Belle II Barrel PID: A DIRC Derivate I

- DIRC: “Detector for Internally Reflected Cherenkov Light”
  - B. Ratcliff, SLAC PUB637
- Excellent solution to barrel PID needs in B-factories
  - Thin: Only radiator + casing in front of calorimeter, sensors outside of barrel region
Belle II Barrel PID: A DIRC Derivate II

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\[
\theta_c = \cos \left( \frac{1}{n \beta} \right)
\]

Quartz:
\[
n = 1.471 \quad (\lambda = 390 \text{nm})
\]
The “Time of Propagation” (TOP) Detector I

- A DIRC, but smaller: use timing instead of large expansion volume
- Instead of reconstructing the full ring image, measure time of propagation (path length) of individual Cherenkov photons.
  - Cherenkov photons from lighter particles arrive earlier on average
  - Since collision timing is well known (in principle), measure ToF at the same time
  - Chromatic dispersion is really not making this easier...
The “Time of Propagation” (TOP) Detector II

- 16 quartz Cherenkov radiator bars arranged around IP
- Forward side: spherical mirror
  - Effectively removes bar thickness for reflected photons
  - Different wavelengths are focused on slightly different points
- Backward side: small expansion prism, sensors, readout electronics

![Diagram of the TOP Detector II](Image)

- Prism length 100 mm
- Prism width 456 mm
- MCPPMT width 444 mm
- Thickness 20 mm
- Length 2600 mm
  2x1250mm+100mm
- Bar/mirror width 450 mm
- PMT
TOP: Total Internal Reflection

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TOP: Total Internal Reflection II
TOP Readout: Requirements

- **Goal:** <100ps single optical photon time resolution
- **Sensor requirements:**
  - single photon efficiency
  - <50ps single photon time resolution
  - ~few mm spatial resolution
  - Operation in 1.5T B-field
- **Electronics requirements:**
  - 30kHz trigger rate
  - <50ps electronics time resolution
  - <30ps clock distribution jitter
TOP Readout: Micro-Channel-Plate PMTs

- Very fast amplification, but not well controlled
  - Good time resolution, single photon efficiency, but large output spread
- (Mostly) resistant to B-fields
- Pixelated anodes for spatial resolution
Hamamatsu MCP-PMTs

- Measured single photon time resolution <40ps
- Lifetime (integrated charge) is limited
  - Original version ~1C/cm² (~50% of TOP)
  - ALD and LE-ALD versions: >10C/cm² (other ~50% of TOP)
TOP Readout: Electronics

- Reads MCP-PMT signals
- Time resolution <50ps
  - ~GSa/s sampling
  - ~500MHz bandwidth
TOP Readout: Electronics

- Reads MCP-PMT signals
- Time resolution <50ps
  - ~GSa/s sampling
  - ~500MHz bandwidth
- 8192 channels
- Affordable
- Low power
- Small form factor
- Online data processing
- etc. etc.
Readout: Electronics

- “Oscilloscope on a Chip”: IRSX ASIC
  - Designed by IDLAB, UH (Prof. Gary Varner)
- Operated at 2.7GSa/s in TOP
  - ~600MHz analog bandwidth
  - 32k analog buffer cells (~10us)
  - 12 bit digitisation w/o deadtime
- Power budget ~600mW/ch
  - ASIC: ~125mW/ch
  - Preamp: ~150mW/ch
  - FPGAs: ~300mW/ch
Online Data Reduction

- Whole TOP stores $22 \times 10^{12}$ samples every second
- Only digitise relevant ASIC samples
  - Based on global trigger, local channel triggers
- Apply all raw data conditioning in frontend
  - Pedestal subtraction
  - Time base calibrations
- Extract waveform features in frontend
  - Photon timing, pulse shape parameters
- Write out only feature parameters
- Powerful frontend processing: 320 FPGAs, 640 ARM cores
  - Based on Xilinx Zynq SoCs: FPGA + ARM CPU
TOP Frontend Readout Modules

- Carrier: 4 ASICs, Zynq 7030
- SCROD: Zynq 7045
- Module: SCROD + 4 Carriers
  - 64 modules in total (4 per bar)
Readout Dataflow

- Carrier FPGAs control ASICs, push waveform segments to SCROD
- Feature extraction on SCROD ARM CPU
TOP Event Timing for Trigger

• Precise event time is important for SVD readout: 25ns frame spacing, can afford only few ns of jitter
  - ECAL and drift chamber trigger timing but resolution is ~tens of ns
• Why not use TOP information for L1 $T_0$ estimate?
• Complicated photon timing structure due to reflections etc.
  - Live likelihood analysis of streamed TOP hit timings (no geometric info available)
  - No tracking information on trigger level
  - Estimated to produce <3ns $T_0$ resolution (eventually)
• FPGA Infrastructure is set up, successfully used TOP timing for cosmics trigger
  - TOPTRG b2link readout it set up and included in local/global data taking
Readout Status

