High Precision Time-Of-Flight: Belle Experience and Future R&D

Gary S. Varner
University of Hawai’i
BESIII Meeting, IHEP
5 June 2002
Presentation Outline

• Belle Experience
  – Performance
  – GEANT understanding
  – Care and feeding
  – Limitations

• BESIII Application
  – Previous R&D
  – Precision Time Encoding
  – Time Walk Correction

• Summary
  – Action items and opportunities for joint development
Belle Detector

BELLE Detector

1. Silicon Vertex Detector
2. Central Drift Chamber
3. Aerogel Cherenkov Counter
4. Time of Flight Counter
5. CsI Calorimeter
6. KLM Detector
7. Superconducting Solenoid
8. Superconducting Final Focussing System

Gary S. Varner, BESIII Meeting at IHEP, June 2002
PID Cross-section
TOF Counter (1 of 64)

- High B-field Operation
- Hamamatsu R6680 Fine Mesh PMTs
  - 24 stages
  - 2000 mesh/in.
  - G > 3x10^6 in 1.5T field
- TSC radius = 118 cm
- TOF radius = 120 cm
Result First!

\[ \sigma(\text{ToF}) \text{ vs. } Z\text{hit} \]

- Both Ends Averaged
- Forward End
- Backward End

Data \( \sigma = 99 \pm 0.2 \text{ ps} \)
MC \( \sigma = 101 \pm 0.2 \text{ ps} \)

Exp.5 data
\( \sigma (\text{ToF}) = 100 \text{ ps} \)
P.c.l. 25 GeV/c

Gary S. Varner, BESIII Meeting at IHEP, June 2002
Current Belle TOF Members

N. Gabyshev, H. Kichimi\textsuperscript{α,β} and J. Yashima  
High Energy Accelerator Research Organization (KEK), Tsukuba  Japan

J.W. Nam\textsuperscript{β}, Y.I. Choi, D.W. Kim and J.H. Kim  
Sungkyunkwan University, Suwon  Korea

B.C.K. Casey, M. Jones, S.L. Olsen, M. Peters,  
J.L. Rodriguez, G. Varner and Y. Zheng  
University of Hawai‘i, Honolulu, HI  USA

J. Zhang  
University of Tsukuba, Tsukuba  Japan

T.H. Kim and Y.J. Kwon  
Yonsei University, Seoul  Korea

\textsuperscript{α} Belle TOF Leader  \textsuperscript{β} Primary authors for recent study\textsuperscript{[5]}
Understanding Performance

• While basic Belle TOF performance good:
  – Wanted to understand limitations
  – Acceptance and Trigger efficiency
  – Nuclear/hadronic interactions
  – Higher Luminosity prediction

• Full GEANT simulation:
  – Full simulator [NIM A479 (2002) 117].
  – Accurate modeling of secondaries
  – Detector response and readout chain
  – Adjust parameters where required
  – Include beam background
  – Results submitted to NIM:
    J.W. Nam et. al
    hep-ex/0204030
# Detector Input Parameters

## TOF scintillator (BC408)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>Polyvinyl toluene</td>
</tr>
<tr>
<td>Density</td>
<td>1.032</td>
</tr>
<tr>
<td>Refractive index</td>
<td>1.58</td>
</tr>
<tr>
<td>Rise Time</td>
<td>0.9 ns</td>
</tr>
<tr>
<td>Decay Time</td>
<td>2.1 ns</td>
</tr>
<tr>
<td>Pulse Width</td>
<td>~2.5 ns</td>
</tr>
<tr>
<td>Atten. Length</td>
<td>~ 300 cm</td>
</tr>
<tr>
<td>λ Max. Emission</td>
<td>425 nm</td>
</tr>
</tbody>
</table>

## FM PMT (R6680)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photocathode Dia.</td>
<td>39mm (effective)</td>
</tr>
<tr>
<td>Transit Time Spread</td>
<td>320 ps (rms)</td>
</tr>
<tr>
<td>Q.E.</td>
<td>~21%</td>
</tr>
<tr>
<td>e⁻ collection</td>
<td>0.6</td>
</tr>
<tr>
<td>Rise Time</td>
<td>3.5 ns</td>
</tr>
<tr>
<td>Fall Time</td>
<td>4.5 ns</td>
</tr>
<tr>
<td>Pulse Width</td>
<td>6 ns (FWHM)</td>
</tr>
</tbody>
</table>
Energy Deposition

