Research on Pico-second Timing TOF Technology

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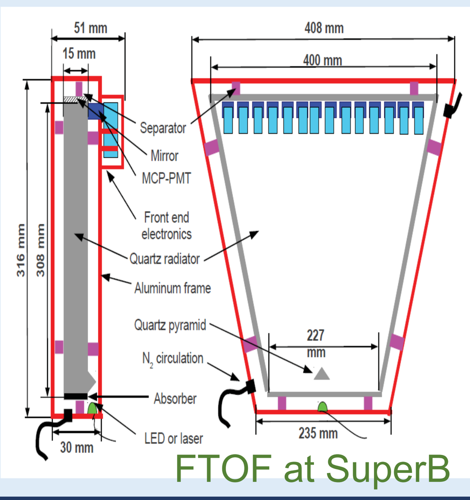
Abstract

To meet the requirement of the new-generation particle accelerators with increasing energy and luminosity, the identification of high density and high energy particles in various states and large momentum range has become a key issue in high energy particle experiments. In order to achieve the high time resolution it requires, Pico-second Timing (PsT) technology has been took as a crucial development of high energy particle detectors. We developed an experimental prototype of pico-seconds timing TOF (Time-of-Flight) counter based on the detection technology of internally reflected Cherenkov lights (DIRC). The detector is consisted of a Cherenkov radiator connected to fast micro-channel plate PMTs (MCP-PMT), and readout by a programmable differential amplifier, a dual-threshold differential discriminator, and a timestamp Time-to-Digital convertor with the dedicated FPGA (Field Programmable Gate Array). The beam test results demonstrate that it could achieve an excellent intrinsic time resolution around 20ps without any time corrections. A GEANT4 simulation framework is also established, simulating its time performance and compared with the experimental data. With its compact structure, fast timing performance, and relatively low material budget, it is a promising candidate of the trigger and timing detector in high-luminosity particle experiments.

PsT based on DIRC-Like TOF

DIRC-like Time-of-Flight detector (DTOF) is an innovative TOF utilizing internally reflected Cherenkov light for high energy charged particle identification. It achieves a high level of timing performance at the extreme data taking conditions under high luminosity and high backgrounds. It is composed of a Fused Silica radiator connected to fast photomultiplier (MCP-PMT or SiPM) array, readout by a dedicated front-end electronics. In recent years, a number of large international experiments have already applied similar technology in TOF upgrade, like TOP at BELLEII [1], TORCH at LHCb [2], and FTOF at superB [3].

- Enable π/K/p separation up to 2GeV/c
- Suitable for high luminosity run – fast timing ~30ps
- Radiation hard, especially in the endcap region
- Compact – reduce costs of the outer detectors
- Modest material budget.

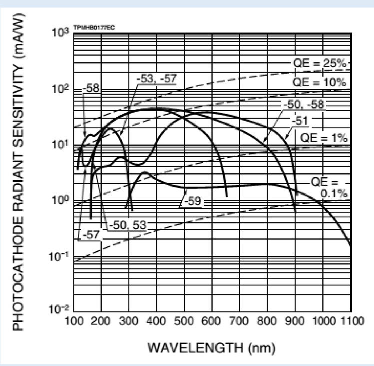


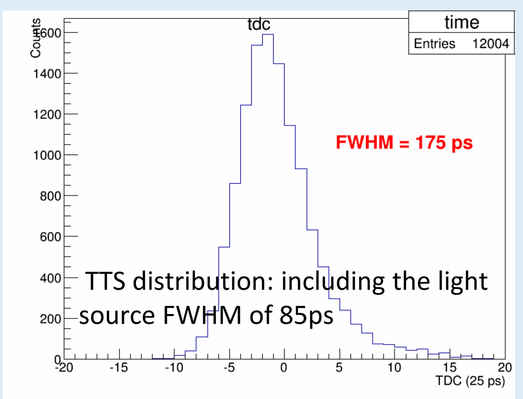
[1] Inami, Kenji for BELLEII collaboration, TOP counter for particle identification at the Belle II experiment, Nucl. Instrum. Meth. A766 (2014) 5-8
[2] N. Harnew et al., TORCH: A Large-Area Detector for Precision Time-of-Flight Measurements at LHCb, Physics Procedia 37 (2012) 626-633
[3] Burmistrov, L., The DIRC-like FTOF: A Time-of-flight Cherenkov detector for particle identification at SuperB, Acta Phys. Polon. Supp. 1 (2011) 91-99

