Lessons learned from Commissioning and first colliding beam data of the Belle II imaging Time-Of-Propagation Detector

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University of Hawaii

TOP Readout Lessons - RT2018 Colonial Williamsburg
Upgrading Belle II 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

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

Available geometry defines form factor
**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

**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

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

\( \sigma \approx 50\text{ps} \) target

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

To include \( T_0 \), clock distrib, timebase ctrl

NIM A602 (2009) 438
Mechanical complexity

- A highly constrained space
Readout Requirements

- Very stringent requirements:
  - 30 kHz trigger rate;
  - no deadtime;
  - low power consumption;
  - ~500 MHz bandwidth;
  - excellent time resolution;

- The output of each electronics channel is sampled at 2.7GHz, with 12 bit resolution;

- No way we can transfer 265 Tbit/s, Feature Extraction (and pedestal subtraction) must be performed online.

128 channels in
~ 7 x 10 x 10 cm!
TOP Readout overview

Waveform sampling ASIC

64 DAQ fiber transceivers

Giga-bit Fiber Transceiver Links

Subdetector Readout Module

ASICs

FPGA

or ADCs

On or in Detector

FPGA firmware consists of 3 parts:
1) ASIC/ADC driver (common)
2) Trigger feature extract (subdet. specific)
3) Unified DAQ transport protocol

Low-jitter clock

64 SRM

64 DAQ fiber transceivers

Clock, trigger, programming module (FTSW)

Clock, Event Timing Distribution

Global Decision Logic

2x UT3 Trigger modules

64 FINESSE
16 COPPER

8k channels
1k 8-ch. ASICs
64 “board stacks”

#534 Itoh-san
(Poster session 1)
• 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
Readout Verification (pre-install, in-situ)

**Single photon timing**

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

**Direct difference**

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<th>Entries</th>
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<tr>
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<tr>
<td>RMS</td>
<td>0.1819</td>
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<tr>
<td>$\chi^2$ / ndf</td>
<td>55.51 / 12</td>
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<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>
</tr>
</tbody>
</table>

**< 100 ps**

**Bell II TOP (TTS+IRSX)**

Time res. = 47.9 [ps]

**< 50 ps**

**Trigger time (single photon)**

- ~10 ns

**Pulser testing**

**Event Time zero**

**Ch. 0 Leading Edge timing**

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<td>RMS</td>
<td>0.02342</td>
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<tr>
<td>$\chi^2$ / ndf</td>
<td>38.38 / 27</td>
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<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>
Quartz: procurement, verification

3 very challenging items: Quartz Radiator/optics #1

- Bars: 
  1250 x 450 x 20 mm³ 
  two bars per module

- Mirrors: 
  100 x 450 x 20 mm³

- Prisms: 
  100 mm long, 456 x 20 mm² 
  at bar face expanding to 456 x 50 cm² 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".
Installation (very tight fit)
Installation Complete (May 2016)
After installation – continued development

These studies used “raw waveform” readout; needed Feature Extracted version (subsequent effort)
Timing alignment

- Effectively need fine tuning for all 8192 channels of TOP;

- Current status: precision ~100 ps (but still margin for improvement!).

Contributions from two different sources to the same channel.
Module Timing alignment

- Idea: use cosmic events to align in time all TOP modules:
  - Compare photon detection times for cosmic rays that hit two different modules, taking into account time of flight and different propagation times;
  - Minimize a $\chi^2$ to find the best calibration constants (one module taken as reference);

- Crosscheck with laser system (uncertainty from uniformity of fiber lengths) shows excellent consistency!

Length mismatch due to timing cables
Cosmic Ray calibration data

- TOP joined the Global Cosmic Runs with other Belle II subdetectors since last Summer (>50M events recorded);
- Debugging opportunity + first performance assessment:

![Images of time vs pixel column graphs for Module 3 and Module 12.](image)

Points: detected photons
Colored bands: pdf

μ vs K separation

Very reasonable performance, despite calibration being still far from perfect!
First Collision Data

“Phase 2” (collisions) started in April

- TOP stably included in DAQ, should have no problem coping with the expected rates this year;
- Hit rates give a robust measurement of (gradually improving) beam background conditions;
- We can use two-track events to determine the event $T_0$ and align with the other subdetectors;
- Cannot show PID performance on collision data yet: we need to reprocess the data with final calibrations... and collect large samples of $K_s$, $D^*$, $\Lambda$, ...
“Fake” Summary
Belle II TOP Detector Readout status

