The TOP counter of Belle II: status and first results

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INFN – Sezione di Torino

Umberto Tamponi
tamponi@to.infn.it
Outline

→ Basic features of the Belle II Time-Of-Propagation counter

→ The first PID results

→ Understanding the first PID results
Part I.

The TOP detector (and Belle II)
The Belle II detector

- EM Calorimeter: CsI(Tl), waveform sampling electronics
- KL and muon detector: Resistive Plate Counter (barrel outer layers), Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)
- Vertex Detector: 2 layers Si Pixels (DEPFET) + 4 layers Si double sided strip DSSD
- Central Drift Chamber: Smaller cell size, long lever arm
- Particle Identification: Time-of-Propagation counter (barrel) Prox. focusing Aerogel RICH (forward)
- CP violation
- Every sub-detector provides PID information
  - dE/dx from Drift Chamber and Vertex detector
  - Cherenkov signal from TOP and ARICH
  - Shower shapes from the calorimeter
  - Penetration depth from the muon system
# The Belle II experiment: a timeline

<table>
<thead>
<tr>
<th>Calendar year</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
<th>2019</th>
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<td>Japan FY</td>
<td>JFY2016</td>
<td>JFY2017</td>
<td>JFY2018</td>
<td>JFY2019</td>
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<td>Summer shutdown (power saving)</td>
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## Phase 1
- MR startup
- DR installation & startup
- w/o QCS
- w/o Belle II

## Phase 2
- MR renovation for phase 2, including installation of QCS and Belle II
- HER start
- LER start
- w/ QCS
- w/ Belle II (no VXD)

## Phase 3
- VXD installation
- w/ full Belle II

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The first Belle II results

Phase II lasted from April 26th to July 17th

→ 0.5 fb\(^{-1}\) of collisions at Y(4S)

→ 0.55 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} maximum luminosity

→ Very extensive background and accelerator studies
The TOP counter principle

The TOP is a “DIRC in the time domain”

→ Cherenkov light trapped and propagated to the readout in a wide bar of fused silica
→ The Cherenkov angle is measured by the time of propagation rather than the ring image on the PMT surface
The TOP counter at Belle II

TOP implementation in Belle II:
→ 16 modules (or slots) arranged around the interaction point
→ Each module is made of two identical bars of fused silica glued together
→ Backward side: expansion prism, PMTs and readout
→ Forward side: spherical mirror
What does the TOP measure?

At a collider machine, we can combine the ToF and the Cherenkov angle in one single measurement.

Key ingredients:
→ Impact point on the detector
→ Single p.e. time resolution (PMT + readout only) < 100 ps
→ RF locking resolution < 10 ps
Readout: The PMTs

The single photoelectron time resolution is the key parameter for the TOP

Our target is $\sigma(1\ \text{p.e.}) < 100\ \text{ps}$

Hamamatsu MCP-MPTs

$\rightarrow (1 \times 1)$ in, $\sim 70\%$ active area

$\rightarrow$ NaKSBsCs photocathode; QE $\geq 24\%$ (28% on average) at 380 nm

$\rightarrow$ 55% collection efficiency

$\rightarrow$ Gain $= 10^5 - 10^6$

$\rightarrow$ Transient time spread $< 40\ \text{ps}$
Readout: The electronics

TOP front end electronics is based on the **IRSX chip** developed by Hawaii University. 
*arXiv:1804.10782*

**Scope-on-a-chip**
- 8 channel waveform digitizer
- 500 MHz Bandwidth
- 2.7 GSa/s
- 11.6 μs storage buffer
- *Full waveform output*

Controlled by Xilinx Zynq FPGAs
- Online pedestal subtraction
- Online waveform analysis

See Maeda-san's poster for more information!
Part II.

First physics results
TOP performances in Phase II

TOP in phase II:

→ Uptime > 90%
→ Active channels = 97.5%
→ Trigger capabilities verified*
→ Preliminary calibrations
→ First evidences of particle identification capabilities

* the TOP does not provide a trigger, but a T0 determination

Next Generation B Factory is back to the game!
The PID in Belle II is managed using **only likelihood values**

→ Each sub-detector provide a set of likelihood values for 6 mass hypotheses (from electron to deuteron)

→ Likelihoods are then combined
**TOP impact on physics**

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**Basic figure for two particle separation:**

**Log-Likelihood difference**

A particle is identified as $x$ rather than $y$ if $\text{LL}(x) > \text{LL}(y)$
Visualizing the Cherenkov rings

Compare the expected PDF with the observed hits for a known particle species

→ Pure Kaon sample from $D^* \rightarrow D^0\pi \rightarrow K\pi\pi$
Visualizing the Cherenkov rings

2.14 GeV prism-facing event

Little room for the Cherenkov cone to open up

ID is dominated by the PDF shift (i.e. ToF) rather than the shape difference
Visualizing the Cherenkov rings

1.41 GeV mirror-facing event

ID is dominated by the PDF shape (i.e. Cherenkov ring) rather than the global offset
From event displays to likelihoods

The PID in Belle II is managed using only likelihood values
- Each sub-detector provide a set of likelihood values for 6 mass hypotheses (e → deuteron)
- Likelihoods are then combined

Result from all the D* - tagged kaons in the first 90 pb\textsuperscript{-1} of data
$\phi \rightarrow K^+K^-$ with both the tracks in the TOP acceptance
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$\int L \, dt = 90 \, \text{pb}^{-1}$

