>
<td>6.376</td>
</tr>
</tbody>
</table>

$T_{\text{res}}$ [ps]
Verification: Event Time Zero

70 Assembled Boardstacks [68 installed]

- Entries: 8960
- Mean: 27.58
- RMS: 3.088
- $\chi^2$/ndf: 2431/25
- Constant: 1436 ± 27.6
- Mean: 29 ± 0.0
- Sigma: 1.813 ± 0.027

Hawaii Tested

U. South Carolina Tested (higher noise)
Verification: Event Trigger Time

Note: Using coarser AXI clock during production testing.

4x faster clock (expect 4x improved resolution) in final trigger firmware [not yet ready]

<table>
<thead>
<tr>
<th>hTrigLabel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>RMS</td>
</tr>
</tbody>
</table>
Direct hit map

S04

S05

S12

S13

Yes – voltage turned down
• 8 channels per chip @ 2.8 GSa/s
• Samples stored, 12-bit digitized in groups of 64
• 32k samples per channel (11.6us at 2.8GSa/s)
• Compact ASICs implementation:
  ▪ Trigger comparator and thresholding on chip
  ▪ On chip ADC
  ▪ Multi-hit buffering
Laser Calibration steps

1. Pedestal subtract
2. Correct Amplitude dependence
3. Run dT Minimizer, obtain results
4. Apply dT values

- All binned, so easily implemented at Look-up tables on the SCROD FPGA

- Both gain/efficiency and timing data taken at same time
- About 8 hours per 128 channel board stack
1. Ped subtract & 50% CFD

Measure peak to determine 50% threshold

Determine timing from interpolation

Before pedestal subtraction

Default samples are ~ 0.37ns/point
1. After 50% CFD algorithm

Laser timing: laser_pixel3_0_gain4_HV3201_18may2015

No corrections applied

TDC assumed exactly 25ps/lsb

TDC INL not considered

Direct difference

<table>
<thead>
<tr>
<th>Entries</th>
<th>92585</th>
</tr>
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<tbody>
<tr>
<td>Mean</td>
<td>0.0001569</td>
</tr>
<tr>
<td>RMS</td>
<td>0.2093</td>
</tr>
<tr>
<td>$\chi^2$/ndf</td>
<td>9191 / 191</td>
</tr>
<tr>
<td>Constant</td>
<td>3577 ± 19.4</td>
</tr>
<tr>
<td>Mean</td>
<td>-0.02746 ± 0.00043</td>
</tr>
<tr>
<td>Sigma</td>
<td>0.1236 ± 0.0005</td>
</tr>
</tbody>
</table>

Kinematic p.e. recoil tail
2. Voltage dependence

IRSX Timing: laser_pixel3_0_gain4_HV3201_18may2015

Initial vPeak Dependence

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
<td>92585</td>
</tr>
<tr>
<td>Mean x</td>
<td>914.2</td>
</tr>
<tr>
<td>Mean y</td>
<td>0.0001569</td>
</tr>
<tr>
<td>RMS x</td>
<td>507.9</td>
</tr>
<tr>
<td>RMS y</td>
<td>0.2093</td>
</tr>
</tbody>
</table>
2. Improved Residual

Laser timing: laser_pixel3_0_gain4_HV3201_18may2015

<table>
<thead>
<tr>
<th>Direct difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries: 92585</td>
</tr>
<tr>
<td>Mean: 0.05014</td>
</tr>
<tr>
<td>RMS: 0.1887</td>
</tr>
<tr>
<td>$\chi^2$/ndf: 2.807/8</td>
</tr>
<tr>
<td>Constant: $5418 \pm 34.2$</td>
</tr>
<tr>
<td>Mean: $-0.005163 \pm 0.000681$</td>
</tr>
<tr>
<td>Sigma: $0.0754 \pm 0.0013$</td>
</tr>
</tbody>
</table>

**pre dT Minimization Timing**

(TTS+IRSX) resolution = 68.3 [ps]
2. TDC resolution residual

Differential and Integral non-linearity in sampling timebase (expected for these types of Switched Capacitor Array ASICs)
3. After Autocalibration

Laser timing: laser_pixel3_0_gain4_HV3201_18may2015

Compare with previous slide – timebase uniform and absolute timing calibrated (clock period closure constraint)
Output After “dT minimizer” algorithm

S011 C001 A0 Ch0 -- Slip 7, FB=111

<table>
<thead>
<tr>
<th>Timing Diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
</tr>
<tr>
<td>Mean x</td>
</tr>
<tr>
<td>Mean y</td>
</tr>
<tr>
<td>RMS x</td>
</tr>
<tr>
<td>RMS y</td>
</tr>
</tbody>
</table>

Time between pulses in agreement,
No matter where look in the window

Absolute timebase cross-calibrated
With respect to SSTin clock period
Production single photon testing

Laser timing: laser_pixel3_0_gain4_HV3201_18may2015

Direct difference
- Entries: 92580
- Mean: 0.001008
- RMS: 0.1819
- $\chi^2 / \text{ndf}$: 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

Belle II TOP
(TTS+IRSX)
Time res. = 47.9 [ps]