Timing of single photons in the Focusing DIRC prototype

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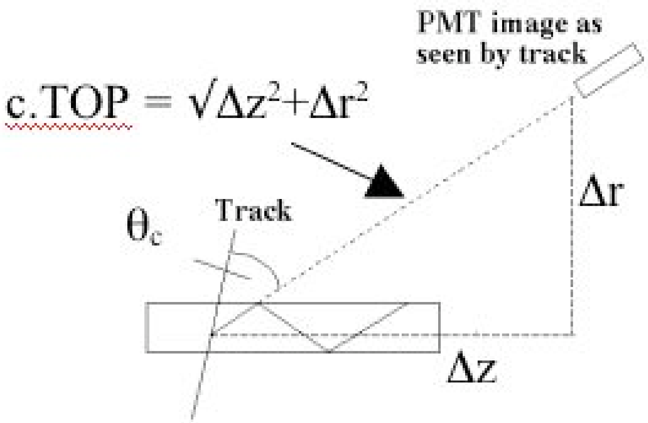
SLAC

Goal

- To develop a reliable photon detector concept & electronics for the Future Focusing DIRC.
- The system should be able to measure the x&y coordinates of each photon to give a similar angular resolution as the present DIRC in BaBar, however, each photon will be measured with a ~100ps timing resolution, which will allow to correct the chromatic error by timing.
- Prove the idea in the test beam.

Time-of-propagation principle in DIRC



- **$TOP(\Phi,\theta_c) = [L/v_g(\lambda)]\ q_z(\Phi,\theta_c)$**

  θ_c - Cherenkov angle,

  L - distance of light travels in the bar,

  $v_g(\lambda)$ - group velocity of light,

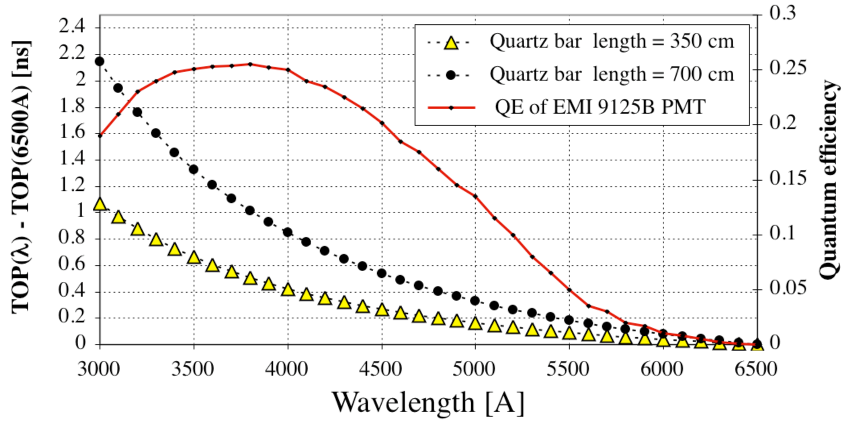
  λ - wavelength , and

  $q_z(\Phi,\theta_c)$ - z-comp. of the unit velocity vector.

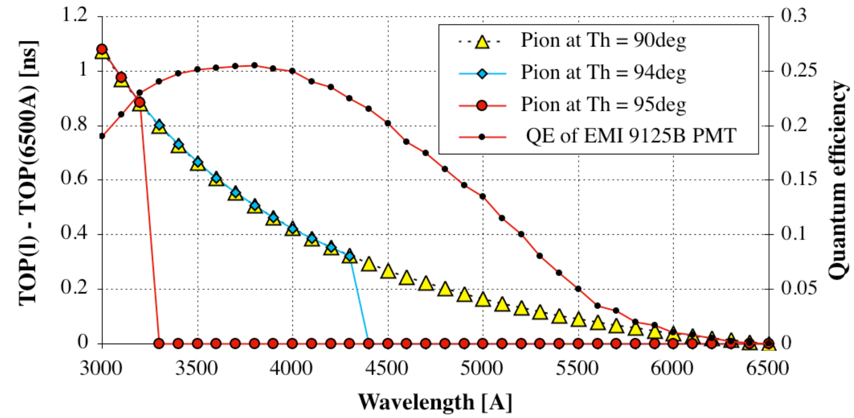
- To determine the Cherenkov angle θ_c, one measures (a) a track position, (b) a photon time-of-propagation (TOP), and Δz and Δr ($\equiv \Delta y$). This over-determines the triangle.
- In the present BaBar DIRC, the time measurement is not good enough to determine the Cherenkov angle θ_c. The time is, however, used very effectively to reduce the background.
- The Focusing DIRC will still measure the x&y coordinates of each photon to give a similar angular resolution as DIRC, however, each photon will be measured with a ~100ps timing resolution, which will be used to correct out the chromatic error, and to suppress the background.

