Development and Construction of the Belle II TOP Counter

Kazuhito Suzuki (Nagoya Univ.)
on behalf of the Belle II TOP Group
Belle II TOP counter (1)

• SuperKEKB/Belle II project
  – Luminosity upgrade of the KEK B-factory.
    ➢ $\int L dt \sim 50 \, ab^{-1}$ (x50)
    ➢ $L \sim 8 \times 10^{35} \, cm^{-2}s^{-1}$ (x40) (BG: x20)
    ➢ Commissioning in 2015-2016.
    ➢ Data taking will start in 2016.
  – Various physics programs will be carried out.
    ➢ Rare decay searches for new physics hunt, exploring exotic particles, etc.

• Barrel PID device
  – TOP counter (16 modules)
    ➢ Good PID performance
      ex.) $\epsilon_\pi \sim 99\%$, $f_K \sim 1\%$ in $B \to \rho \gamma$
    ➢ Less material inside the calorimeter, c.f. Belle: ACC+TOF
    ➢ Operative under higher backgrounds,
    ➢ To be installed in Feb. 2015.
Belle II TOP counter (2)

Internally reflected Cherenkov photons bounce off ≥ 100 times at the large faces.

\[
\cos \theta_c = 1 / n \beta
\]

\[
S = \frac{\Delta \text{TOF} + \Delta \text{TOP}}{\sigma_{\text{TOP}}} \sqrt{N_{\text{det}}} \quad \sigma_{\text{TOP}} = \sqrt{\sigma_{\text{opt}}^2 + \sigma_{\text{PD}}^2}
\]

- \( N_{\text{det}} \): number of photons detected
- \( \sigma_{\text{opt}} \): chromatic dispersion (> ~50 ps)
- \( \sigma_{\text{PD}} \): time resolution (TTS and elec.)

[target: 20-30 photons]

[target: ~50 ps]
Quartz optics (1)

• Optical components
  – Tight requirements on material quality and dimensional tolerances.

- Synthetic silica (Corning 7980 class 0, grade F or better)
  - Homogeneity $< 5$ ppm
  - Radiation hardness $> 10k$ gray ($\gamma$), $10^{12}$ n/cm$^2$ ($n$)
  - Straia $< 5$ straia/thickness direction
  - Bifringence $\leq 1$ nm/cm

- Bar dimensional tolerances
  - Flatness $\leq 6.3$ µm (10 waves) for S1-S4
  - Roughness (RMS) $\leq 0.5$ nm for S1-S4
  - Parallelism $\leq 4$ arcsec (24 µm) for S1 // S2
  - Perpendicularity $\leq 20$ arcsec (2 µm) for S1 $\perp$ S3, S4

- Group velocity of light $\sim 350$ nm

- Optical coupling
- Optical glue

- PMTs + opt. filter + front-end elec.
- “Prism” (image expansion)
- “Bar” (radiator/propagator)
- “Mirror” (focusing)
Quartz optics (2)

• Procurement
  – Optical components for the first 4 modules have been in process.
    ➢ Multi-vendor production to assure the delivery rate.
  – 2 bars and 4 prisms have been delivered so far.
    ➢ Bar #5 was delivered in Oct. 2013, and has been inspected.
    ➢ The other ones have been delivered recently and are under inspection.
  – Component production for the rest of the modules will start in May 2014.
    ➢ After a review for the US funding to be held in Mar. 2014.
Quartz optics (3)

- **Bar inspection**
  - Measured the bulk transmittance and surface reflectivity.
  - Bar #5 meets the requirements.

\[
I_0(1 - R_0)\tau(1 - R_1) = I_1
\]

- \(I_0, I_1\): Measured with PD.
- \(R_0, R_1\): Calculated via Fresnel eqs.

\[
(I_1 - R_1) = (I_0 - R_0) \cdot \alpha^N \cdot \exp\left(\frac{L}{\Lambda} \cdot \sqrt{1 + \left(N h / L\right)^2}\right)
\]

- \(N\): Number of reflections.
- \(\Lambda\): Attenuation length (> 1000 m @ \(\lambda = 530\) nm).
- \(L\): Bar length (1250 mm), \(h\): Bar height (20 mm).

\(<\tau> = (99.66 \pm 0.07)\%/m\) (bar #5)

\(<\alpha> = (99.971 \pm 0.004)\%\) (bar #5)

> 98% (requirement)

> 99.9% (requirement)
Quartz optics (4)

• **Prism inspection**
  – Measured the prism angle.

- \[ \theta = 18.07 \pm 0.4 \text{ deg.} \]

- Our meas.: \[ <\theta> = 18.085 \pm 0.003 \text{ deg.} \]

- Prototype spec.: \[ r = 5000 \pm 100 \text{ mm} \]
- Vendor: \[ r = 4960 \text{ mm} \]
- A delivered prism meets the requirement.