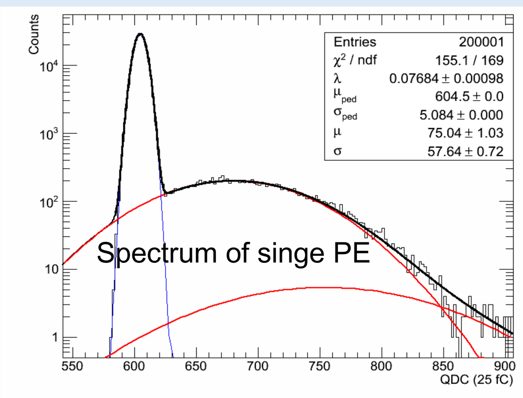
Fast Timing MCP-PMT

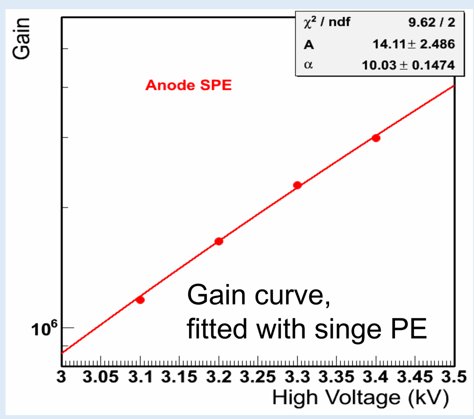
Hamamatsu R3809U

- Pico-second time response (rise time ~150ps)
- A good sensitivity for Cherenkov lights ~300nm
- Up to 10^6 gain at -3100V



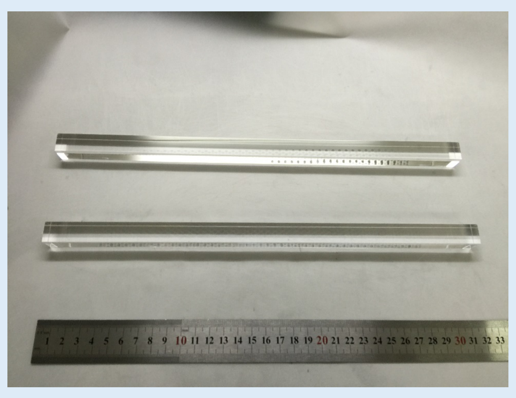


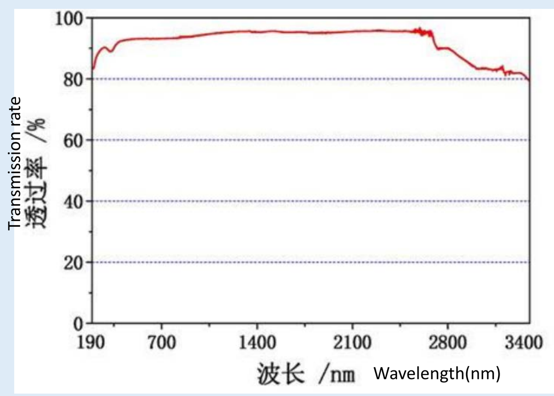




Fused Slica Radiator

JC-H02 pure quartz glass made by Beijing Quartz and Special Glasses Institute, metal impurities <1ppm. The quartz glass uses silicon tetrachloride as raw material, with transmission index from far ultraviolet to near-infrared spectrum.