Deposition in steps along path length:
- One $\gamma$ per 100 eV
- Isotropic angular distribution
Scintillation Photon Timing

\[ P(t_{\text{emit}}) = \frac{1}{1 + R} \left( e^{-t_{\text{emit}}/\tau_2} - e^{-t_{\text{emit}}/\tau_1} + \frac{R}{\tau_3} e^{-t_{\text{emit}}/\tau_3} \right) \]

- \( \tau_1 = 0.9 \text{ ns} \)
- \( \tau_2 = 2.1 \text{ ns} \)
- \( \tau_3 = 14.2 \text{ ns} \)
- \( R = 0.27 \)

*NIM A292 (1990) 329
Photon Propagation

\[ \theta_{\text{trap}} = \sin^{-1}\left( \frac{n_{\text{air}}}{n_{\text{scint}}} \right) \]  

\[ t_{\text{pro}} = \frac{l_{\text{pro}}}{v_{\text{scint}}} \]  

\[ R(t_{\text{pro}}) = e^{-t_{\text{pro}}/\lambda_{\text{pro}}} \]

Simplification 1:

Simplification 2:
Additional Modifiers

\[ R_{\text{angle}} = \cos \theta_i \]

Average efficiency over all \( \theta \): 66%

\(<q.e.> \sim 21\%\)

“collection factor” \(~ 60\%\)
PMT Response

\[ t_{pe} = t_{traj} + t_{emit} + t_{pro} + t_{TT} \]

Transit Time: \((5.5 \pm 0.31)\) ns

\[ V_{PMT}(t) = \sum_{i=1}^{n_{pe}} v_{i}(t), \]

\[ v_{i}(t) = G C e^{t^2 e^{-t^2 / \tau^2}} \int t^2 e^{-t^2 / \tau^2} dt \]

\( \tau = 6\) ns

2.0 GeV/c \( \mu^{-}, z=0 \)

Entries
Mean
RMS

154
24.87
3.585

\( V_{i}(t) \)
Readout Electronics

- In addition, introduce timing uncertainty
  - Gaussian parameterization, 45ps width
    - $t_o$ determination, discrim/system noise, TS quantization/RF jitter, fudges
TDC Distributions

- Nice agreement
  - Requires timing uncertainty
    - 45 ps

- Higher order z-dependent effects not shown
ADC Distributions

- Simulated charge distribution much narrower than data
  - Requires modification
  - Scaled Poisson distribution:

  \[
  \text{ADC} = Q_{\text{orig}} \left( s_w \left( \frac{N(n_{pe}) - n_{pe}}{n_{pe}} \right) + 1 \right)
  \]

  Width scale parameter = 2 for best data match

  Poisson distributed r.v.
  \( <N> = n_{pe} \)
Overall, good agreement

Large scatter in both simulation and data for large pulse heights
Degradation Modeling

“unholy Trinity”

Pile-up

Accidentals

Overflow

Gary S. Varner, BESIII Meeting at IHEP, June 2002
Degradations Reproduced!

Data, Background Data limited For >100kHz

Fixed, Geometric Inefficiency

TOF

TSC

TOF trigger rate (kHz)
Simulation Summary

Data $\sigma = 99 \pm 0.2$ ps
MC $\sigma = 101 \pm 0.2$ ps

Reproduces tails

Always room for improvement
Care and Feeding: Manpower

- **Jorge Rodriguez**
  - CLEO Cal. Expertise
  - Original $T_0$

- **Karim Trabelsi**
  - Backward Kalman
  - “EXT”, $\Sigma$ path
  - Tracking group

- **Mike Peters**
  - RecTOF
  - Combining statistics (1-4 dof)

- **Mike Jones**
  - Daily monitoring
  - Always finding problems

- **H. Kichimi**
  - TOF leader
  - Constant attention

- **And many others!!**
  - In particular many students who are based at KEK continually monitoring laser/Cal data

Gary S. Varner, BESIII Meeting at IHEP, June 2002
Collision Point/Timing Stability

- Run-by-run $T_0$

200ps jump!
Care and Feeding: monitoring

Charge dependence!
Limitations (1)

- **Intrinsic Performance:**
  - Tough to get
  - Beam tests don’t require sustained operation
  - Hadronic Calibration!
    - Very important – details omitted due to space limitations
    - Much work, no fundamental understanding
    - Velocity dependent (dE/dx?) fudge
    - Systematic, so no SQRT(2)
    - May be TWC technique dependent
  - Sad history of underperformance:
    - CLEO, CPLEAR, BESII, ...
  - Error Budget!!
Limitations (2)

PID Bake Off

BaBar

Looks like BaBar does better.

