

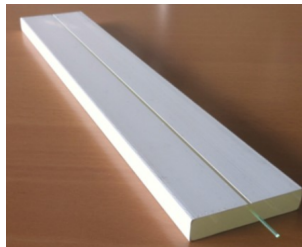
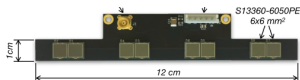
Optical TOF for ILD

Exploring modern WLS/scintillator/Cherenkov detection concepts for ILD

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Why should we care about timing layers?

- Particle ID at low momentum. In practice with excellent dE/dx need good timing precision and large flight distance for TOF to be competitive.
- Hermeticity and background rejection. Includes cosmic-ray muons and beam-related backgrounds. Key-idea: Two spatially separated timing layers with sufficient spacing/time resolution for direction discrimination.
- Bunch crossing ID. Bunch separations of 25 ns for nominal FCC-ee at Z.
- Trigger
- Time-tagging of photons
- Inter-calibration of calorimetry timing.
- Robust and low cost solutions may have their place.

$x = vt$. So $L = \beta ct$, $1/\beta = ct/L$.

Precision on β depends on t resolution and L resolution (includes track model - see eg. 2107.002031 (Mitaroff)). Particle separation benefits from large L .

Helix radius, $\rho_H = \frac{p_T}{0.29979B}$ with ρ_H in m, p_T in GeV/c, and B in T.

For barrel geometry, located at a radius R_{TOF} , photon flight distance is simply, $L = R_{\text{TOF}}/\sin\theta$, and the undisturbed charged track length is

$$L = \frac{2\rho_H}{\sin\theta} \sin^{-1} \left(\frac{R_{\text{TOF}}}{2\rho_H} \right)$$

For endcap geometry, located at $z = z_{\text{TOF}}$, undisturbed charged track length and photon flight distance are simply

$$L = z_{\text{TOF}}/\cos\theta$$

If barrel directed tracks have $p_T < 0.1499 B R_{\text{TOF}}$, they loop, and the endcap formula holds in principle (although energy loss large), and will give large L and t . So for very low momentum, the **endcap** is the natural place to do PID.

Some history and current motivations

My early OPAL contributions focused on measuring N_ν directly using $e^+e^- \rightarrow \nu\bar{\nu}\gamma(\gamma)$ events near the Z. Enabled by a trigger on such low energy photon events and “precision” timing with **TOF**. Plots: **Z Phys C 65 (1995) 47**.

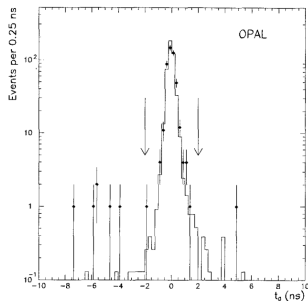
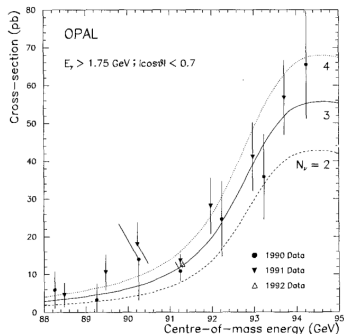


Fig. 5. t_0 distribution for single photon candidates (data-points) compared to photons from the photon control sample (histogram). The arrows mark the positions of the timing cut (A3)

I worked on the TOF trigger and TOF calibration in OPAL. Achieved $\sigma_t = 250$ ps for low energy photons. *Currently* working generally on re-analysis of OPAL data. Including a recent effort to analyze unpublished OPAL TOF PS test-beam data; partly motivated by: Does a modern TOF system make sense for ILD?

Talk Genesis

I was looking into improving the calibration of the OPAL scintillator-based timing detectors: the (long) barrel TOF (TB) ($\sigma_{MIP} = 0.4$ ns) and the endcap (TE) ($\sigma_{MIP} = 3$ ns) as part of OPAL data reanalysis.