• Present status:
  - Many small Production Firmware issues
  - Readout basically working

• Phase 2 (no vertexing):
  - Detector alignment
  - Di-muon, event T0 calibration
  - Verify PDFs

• Phase 3 readiness (early 2019):
  - Basically ready
  - Speeding up digitization, feature extraction
THINKING BACK
LOOKING FORWARD

ALICE, I'VE NOTICED A DISTURBING PATTERN. YOUR SOLUTIONS TO PROBLEMS ARE ALWAYS THE THINGS YOU TRY LAST.
Student Question?

What is the Shortest Distance Between 2 points A & B ??
One answer

The cynic might answer:

Point A

Point B
Another view

The answer is usually more subtle
The full calibration suite

- **Time Base Calibration**: Ensure the linearity of time digitization: performed by measuring the interval of double charge pulses across the sampling range.

- **Module $T_0$ Calibration**: Align in time all modules of the TOP counter, using cosmics and collision data.

- **Common $T_0$ Calibration**: Align in time with the other Belle II subdetectors.

- **Local $T_0$ Calibration**: Align in time all channels within a module, using the laser calibration system.

- **Geometrical Alignment**: Determine the actual position of each TOP module in the common reference frame using collision (cosmic) data.

**GOAL**: uncertainty < 100 ps on the single detected photons.
Timebase Calibration

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

/group/bellc2/users/wangxl/ITOP/TBC/DB201612b/xval/. The data of run3523 and run3524 are also processed and skimmed, and finally saved at /ghi/fs01/belle2/bdata/group/detector/ITOP/Skim-wangxl/2016-12/.

![Graphs showing data analysis](image)

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

![Graphs showing ASIC data](image)

**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.
Region of Interest and Feature Extraction

Reference pulse

Single p.e. laser pulses

Region of Interest and Feature Extraction Firmware running on Zynq "PS" side – too slow at highest rates
Single p.e., why bother?

• Postulate 1 (background level stays constant)
  – PMT gain: $5 \times 10^5$
  – Background hit rate: 500 kHz/PMT on average
  – Total exposure time in phase 2: 10 hours/day $\times$ 60 days = $2.16 \times 10^6$ sec
  $\rightarrow$ 0.016 C/cm$^2$ (could be acceptable)

• Postulate 2 (background level normalized by the luminosity)
  – PMT gain: $5 \times 10^5$
  – Background hit rate and luminosity at this moment:
    500 kHz/PMT and $8 \times 10^{32}$ /cm$^2$/s on average
  – Integrated luminosity in phase 2: 20 fb$^{-1}$
  $\rightarrow$ 0.189 C/cm$^2$ (not acceptable)

cf. life of conventional MCP-PMT = 0.3-1.8 C/cm$^2$

K. Matsuoka (Nagoya) – 50% of PMTs are conventional
Gain and Efficiency

laser efficiency ASIC 3, ch 6

<table>
<thead>
<tr>
<th>Laser on -- no trigger</th>
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<tbody>
<tr>
<td>Entries: 137863</td>
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<tr>
<td>Mean: 0.03772</td>
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<tr>
<td>RMS: 0.475</td>
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<tr>
<td>(\chi^2 / \text{ndf}): 234.8 / 13</td>
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<tr>
<td>Constant: 3.632e-004 ± 1.219e+002</td>
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<tr>
<td>Mean: -0.01024 ± 0.00044</td>
</tr>
<tr>
<td>Sigma: 0.1631 ± 0.0003</td>
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laser efficiency ASIC 3, ch 6 (gain = 4x), HV3051

<table>
<thead>
<tr>
<th>Laser on -- triggered</th>
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<tbody>
<tr>
<td>Entries: 4338</td>
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<tr>
<td>Mean: 2.645</td>
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<tr>
<td>RMS: 1.556</td>
</tr>
</tbody>
</table>

Trig. Efficiency = 100.0 %
Extr. Mean Gain = 2.6 \times 10^5

laser efficiency ASIC 3, ch 3 (gain = 4x), HV2901

<table>
<thead>
<tr>
<th>Laser on -- triggered</th>
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<tbody>
<tr>
<td>Entries: 2727</td>
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<tr>
<td>Mean: 1.36</td>
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<tr>
<td>RMS: 0.6429</td>
</tr>
</tbody>
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Trig. Efficiency = 70.6 %
Extr. Mean Gain = 1.1 \times 10^5