Timing dependence on the chromaticity in a long DIRC bar as a function of bar length, particle type and bar angle

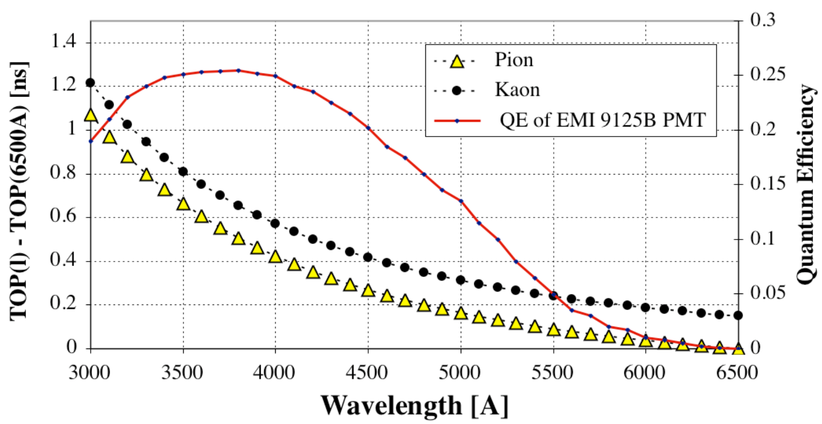
Dependence on bar length:



Bar angle can introduce a chromatic cut:



Dependence on particle type:



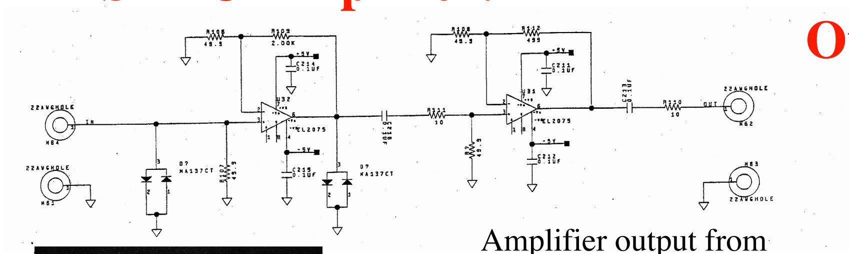
- **Bialkali photocathode bandwidth.**
- **Θ_{track} = 90^{o} (perpendicular to bar).**
- **Photons propagate in y-z plane only in these calculations.**
- **4 GeV/c, L = 3.5m or 7m long bar.**
- **1-2 ns overall range. Need 100-150ps timing resolution to parameterize it.**
- **One can also introduce a chromatic cut by a slight change of incident angle (a neat trick to be used in test beam).**

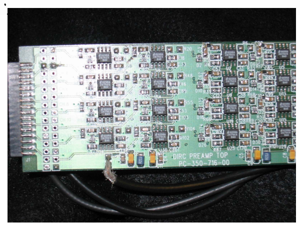
Examples of the transit time distribution σ_{TTD} of typical photon detectors

Manufacturer	Name	PMT	σ_{TTD} [ps]
Photonis	Quantacon	XP2020	250
Photonis	PMT	XP2020/UR	150
ETL	**DIRC PMT**	9125B	1500
Hamamatsu	**Flat-panel**	H-8500	~130
Hamamatsu	Multi-mesh	R-6135	~80
Burle	**MCP-PMT**		~60
Dolgoshein	Silicone PM	SiPM	~60

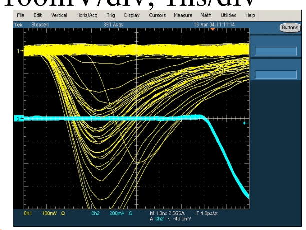
Focusing DIRC electronics

SLAC Amplifier:

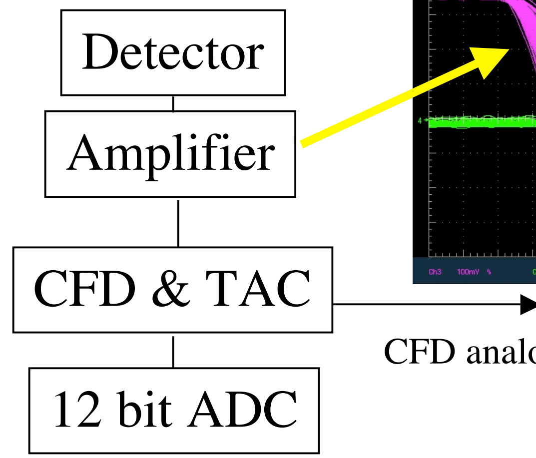




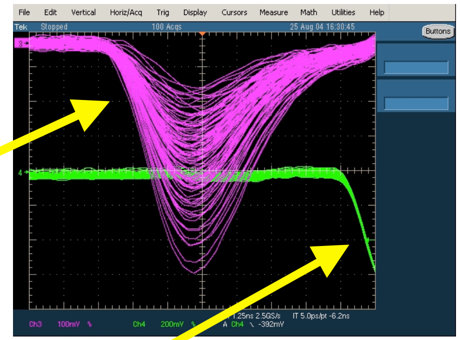
Amplifier output from MCP-PMT (trigger on PiLas), 100mV/div, 1ns/div