I realized after Imad Laktineh's presentation in the summer on muon detectors, and in discussion with Charlie Young (SLAC) about modern faster wavelength shifter (WLS) fibers that there are a lot of opportunities to use optical timing measurements for precise timing with modern photo-detectors.

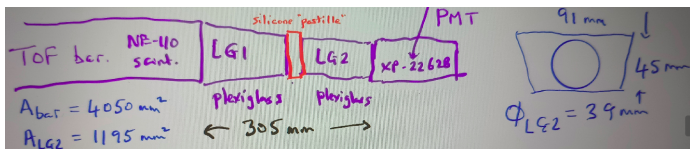
- ➊ How would you design an OPAL-inspired TOF-like system for ILD today targeting 50 ps per MIP? CDF achieved about 125 ps.
- ➋ Can a WLS-fiber approach make sense? While more light-yield challenged, and longer decay constants, time dispersion in a fiber is reduced. Compact and efficient light collection.
- ➌ Cherenkov bar concepts such as Cherenkov-Correlated-Timing (CCT), iTOP, TORCH may be interesting. Prompt light! Use internal reflection and highly-pixellated photodetectors to reconstruct θ_C using time and position.

Thinking about question 1, it became apparent that understanding better the limitations of the OPAL TOF would be a good idea.

Consequently I have been looking to better understand/calibrate the OPAL TOF using test-beam data (see later slides).

OPAL Time-of-Flight (TOF) Barrel Detector at LEP

- Consisted of 160 6.84 m **long** NE-110 scintillation counters located in the barrel region with trapezoidal cross-sectional area, 45 mm thick, 89–91 mm wide and at a mean radius of 2.362 m.
Acceptance: $|\cos \theta| < 0.82$, 2π in ϕ but azimuthal gaps of 2.6 mm.
- Located outside the solenoid. So B-field OK for conventional photomultipliers. Mainly XP2262B with $\sigma_{\text{TTS}} = 0.5$ ns. Constant-fraction discriminators. Both PMTs digitized using TDCs and ADCs.
- I was responsible for the initial collision based calibration for LEP1. This used a simple model where the scintillation light propagation speed was assumed constant at 17.5 cm/ns for all bars and propagation distances.
- LEP data 1989–2000. Test-beam data (1986–1988) never published.



Initial ideas on TOF for ILD

Focussed so far on the barrel. Considering both direct readout and WLS fiber readout.

- OPAL TOF was FAR too long. ILD barrel ECAL is 4700 mm long. Need at least 3 segmentations in length for ILD for timing and occupancy. For example: 1700:1300:1700 (central has more solid angle and shorter scintillator path-length).
- ILD octagonal ECAL model. Make sure each octagon has odd number of bars (avoid pointing cracks).
- Require compact B-field compatible optical readout directly at both ends of the bar. Essential for noise reduction especially with SiPMs.
- For robustness. Require 2 independent measurements per end and/or 2 independent layers.
- Transverse area. Depends on photo-detector choice and WLS or not. Should be at least a factor of 2 smaller in $\Delta\phi$, eg 4cm wide at 1.8 m.

Fast timing with SiPM TOF approach

Maybe there are other examples. Cast scintillator.

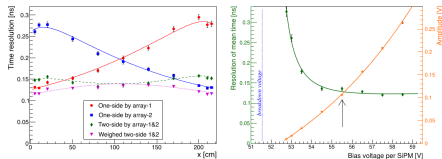
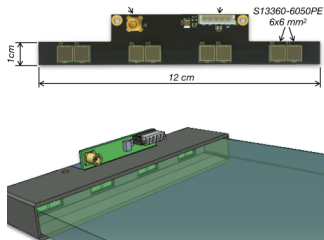


Figure 5. Left: time resolution of one-side readout (approximated by solid curves), the resolution of two-side readout (approximated by broken curves) as a function of distance along the bar. Right: two-side resolution (left axis of histogram) and the signal amplitude (right axis of histogram) at the center of the bar, $x = 110$ cm, versus the bias voltage. The voltage used during data taking is indicated by the arrow.