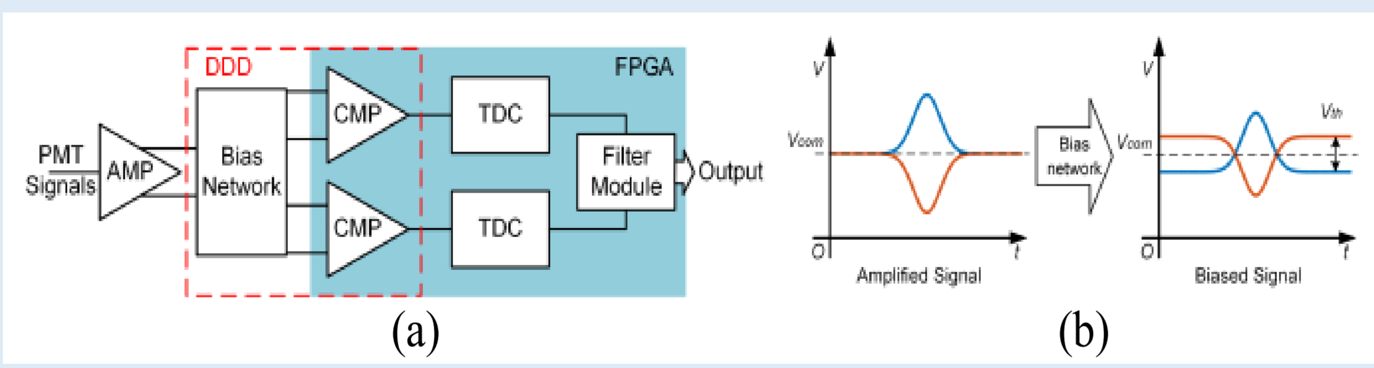




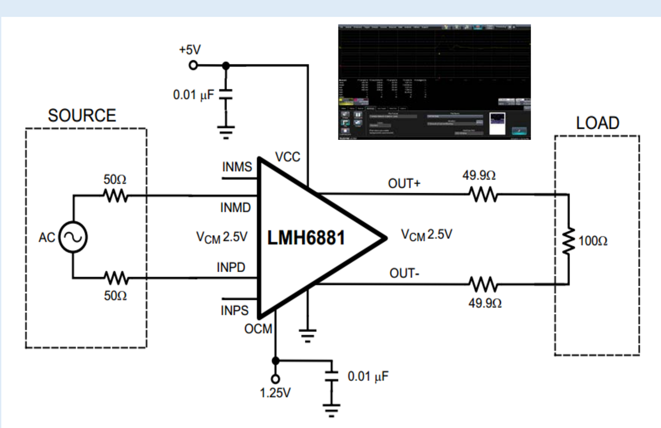
- Spectrum transmittance (especially UV) > 90%
- All surface flatness 0.1 mm or better
- All edge width less than 2.5 mm
- All surface roughness reached 200 angstroms RMS
- Typical perpendicularity between two surfaces: < 0.1 °

Readout Electronics

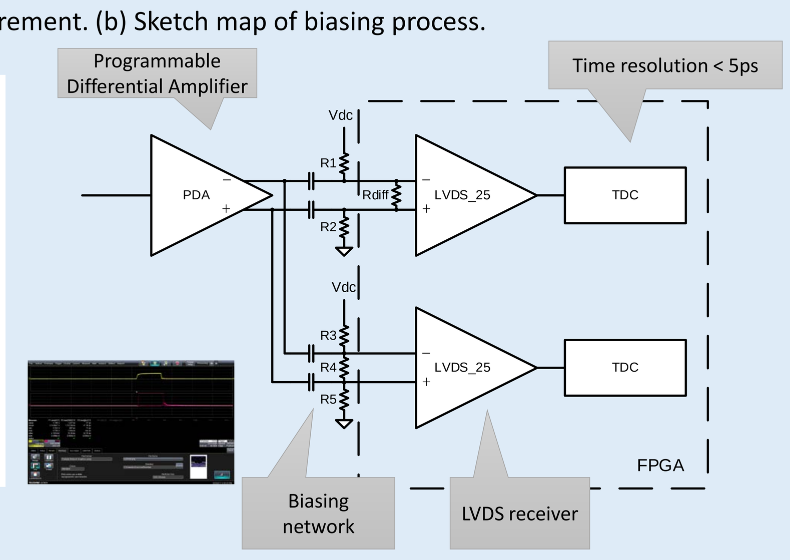
The readout electronics with the dual-threshold front-edge timing scheme is designed by electronics group at USTC. It is mainly consisted of a programmable differential amplifier (PDA), a dual-threshold differential discriminator (DDD), and a timestamp TDC with the dedicated FPGA. The bandwidth of this amplifier is 2.4 GHz over the gain range from 6 dB to 26 dB.