Belle II TOP 2018 (Preliminary)
TOP impact on physics: $p$–$\pi$ separation

$\Lambda \to p\pi$ with the **proton candidate** in the TOP acceptance

![Histogram](image)

- Entries/(0.3 MeV/c^2)
- Belle II TOP 2018
- (Preliminary)
- $\int L = 90 \text{ pb}^{-1}$

M($p\pi$)[GeV/c^2]
TOP impact on physics: $p$-$\pi$ separation

$\Lambda \rightarrow p\pi$ with the **proton candidate** in the TOP acceptance

![Graphs showing $M(p\pi)$ distributions with and without PID](image)

Belle II TOP 2018

(Preliminary)

$\int L = 90\ \text{pb}^{-1}$
Quantitative estimations: $K_s \rightarrow \pi\pi$

Large sample of pions tagged by the $K_s \rightarrow \pi\pi$ decay

→ Test of both identification efficiency and mis-identification probability

→ Measure the $K_s$ yield when requiring, on one of the two pions:
  \[ LL(\pi) > LL(K) \]
  \[ LL(K) > LL(\pi) \]
  \[ LL(p) > LL(\pi) \]
  \[ LL(e) > LL(\pi) \]
Quantitative estimations: $K_S \rightarrow \pi\pi$

**Efficiency Results**

- **Data**
  - $\text{Eff(data)} = 80\%$
  - $\text{Eff(MC)} = 93\%$

- **MC**
  - $\text{Eff(data)} = 19\%$
  - $\text{Eff(MC)} = 7\%$
Quantitative estimations: $K_S \rightarrow \pi\pi$

**Belle II TOP 2018 (Preliminary)**

\[ \int L \, dt = 90 \, \text{pb}^{-1} \]

$\pi \rightarrow p$ mis-identification

\[ \log \mathcal{L}(p)_{\text{TOP}} > \log \mathcal{L}(\pi)_{\text{TOP}} \]

- **Eff(data)** = 20%
- **Eff(MC)** = 7%

$\pi \rightarrow e$ mis-identification

\[ \log \mathcal{L}(e)_{\text{TOP}} > \log \mathcal{L}(\pi)_{\text{TOP}} \]

- **Eff(data)** = 25%
- **Eff(MC)** = 20%
Part III.

Understanding the performances
Most of the TOP calibration is time calibration

IRSX sampling linearity (electronic pulses)  \rightarrow \text{Synchronization of the channels within one module (laser flashes)}

Synchronization of the whole detector with the radiofrequency clock (di-muons)  \rightarrow \text{Synchronization of the modules within each other (di-muons or cosmics)}

Geometrical alignment (di-muons)
TOP Calibration

Most of the TOP calibration is time calibration

IRSX sampling linearity
(electronic pulses)

Synchronization of the
channels within one module
(laser flashes)

Synchronization of the whole detector
with the radio-frequency clock
(di-muons)

Geometrical alignment
(di-muons)

Synchronization of the modules within each other
(di-muons or cosmics)

Not Done
Finalized
Preliminary
Preliminary
The time resolution on the single channel is estimated using laser flashes.

Due to the reflection inside the expansion prism, multiple paths can lead to the same pixel.

Each path is fitted with a crystal ball PDF for reproduce the tails in the PMT response time.
**Single channel time resolution**

**Example** of one laser run

→ Color: resolution PDF

→ Points: 68% quantiles

Note: laser and laser-related jitters are **not** deconvolved
**TOP synchronization**

The TOP sampling clock is locked to the accelerator radio-frequency clock (RF clock) → Any offset between the two will result in a mis-reconstruction of the PDFs

Most probable collision time
→ reconstructed back-fitting the higher momentum tracks in the event

→ If calibrations are correct, it will match with a tick of the RF clock

→ Resolution on data: 150 ps (bunch crossing: 2 ns)
→ Synchronization with the RF is still not optimal
What’s missing

Where can we improve the TOP performances?

1) Electronics
   → 10-20% firmware inefficiency (partially solved)
   → ASICS parameters not optimized
   → Template fit
   → Amplitude and gain corrections

2) Tracking
   → Any improvement in the tracking will improve the TOP PID

3) Calibrations and time resolution
   → Affected by tracking and electronics performances
   → Still statistically limited!
Conclusions

The Belle II experiment has successfully concluded the phase II pilot run:

→ The TOP is working
→ The PID performances are still ~10% worst than in the MC

Still lot of work to be done!
→ Preliminary tuning of the electronics
→ Preliminary calibrations
Backup
Channel synchronization in collision events

Very first test of the calibrations:
→ All the 8192 channels are aligned correctly
→ Clear distinction of direct and reflected light
TOP as a background monitor

- From separate LER/HER current scans
- Showing average of all fits (>90% of channels give good fits)

The TOP is an excellent background detector
Asymptotic resolution

The timing has a quite strong dependence on the slope of the hit rising edge (dV/dt). Steeper pulses get more precise timing, since the noise term gets smaller.
Each module is read by 64 ASICs packed into 4 **boardstacks**

- 16 IRSX asics
- 4 Xilinx Zynq Z-7030 (1 per 4 Asics)
- 1 Xilinx Zynq Z-7045 (global data flow)
- 1 HV board

Computing power used mostly for
→ Online pedestal subtraction
→ Online waveform analysis

See Maeda-san’s poster for more information!