Korzenev et al. Scintillator is $120 \times 10 \times 2200 \text{ mm}^3$.

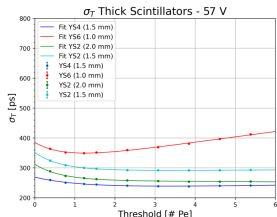
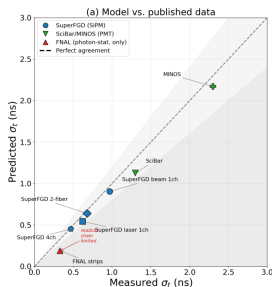
How to apply to ILD?

Potentially $18 \times 10 \times 1300 \text{ mm}^3$ with two 6×6 SiPMs per end. Likely better with at least two independent layers, potentially offset in ϕ .

Understanding time response ab initio is a complex business. Also potential for highly pixellated and waveform based data records (a la iTOP etc).

Fast timing with WLS

Focus has been on muon detection with (cheap) extruded scintillator. Now faster WLS (YS2/4: 3.2/1.4ns).



Che & Yang, 2607.14290. Red triangle is with 12 mm thickness.

LEMUR talk cited in Riccardo's muon talk yesterday. 16mm thick, 95 cm long. Expect 200 ps with single YS4 2mm. Scope for more fibers per strip.

How to apply to ILD for TOF?

Considering large extruded hole with 4 or 7 YS4 fibers to increase fast capture acceptance. (Need to understand issues with air gaps ...) Also likely 2 layers. How about 2 large extruded holes with 2 SiPMs per bar end?

Minimally-invasive Cherenkov-inspired possibilities

Example BELLEII-iTOP (2504.19090)

IR of Cherenkov light in 2cm thick fused silica bars.

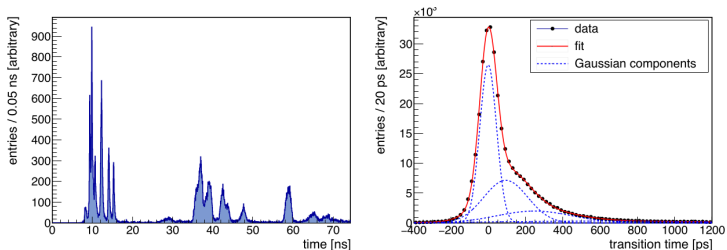


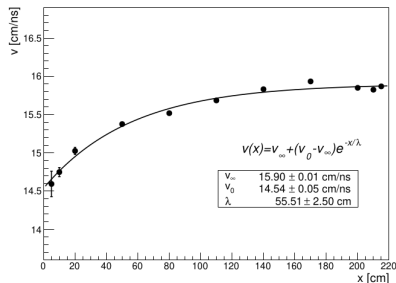
Figure 37: Typical timing peaks of Cherenkov photons for one pixel (left), and the TTS distribution measured on the bench of an ALD-type MCP-PMT. The latter is fitted with the sum of four Gaussians. The respective widths (σ) of the Gaussian components, after correcting for the resolution of the electronics, are 33.5 ps, 114 ps, 199 ps, and 552 ps; the respective fractions are 46%, 32%, 15%, and 7%.

Reconstruct Cherenkov angle using (x,y) position of detected photon and time of arrival. Multi-anode MCP-PMT. Bars are $450 \times 20 \times 1250 \text{ mm}^3$ with 32 MCP-PMTs with 16 anodes (512 "pixels" per bar ...) - single end readout. Consider something similar for scintillator with double-ended readout.

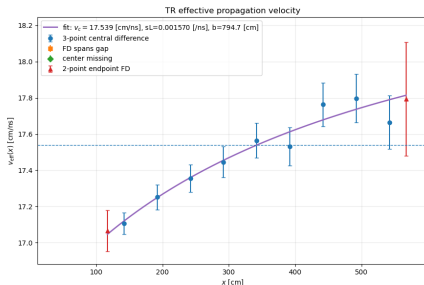
- Need to adapt to endcap ECAL geometry too.
- Each quadrant is 1850 mm in radial extent.
- Need narrow x-strips and y-strips per quadrant of different lengths.
- Presume readout at both ends.
- Need narrower strips at small r ?
- May also argue for shorter strips for occupancy concerns.