(a) Schematic diagram of pico-second time measurement. (b) Sketch map of biasing process.



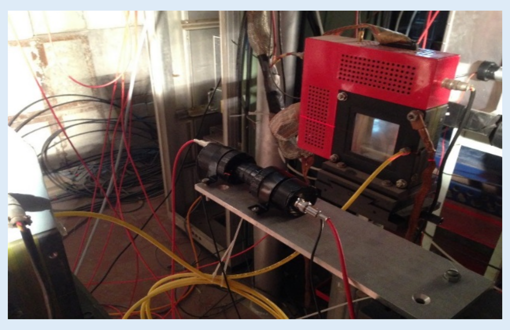
Schematic diagram of PDA and its amplified pulse

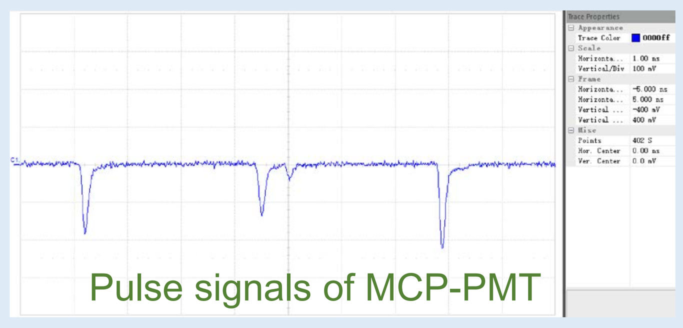


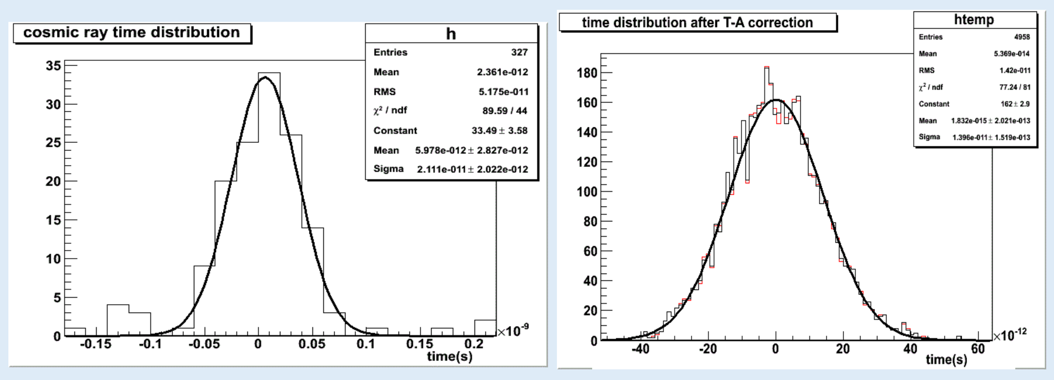
Schematic diagram of DDD and its converted signal:
lower threshold for event timing
upper threshold for identifying signal from noise

Cosmic Ray and Beam Test

In order to understand the detector's output characteristics, we used a high-bandwidth oscilloscope (sampling rate 40Ghz/s) to directly measure the time distribution of output signals by cosmic ray and BEPC-E3 beam (800MeV protons).