Belle

DIRC + MDC
Expectations? (1)

- **Q:** what does this mean for BESIII TOF?

<table>
<thead>
<tr>
<th></th>
<th>Belle</th>
<th>BESIII</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spec. guess?</strong></td>
<td>Spec.</td>
<td>Spec.</td>
</tr>
<tr>
<td><strong>RF/BCO</strong></td>
<td>&lt;35 ps</td>
<td>35 ps</td>
</tr>
<tr>
<td>uncorrected t=0</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Discrim. Overdrive</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td><strong>Beam bunch length</strong></td>
<td>2.5 mm</td>
<td>8.3 ps</td>
</tr>
<tr>
<td>Time Encoding</td>
<td>&lt;20 ps</td>
<td>22 ps</td>
</tr>
<tr>
<td>Total</td>
<td>&lt;40 ps</td>
<td>~45 ps</td>
</tr>
<tr>
<td></td>
<td>(~42 ps)</td>
<td></td>
</tr>
</tbody>
</table>

- **GEANT/full simulator contribution:**

\[
\sigma^2_{\text{fin}} \rightarrow 100\text{ps} \quad \text{“known”} \sim \text{“physics”} \rightarrow 40\text{ps}
\]

(Belle detector/KEKB environment dependent)

- **In summary, can parameterize:**
Expectations? (2)

- Must minimize irreducible Systematics
Time Stretcher Concept

- In a pipelined/MTDC DAQ need a reference $T_0$
  - Map ~25ps desired lsb onto MTDC 0.5 ns (HPTDC 0.1ns ? [7])
- In principle, improve by the stretch factor
Time Stretcher Module

- Designed with LRS
  - R&D 100 Award

- 16 Channels/1 per DC
- Stretch factor 20x
- RF clock Reference

VIPA Standard Module
TS + MTDC Performance

- ~20ps jitter

\[ \sigma = 22.5\text{ps} \]
Monolithic Time Stretcher (MTS1)

- 16/32 LV TTL or LVDS inputs

- Target to use with HPTDC
  - Common development w/Belle High L upgrade

Detailed SPICE Simulations to be Presented @ High L Workshop in August

LVDS outputs to HPTDC

Specifications under discussion (with BESIII input), could submit prototype August/Sept.
Time Walk Correction

- Reasonable functional form
  - But can do better?

- Many ideas: e.g. direct digitization at high speed?
STRAW2 Chip

- 32 (16) Channels of 256 deep SCA buckets
- Optimized for RF input Microstrip 50Ω
- Follow-on to the ATWD Chip (LBL)
- Target input Bandwidth: >700MHz
- Primary application: Askaryan-effect RF UHE cosmic detectors

Die: ~2.5mm²

Self-Triggered Recorder Analog Waveform (STRAW)

Self-Triggering:
- LL and HL (adj.) for each channel
- Multiplicity trigger for LL hits

On-chip ADC:
- 12-bit, >2MSPS

Sampling Rate:
- 1-2GSa/s (adj.)
- >~8GSa/s possible w/ 0.25µm process

External option:
- MUXed Analog out

Submission Date: 15 July
Summary

• Desired TOF system performance challenging

• Two specific areas for R&D:
  – Encourage further, detailed simulation to obtain more realistic performance estimate
  – Joint development of precision timing encoding (also needed for Belle high Luminosity upgrade)

• Plans
  – HPTDC Evaluation board
  – Monolithic Integrated Time Stretcher (MTS1)
  – STRAW2 Submission mid-July
References


Background: HPTDC Testing

$\sigma_{100\text{ps}} = 75.9\text{ps}$

Better for logic clock turned off

$\sigma_{500\text{ps}} \sim 330\text{ps}$
For LRS 1877S

Figure 6: DNL and INL graphs (100ps mode – enhanced package, logic fully functional).

$\sigma_{25\text{ps}} = 69.8\text{ps}$

Figure 9: DNL and INL graphs (25ps mode – enhanced package, logic fully functional).