• **Mirror focal length**
  – Established the focal length measurement.

- \[ r = 4956.4 \pm 8.1 \text{ mm} \]

2/26/2014

INSTR14 @ BINP
Quartz optics (5)

• Gluing of the components

- Autocollimator alignment (angle < ±0.2 mrad.)
- Laser sensor alignment (displacement < ±0.1 mm)

- Accuracy: ±0.01 mrad.
- Accuracy: ±5 μm

Wait ~1-hour for the glue to go down
Put the glue
~100 μm gap
Curing with UV

Full-size prototype glued

Being prepared for coming module assembly.
Photodetectors (1)

- **Micro channel plate (MCP) PMT**
  - Square-shape to minimize the dead area.
  - High-gain for single photon detection.
    - $2 \times 10^6$ at nominal HV.
  - Fast time response.
    - Transit Time Spread (TTS) < 50 ps.
  - Good quantum efficiency (QE).
    - $QE \geq 24\%$ (ave. $28\%$) @ $\lambda=380$ nm.
  - Dark noise rate < 100 kHz.
  - Operative under a magnetic field (1.5 T).

<table>
<thead>
<tr>
<th><strong>SL-10 Specification</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Photo-cathode</td>
<td>NaKSBcCs</td>
</tr>
<tr>
<td>Anode channels</td>
<td>$4 \times 4$</td>
</tr>
<tr>
<td>Entrance window</td>
<td>synthetic silica</td>
</tr>
<tr>
<td>Sensitive region</td>
<td>69%</td>
</tr>
<tr>
<td>Collection eff.</td>
<td>50-55%</td>
</tr>
<tr>
<td>Nominal HV</td>
<td>$\sim 3.4$ kV</td>
</tr>
</tbody>
</table>

Hamamatsu Photonics SL10 (Co-developed with Nagoya Univ.)

Micro Channel Plate (MCP)

Photocathode MCP plates Anode

- Capillaries $\phi: \sim 10\mu$m
- Bias angle $\theta = 13^\circ$
- $23$ mm

- $\sim 400\mu$m

- Fast 2 ms response.
- Good quantum efficiency (QE).
  - $QE \geq 24\%$ (ave. $28\%$) @ $\lambda=380$ nm.
- Dark noise rate < 100 kHz.
- Operative under a magnetic field (1.5 T).
Photodetectors (2)

- Gain and Time Transit Spread (TTS)
  - Single photon measurement

- Gain variation over the 16 anode channels

Central 4 channels seem to have smaller variations.

Handled by the front-end electronics.

Under negotiation with HPK for replacement

@ 16 ch-average
gain = 1 x 10^6

Max./min. ratio

TTS: 44.6 ps

Fine 2D scan of gain (1.1 mm steps)
@ the nominal gain (2 x 10^6)

JT0928 (PV = 5.69)

KT0132 (PV = 2.40)

JT0587 (PV = 2.21)

JT0580 (PV = 1.21)

2/26/2014
Photodetectors (3)

• Quantum efficiency (QE)
  – Photocathode current meas.
    \[ QE_{MCP} = \frac{I_{MCP}}{I_{PD}} \times QE_{PD} \]

• Photocathode lifetime
  – Deterioration due to the out-gases from MCPs.
    ➢ Serious issue under the high-bkg environment of Belle II.
  – Improved by Atomic Layer Deposition (ALD) on MCP.
    ➢ Still trying to eliminate the variation across the PMTs.

\[ @ \lambda = 380 \text{ nm} \]

\[ \text{Ave. peak QE meets our requirement (28%).} \]

\[ \text{Output charge [C/cm}^2\text{]} \]

\[ \text{Belle II 80 /ab @ 1x10}^6 \text{ gain (3.2 C/cm}^2\text{)} \]

\[ \text{ALD MCP-PMT @ 1x10}^6 \text{ gain (≥ 10 C/cm}^2\text{)} \]

\[ \text{Nagoya meas.} \]

\[ \text{Prior meas. @ HPK} \]

\[ \text{ALD (XM0142)} \]

\[ \text{ALD (XM0239)} \]

\[ \text{ALD (XM0240)} \]

\[ \text{Nagoya meas.} \]

\[ \text{ALD MCP-PMT @ 1x10}^6 \text{ gain (~1 C/cm}^2\text{)} \]

\[ \text{Hit rate ratio betw. before and after LED irradiations.} \]

\[ \text{1x10}^6 \text{ gain (worst)} \]

\[ \text{Output charge [C/cm}^2\text{]} \]

2/26/2014 INSTR14 @ BINP
Photodetectors (4)

• Mass production status
  – 550 PMTs in total to produce.
    ➢ ~20 PMTs/months are being delivered.
  – Inspections are catching up the delivery rate.
    ➢ 16 normal MCP-PMTs failed so far; to be replaced with the ALD-coated ones.
    ➢ ~50% (or more) will be the ALD-coated ones.
    ➢ Set-up for a 1.5 T field is being upgraded to measure the photon detection efficiency.