Analyzing OPAL Test-beam Data

Each OPAL TOF counter was tested with 5 GeV/c charged pions. For each counter there are essentially 6 measurements: T_L , T_R , A_L , A_R and the standard deviations of T_L and T_R as measured at 11 different points from -250 cm to +250 cm from the bar center at normal incidence. Why my interest?



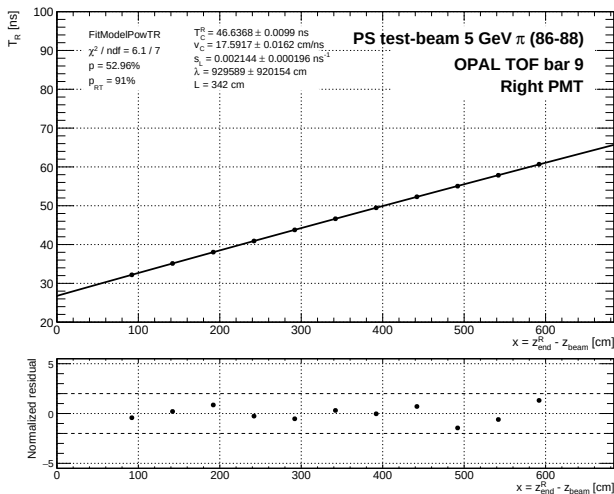
Modern TOF papers measure the effective propagation velocity vs propagation distance (x). ND280/T2K TOF upgrade (EJ-200) [Korzenev 2022]



OPAL test-beam data for TOF 10R. v_{eff} does depend on propagation distance! Note different v_{eff} scales! Correcting this effect likely essential for ultimate σ_t .

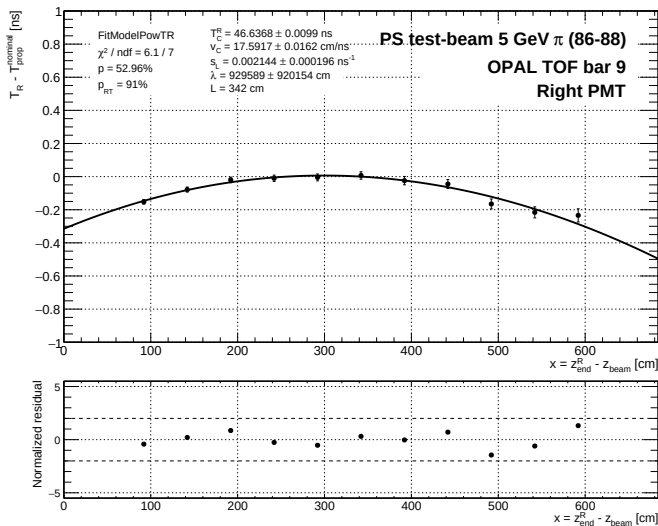
Time vs propagation distance

Fit such that $v(u) = v_C + s_L \lambda u / (u + \lambda)$ where $u = x - x_C$. In many cases the fit ends up with λ large, corresponding to essentially $v(u) = v_C + s_L u$.