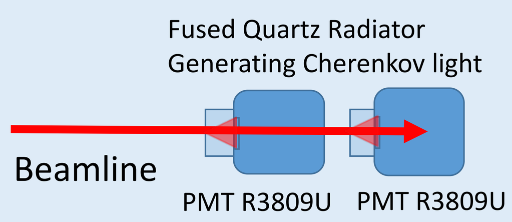


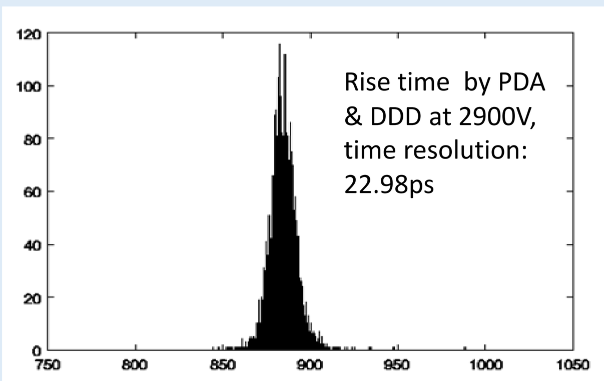


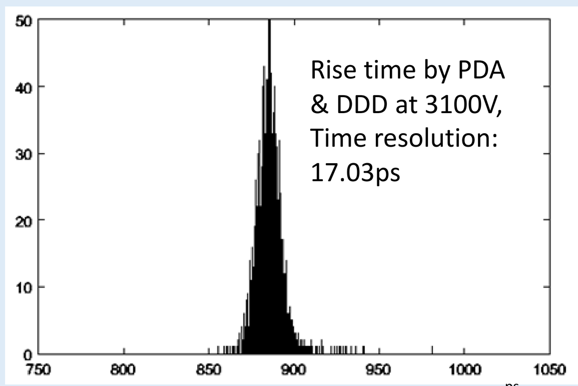
The Cosmic Ray Test with Time Resolution ~ 21ps (left) and Beam Test (BEPC-E3)with Time Resolution ~ 14ps (right)

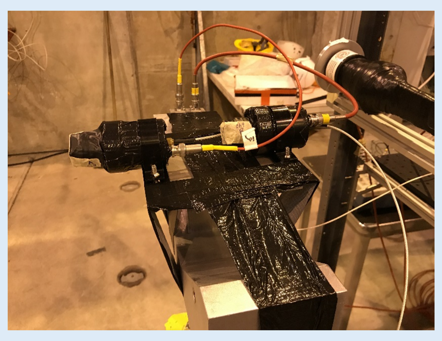
Beam Test at CERN H4

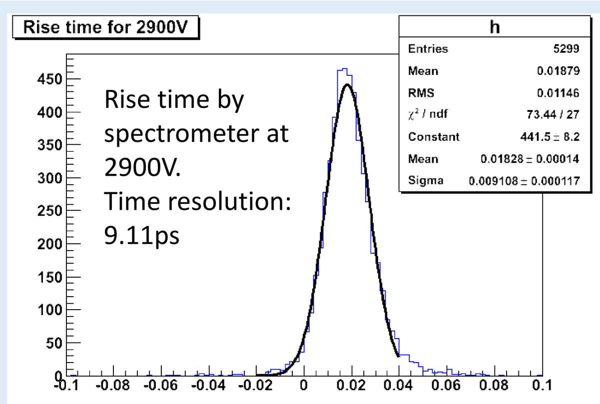
To test the performance of the prototype in field, we corporate with RD51 group, attending the beam test in H4 beam（150GeV/c, Muon) at CERN. Here we used two radiator + MCP-PMT detector, matched their signals and obtain the timing distribution from each of them. The trigger signal is provided by the beam system and the reference timing (T0) accuracy is 5 ps. PDA gain is 20dB. The threshold setting is: upper threshold of 390.6mv (to identify signal from noise), lower threshold 28.7mv (to measure signal arriving time).