• SCROD CPU crashes at ~1 BS/day
  - Recover by powercycle of the frontend (~20min)
  - Strong dependence on background conditions: happens more often when background rates are high and "spiky"
  - Don’t the know the exact reason, difficult to debug, cannot reproduce reliably
  - Maybe SEUs? Implementing SEU detection cores and DDR error checking into FW now. (but issue also happens in null runs without beam, though very rarely)

• Some ASICs self-masking in some runs (no response from ASIC within timeout)
  - Negligible hit loss, mostly recovered on run restart/SALS

• Configuration/pedestal acquisition works through slowcontrol system, will be tested and refined until beam start.
Operations

- Stable Readout with injected occupancy (>>average physics occupancy) tested and verified at 20kHz
  - However: we don’t have a good idea how to generate “spiky” “beam-background-like” occupancy for testing
- TOP conditions are fully monitored through nsm2 network
- TOP configuration and “setup for data taking” is now implemented and confirmed working from the TOP copper library
  - Needs some more testing
  - Frontend programming daq_slc app still missing (but simple)
PMT Degradation and Replacement Plans

QE degradation (15\textsuperscript{th} MC + 4 MHz/PMT)

- Conventional: slot10-16
- ALD: slot03-09

PMT hit rate follows 15\textsuperscript{th} background campaign + 2 MHz/PMT const. PMT gain is $3\times 10^5$. 

**Timeline**: 2018, 2019, 2020, 2021, 2022, 2023, 2024, 2025, 2026, 2027
Summary

- TOP is the first detector of its kind
  - Novelties in design and implementation
  - Cutting edge performance requirements

- TOP was basically stable in Phase 3 so far…
  - … except for crashing boardstacks, losing about 30-45min of luminosity per day for power cycling frontends.

- TOP PID performance is approaching MC predictions
  - Finally getting complex calibrations under control
Hawaii Waveform Sampling ASICs

- Hawaii Instrumentation Development Lab spinoff: Nalu Scientific
  - Founded by Isar Mostafanezhad (ex-postdoc of IDLab)
- Commercialisation of switched capacitor waveform sampling ASICs based on IDLab designs
- Three ASICs available:
  - SiRead: 32 channels, ~1 GSa/s
  - ASoC: 8 Channels, ~3 GSa/s
  - Aardvarc: 4 Channels, ~14 Gsa/s
Single Photon Time Resolution

- Intrinsic resolution <100ps on most channels
  - Laser jitter, pulser reference included (but small)
- Dominated by electronic noise in signal chain due to PMT operation at low gain
TOP “Cherenkov Rings” I

- \( D^{*+} \rightarrow D^0 \pi^+; D^0 \rightarrow K^- \pi^+ \) “Nature’s MC truth”
- Kaon facing prism-side of TOP bar
  - Little room for Cherenkov cone to open up
  - PDF differences dominated by ToF offset

$D^* \rightarrow D^0 \pi^+; D^0 \rightarrow K^- \pi^+$

\[ D^* \rightarrow D^0 \pi^+; \quad p = 1.68 \text{ GeV/c}, \quad \theta = 133.3^\circ \]

Pion PDF
\[ \log L(\pi) = -139.04 \]

\[ \log L(K) = -125.28 \]

\[ \log L(p) = -142.16 \]
TOP “Cherenkov Rings” II

- \( D^{*+} \rightarrow D^{0} \pi^{+}; D^{0} \rightarrow K^{-} \pi^{+} \) “Nature’s MC truth”
- Kaon facing mirror-side of TOP bar
  - PDF differences dominated by shape
TOP PID Peformance: K-π Separation

**VERY PRELIMINARY**

![Graph showing K Efficiency vs Likelihood Ratio R[K/π]](image1)

**Belle II 2019**
Phase III Data

- bucket 6 K efficiency
- bucket 6 π efficiency
- MC12 K efficiency
- MC12 π efficiency

![Graph showing K Efficiency vs π Fake Rate]](image2)

**Belle II 2019**
Phase III Data

- MC12 (80 fb⁻¹)
- Phase II proc 8 (368 pb⁻¹)
- bucket 6 (332 pb⁻¹)
TOP PID Performance: K-\(\pi\) Separation II

**VERY PRELIMINARY**

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**Belle II 2019**
Phase III Data

- **K Efficiency/\(\pi\) Fake rate** vs **Likelihood Ratio R[K/\(\pi\)]**
  - Bucket 6 K efficiency
  - Bucket 6 \(\pi\) efficiency
  - MC12 K efficiency
  - MC12 \(\pi\) efficiency

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**Belle II 2019**
Phase III Data

- MC12 (80fb\(^{-1}\))
- Bucket 6 ALD PMTs
- Bucket 6 conv. PMTs
- Bucket 6 (344pb\(^{-1}\))

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\(\pi\) Fake Rate