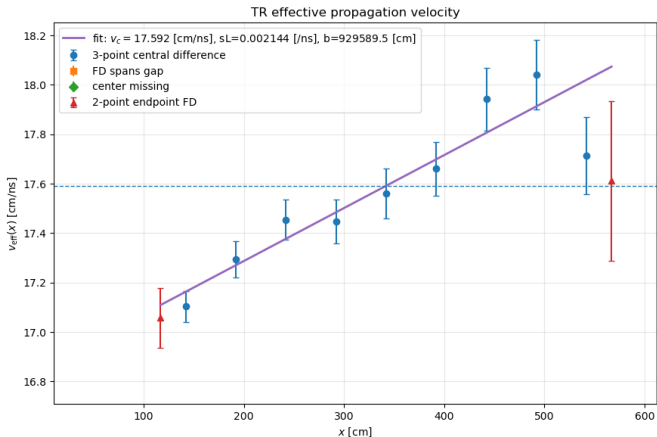
Time vs propagation distance

Same fit, but subtract the nominal propagation time (using 17.5cm/ns) in the linear model.



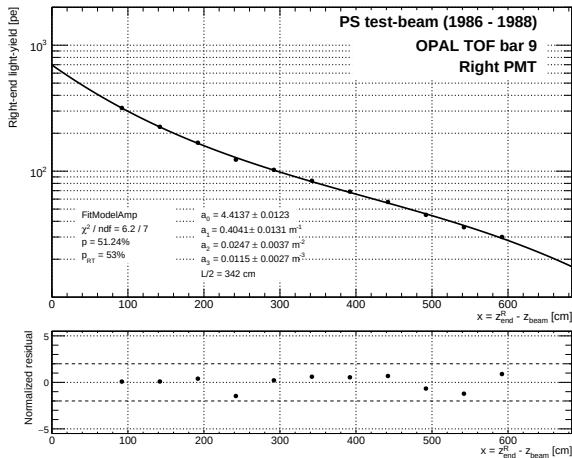
Effective velocity vs propagation distance

Estimate effective velocity using finite differences. Here OPAL TOF-9R.



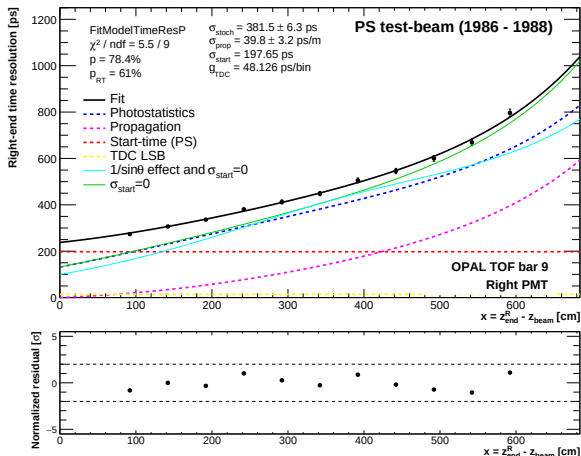
This uses the T vs x modeling and extracted finite difference estimates for effective speed. Could also fit directly if correlations accounted for. Reasoning: Detected far light travels at more direct angles (shorter path) due to attenuation.

Fitted pulse-height vs propagation distance



Use these parameters to model N_{pe} vs x .

Fitted time resolution vs propagation distance



$$\text{Model: } \sigma_t^2(x) = \sigma_{\text{start}}^2 + \sigma_{\text{TDC}}^2 + [\sigma_{\text{stoch}}^2 + (\sigma_{\text{prop}} x)^2] N_{\text{pe}}(x_C) / N_{\text{pe}}(x)$$

Excellent fits to all 320 bar-ends. Need flexibility of the additional linear in x propagation term.

Summary

- Identified three potential approaches to optical TOF that can be considered for application in ILD.
- Current focus has been on time resolution for pre-ECAL layer(s).
- Should also plan on a hermetic wrapper timing layer guaranteeing direction ID likely between ECAL and HCAL for particles traversing the ECAL.
25 cm separation or so. Assuming 50 ps from R_{TOF} , could relax to 200 ps resolution for the outer layer(s) for $8\text{-}\sigma$ direction ID in barrel and endcap.
- Classic TOF with long bars has limitations from propagation dispersion - needs accurate modelling of z -dependent effective propagation speed.
Improved performance for OPAL TOF looks feasible using test-beam based calibration improvements.
- Many open questions on utility of various segmentation/readout options in the context of timing response.