• Gain and TTS at 1.5T

As of 2/02/2014

<table>
<thead>
<tr>
<th>Inspected item</th>
<th>Normal</th>
<th>ALD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delivered</td>
<td>293</td>
<td>179</td>
</tr>
<tr>
<td>Visual</td>
<td>168</td>
<td>179</td>
</tr>
<tr>
<td>QE</td>
<td>285</td>
<td>120</td>
</tr>
<tr>
<td>HV test</td>
<td>265</td>
<td>122</td>
</tr>
<tr>
<td>Gain/TTS @ 0 T</td>
<td>237</td>
<td>37</td>
</tr>
<tr>
<td>Gain/TTS @ 1.5 T</td>
<td>87</td>
<td>5</td>
</tr>
<tr>
<td>To be used</td>
<td>≤277</td>
<td>≥273</td>
</tr>
</tbody>
</table>

Gain drops to 15-90%.
Front-end electronics (1)

- High-speed waveform sampling ASICs ("IRSX")
  - Fabrication will be completed in Apr. 2014.

- IRS3/X ASIC
  - 8 chs./chip @ 2.7-4 GSa/s.
  - Samples stored, 12-bit digitized in groups of 64.
  - 32k samples/ch. (8 μs @ 4 GSa/s).
  - Developed by Univ. of Hawaii.

- Front-end module
  - Integrated in a board stack.

Time resolution of pulsed laser irradiation at a test bench.

$\sigma = 59.1 \pm 0.5$ ps (target: $\sigma \approx 50$ ps)
Front-end electronics (2)

• Handling of the large gain variation over the PMT anodes
  – Design for smallest pulses and handle overflow.
    ➢ Use time-over-threshold method for saturated pulses.
    ➢ Fixed threshold time is highly correlated with pulse width.
  – Obtained ~50 ps time resolution for saturated pulses.
    ➢ Slightly better than the total time resolution (~60 ps) as no small pulses.
    ➢ Need to understand outliers in time distribution.

σ = 44.9 ± 0.6 ps
Optical contact

• Pogo pins
  – Separate the mechanical function from the front-end module.

• Optical cookie
  – Utilize the elasticity of Si rubber.
    ➢ “TSE3032” (refractive index= 1.406, elongation= 210%).
  – Semi-cylindrical shape to easily eliminate air.
    ➢ Peak-to-valley: 0.05 mm,
    ➢ thickness: 2-3 mm.

A 3 mm-thick cookie can stick to a glass plate with 40 N (~1 kgf/PMT).
Beam test (1)

- Beam test at the LEPS beam line in SPring-8.
  - Having nearly the final optics.
    - Nearly full-size optics.
    - Prototype prism was glued for the first time.
  - Having 32 PMTs for full coverage.
  - Using a prototype front-end electronics.
    - “IRS3B” (prototype ASIC).
Beam test (2)

• Ring images (preliminary)
  – Dead channels are simulated in MC.

• Time projections (preliminary)
  – Discrepancy in the peak regions:
    ➢ Alignment, geometry.
    ➢ Incident angle dependence on QE.
  – Discrepancy in the tails and off-peak regions:
    ➢ Event selection.

Data vs MC simulation

Peak positions agree fairly well.

Excess of hits in data is largest at early times.

Disagreement of peak height can be seen in some cases.
Beam test (3)

- **Time resolution** (preliminary)
  - Further improvements can be expected.
    - Various calibrations,
    - Firmware updates,
    - Final hardware design.

- **Number of photon hits** (preliminary)
  - For the photon arrival time $< 50 \text{ ns}$.
  - Adding the data bkg. into simulation.
    - Scaled based on the entries in sidebands.
  - Reasonable agreement can be seen.
    - Tail component can be reproduced in simulation.

\[
\sqrt{(120 \text{ ps})^2 + (100 \text{ ps})^2} = 156 \text{ ps}
\]

- Intrinsic term (simulation)
- PMTs, IRS3, back-end modules, etc.
Summary

• Production of the quartz optics is in progress.
  – Procedures for the inspection and assembly are being developed.
  – Various efforts are being made to recover the delay of the delivery schedule.

• Production of the MCP-PMTs is going well.
  – Inspection procedure is mostly established.
  – ALD-coating greatly improved the lifetimes.

• Beam test data is giving better understanding of the detector.
  – Various feed-backs have also been obtained to the front-end elec. and the associated opt-mechanical components.

• Detector development is being finalized.
  – Turning into the construction phase targeting the installation in Feb. 2015.
Beam test (4)