The Belle II TOP PID detector

Roberto Mussa
INFN Torino

Photo by K.Inami, Nagoya U

FCC-ee Workshop  CERN, 9/1/19
Belle II Detector

EM calorimeter: waveform sampling
Electronics upgrade

Inner tracking:
2 layers PXD (DEPFET)
4 layers DSSD

Central Drift Chamber: smaller cell size
long lever arm

Muon/K_μ:
Plastic scintillator
+ Si-PM replacing
RPCs in inner two
barrel layers and
All of end-caps

Particle ID:
Imaging Time-of-
Propagation (barrel)
Aerogel RICH
(forward)

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TOP detector geometry

16 quartz Cherenkov radiator bars arranged in barrel region
- Forward side: spherical mirror
- Backward side: small expansion prism, sensors, readout electronics
TOP optics

Quartz bars: 1250x450x20 mm$^3$

Mirrors: 100x450x20 mm$^3$

Prisms: 100x456x20 mm$^3$ at bar face, expanding to 456x50 mm$^2$ at PMT

Material: Corning 7980

Cherenkov ring imaging with precision time measurement (better than 100ps)

Installation completed! 2016, May 11

<table>
<thead>
<tr>
<th>Quartz Property</th>
<th>Requirement</th>
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</thead>
<tbody>
<tr>
<td>Flatness</td>
<td>&lt;6.3μm</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; 0.5nm (RMS)</td>
</tr>
<tr>
<td>Bulk transmittance</td>
<td>&gt; 98%/m</td>
</tr>
<tr>
<td>Surface reflectance</td>
<td>&gt;99.9%/reflection</td>
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</table>
TOP sensors: Hamamatsu MCPPMTs

MCPPMT: Microchannel plate PMT

Developed in collaboration with U. Nagoya

~70% active area; 55% collection efficiency

NaKSBcCs photocathode

QE > 24% (average 28%) at 380 nm

HV = 2.1-3.5 kV; Gain from 105 to 106

Transient time spread <40 ps
TOP Front-end Electronics

Based on IRSX chip
(developed at UH Manoa)

- 8 ch. 12-bit waveform digitizer
- ~600 MHz analog bandwidth
- 2.7 GSa/s
- 11.6 μs storage buffer (32k)
- Full waveform output

Online processing
(via Xilinx Zinq FPGAs)
Raw ASIC output ~ 265 Tbit/s!

Power budget:
ASIC : 125 mW/ch
Preamp : 150 mW/ch
FPGA: 300 mW/ch
TOP F/E in Belle II DAQ

- Waveform sampling ASIC
- 64 DAQ fiber transceivers
- 8k channels
- 1k 8-ch. ASICs, 64 "board stacks"
- Global Decision Logic
- Low-jitter clock
- 64 SRM
- Clock, trigger, programming module (FTSW)
TOP time calibration: overview

What we have to calibrate

Module T0
Synchronization of the modules one with the others

Local T0
Synchronization of the channels within a single quartz bar

Time base calibration (TBC)
Calibration of the bin size of the digitizer

PMT channel gain

+ PMT channel gain

Double cal pulse

Laser pulse calibration

Alignment

\[ \chi^2 \equiv -2 \sum_{i=1}^{n} \log L_{\mu}^{(i)}(\hat{\rho}) = \min, \]

\[ \hat{\rho} = (\Delta x, \Delta y, \Delta z, \alpha, \beta, \gamma, t_0) \]
TOP time calibration: light distribution system

Designed and built by INFN and Univ. Torino and Padova

The challenge:
- 512 pixels per module
- 9 light sources per module
- Laser peak is a combination of 2 or 3 PDFs with the same width: 0,1,2 reflections.

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Results: laser calibration

Distribution of rising (left) edge and trailing (right) edge time resolutions

Synthetic summary of multigaussian fits on all pixels (16x512) of the TOP detector

Example of one laser run
→ Color: PDF distribution
→ Points: 68% quantiles

Single modules with temporarily issues

Belle II TOP 2018
(Preliminary)
Laser run 8245
TOP time calibration: overview

Time Base Calibration
- Ensure the linearity of time digitization

After TBC calibration
timing resolution of electronics < 30 ps

Local $T_0$ Calibration
- Align in time all channels within a module.