Trigger Efficiency vs. Extr. Gain

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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

Significant improvement at low pulse heights

use template fitter to improve resolution at small amplitudes/high noise

Necessary to maximize MCP lifetime

Studying how best to implement (PS is probably too slow)
Multi-hit Analog Buffer Management

SSTIn Period (~47.1ns) divided in 4 phases:

1. **WRitePTR** update (WR_ADDR send)
2. **HitPTR** update (hits prev SSTIn cycle)
3. **TrigPTR** update (L1 Trig hit match)
4. **DonePTR** update (clear finished buffers)

"simplified" version

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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
Region of interest (ROI) firmware on carrier selects only windows with threshold trigger matches and passes them to the crossbar.

Data transfer between boards is via PGP (SLAC), a multi-virtual channel high-speed serial link.
True Summary

Belle II TOP Detector Readout status
True Summary

Belle II TOP Detector Readout status

• The Good:
  ➢ Mostly things are working as designed
  ➢ Quite a bit of margin for increased performance

• The Bad:
  ➢ Programming and configuration lengthy
  ➢ At thermal limit

• The Ugly
  ➢ Detector installed 2 years ago, Production FW still a work in progress
  ➢ Very complicated (huge barrier to entry)
What might do differently?

1. Programming and Configuration
   - Higher speed JTAG interface (or …)
   - Taking on both Vivado and Zynq (SDK)?

2. Architecture
   - High speed serial communications – reduce to single FPGA?
   - Dedicated amplifier ASIC?

3. ASIC
   - Simpler storage scheme
   - Incorporate simple buffer management, readout state machines on chip
Back-up slides

Photo by K. Inami, Nagoya University
iTOP Readout “boardstack”
(1 of 4 per TOP Module)
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.

“1x BG”
Single photon timing

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

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

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<tr>
<td>Entries</td>
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<tr>
<td>Mean</td>
<td>70.8</td>
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<tr>
<td>RMS</td>
<td>6.376</td>
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Geometrical Alignment

- Still missing: precise determination of actual position of TOP modules;
- Strategy: select a sample of muons, and iteratively maximize the Likelihood $L_\mu$ varying the shifts $\Delta x$, $\Delta y$, $\Delta z$ and rotation angles $\alpha$, $\beta$, $\gamma$ about the three coordinate axes;
- With $e^+e^- \rightarrow \mu^+\mu^-$ events, can get a precision of $\sim 0.3$ mm on the shifts and 0.3 mrad on the rotation angles;
- Tested the procedure on cosmic data (some biases are expected).

Alignment on 5 independent samples of cosmic data. Very preliminary!
PMT Rotation Update (2 rotation issues)

- The PMT tube is made of Kovar and suffers ~1 kgf/PMT in 1.5 T (maximum ~1.4 kgf/PMT in ~1.1 T).

**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 ~43° if the peel-off surface is clear.
- Will be fixed if necessary after phase 2

**Plan in place to replace ~50% of PMTs**

Study of physics impact of decoupled PMTs (Modest effect)
### Verification: Event Time Time Zero

**Graph:**
- Histogram of Leading Edge Timing [ps]
- Y-axis: Entries [channels/ps]
- Data points highlight Hawaii-tested and U. South Carolina-tested (higher noise) conditions.

**Table:**

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
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<tbody>
<tr>
<td>Entries</td>
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<td>$\chi^2 / ndf$</td>
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<tr>
<td>Constant</td>
<td>1436 ± 27.6</td>
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<tr>
<td>Mean</td>
<td>29 ± 0.0</td>
</tr>
<tr>
<td>Sigma</td>
<td>1.813 ± 0.027</td>
</tr>
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**Note:**
- 70 Assembled Boardstacks [68 installed]
- Data collected during the TOP Readout Lessons - RT2018 Colonial Williamsburg event.
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]
Production single photon testing

Laser timing: laser_pixel3_0_gain4_HV3201_18may2015

Direct difference

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<th>Entries</th>
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<td>RMS</td>
<td>0.1819</td>
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<tr>
<td>Mean</td>
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~31ps TDC + phase

SL-10 TTS ~35ps

IRSX electronics: ~33ps

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