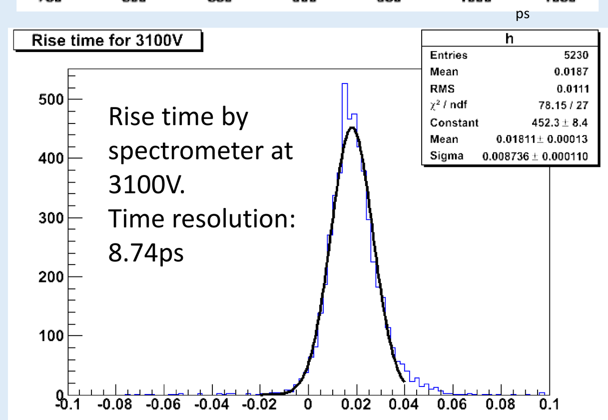










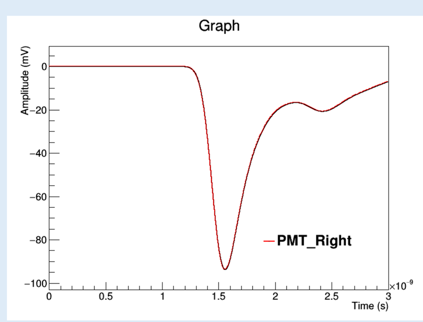


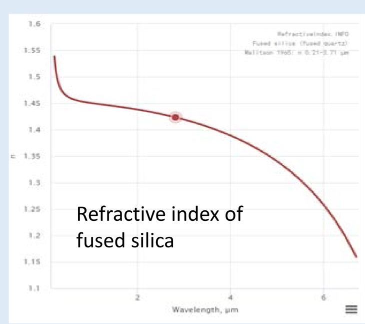
The intrinsic time resolution readout by DDD&PDA (upper ones) and spectrometer (lower ones) in H4 beam test

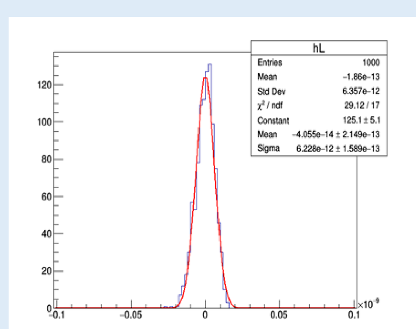
GEANT4 Simulation

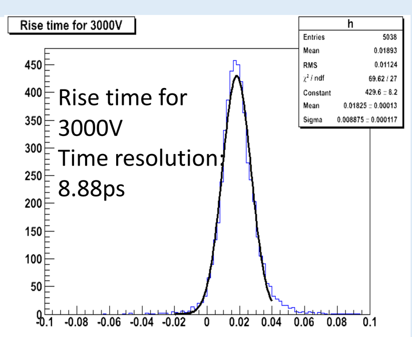
Monte Carlo simulation is based on GEANT4 simulation kit and ran in the following steps:

- Generate a 150 GeV Muon across the fused silica radiator and produce Cherenkov photons same as in the beam test.
- Simulate photons' transmission process in the radiator, record the arrival time if photons hit the MCP active area.
- Simulate the output signal of MCP by C++.
- Discriminate the signal by threshold and extract the timestamps. Use a Gaussian fit to obtain the time resolution.









Comparison of Time resolution between Monte Carlo (left) and beam test (right)

Summary

Pico-second time TOF is a very challenging technology in particle detectors, especially its compact structure and multi-channel fast electronics. The prototype we proposed exhibits an excellent time performance, showing great potential for high energy particle identification. Considering the prototype and readout electronics are preliminary design, we believe that it's worthwhile for further research and development.

Special thanks for all help and supports from RD51 group and USTC colleagues!