Current status: precision $\sim$100 ps (but still margin for improvement!)

Module $T_0$ Calibration
- Align in time all modules of the iTOP counter.

Will be improved by geometrical alignment
Phase II physics run: 
Apr 26 to July 17, 2018 
(without vertex detector) 
- $L_{\text{peak}} = 0.55 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ 
- $L{\Delta}t = 0.5 \text{ fb}^{-1} @ Y(4S)$

TOP commissioning results: 
- Uptime > 90% 
- Active channels = 97.5% 
- First PID tests on collisions
BelleII first collisions

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First results: TOP working principle

Every black dot is a photon on the PMT pixel array. Caustics are formed by the Cerenkov light cone, after many reflections, on this array.

In this case, the particle is entering the quartz close to the prism, and all light directly reaches the PMT array after few reflections. The TOP is mostly measuring the time of flight from the interaction vertex to the quartz.
First results: TOP working principle

Every black dot is a photon on the PMT pixel array. Caustics are formed by the Cerenkov light cone, after many reflections, on this array.

In this case, the particle is entering the quartz close to the mirror, and all photons reach the PMT array after many reflections. The TOP is mostly measuring the time of propagation of light inside the quartz.
TOP Preliminary results on $\pi K$ and $\pi p$ discrimination

$\Phi \to K^+K^-$
With both K in TOP acceptance

$\Lambda \to \pi p$
With proton candidate in TOP acceptance

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Preliminary Results: PID performance vs momentum

Process:
\[ D^{*+} \rightarrow D^0 (K^+\pi^-) \pi^+ \]

Data set:
\[ L_{\text{dt}} = 355 \text{ pb}^{-1} \]
914±34 candidates

\[ P^* > 2.5 \text{ GeV} \]
\[ |\Delta M - 145.43| < 1.5 \text{ MeV} \]

TOP performance
10-20% worse than MC expectation

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PID with TOP at Belle II
Where to work to improve PID performance

Core level improvements:

- We achieved a core time resolution of 120 ps with laser calibrations, pixel by pixel distributions are not yet well reproduced by MC;

- Still debugging firmware and optimizing ASIC operational parameters.

- We have residual non-linearities in the time base calibration which can explain the higher time resolution and PID performance degradation. New calibration algorithms are being prepared.

- Geometrical alignment is currently limited by the available statistics

High level analysis:

- Performance metrics show that TOP working principle and PID performance are OK, but still worse than MC expectations. Software algorithms still need full debugging.
Future prospects with dimuons

iTOP resolution estimation
Global performances

Preliminary study to estimate extra-time resolution from MC di-muon events

Convolution between MC PDF and Gaussian MC Data PDF

Muon-pairs events are generated in all permitted kinematic and acceptance areas and involve globally all TOP modules
Photon background levels are a major concern for the MCPPMT performance: the first batch of devices will surely NOT STAND operation at high luminosity.

Atomic Layer Deposition (developed recently by Hamamatsu) will allow to increase sensors' lifetime by ~10x.

9/16 modules are equipped with ALD PMTs.

The high backgrounds observed in Phase II, rescaled even at $10^{35}$, raise even more concerns. Mitigation strategies are being studied.
Summary
TOP has been stably taking data during the first period of data taking at Y(4S) energy (phase II): it will play a major role in Belle II physics program.

We performed the first measurements of TOP PID performance with hadrons from e+e- collisions.

TOP is positively reducing the expected backgrounds, but ....

In order to achieve the desired time resolution, we need to improve:
- the time base calibration for all sampling windows
- the relative timing of each pixel in each quartz bar (laser calibration)
- the alignment of all quartz bars with the inner tracking chambers

Firmware development will allow to further improve performance.

Standard MCPPMTs will be replaced with life extended ALD PMTs to cope with expected sensor aging at high luminosity.

THANK YOU!
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