Overall chain:

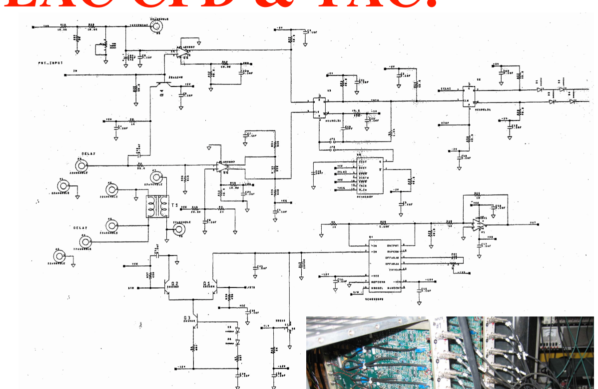


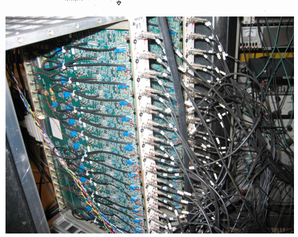
Amplifier outputs from MCP-PMT (trigger scope on CFD analog output), 100mV/div, 1ns/div



CFD analog pulse out

SLAC CFD & TAC:

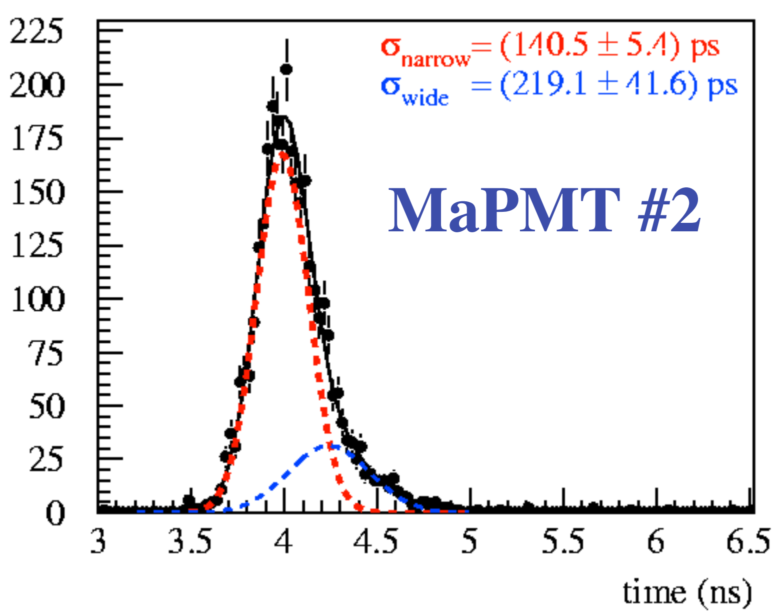




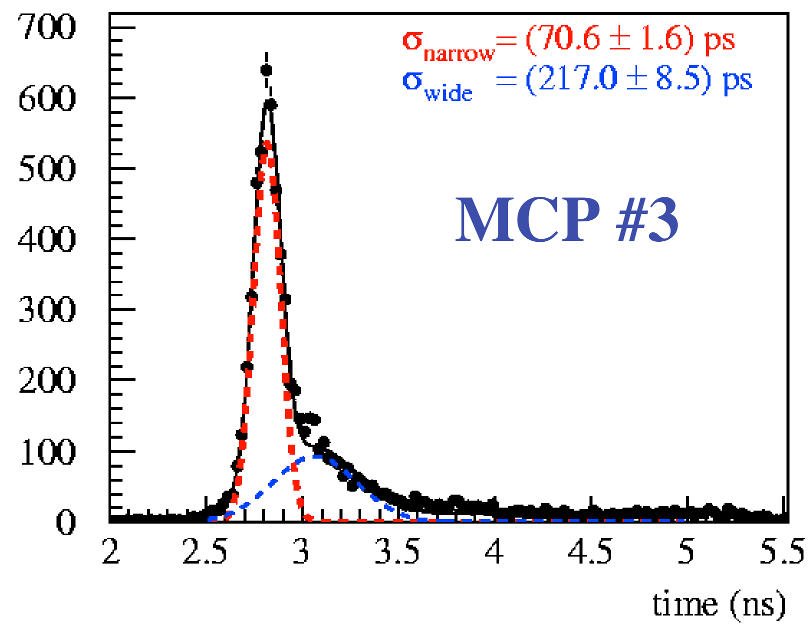
- Signals from Burle MCP-PMT #16, P/N 85011-430. PiLas laser diode is used as a light source, and as a TDC start/stop.
- Amplifier is based on two Elantek 2075EL chips with the overall voltage gain: ~130x, and a rise time of ~1.5ns.
- Constant-fraction-discriminator (CFD) analog output is available for each channel (32 channels/board), and can be used with any TDC for testing purposes (proved to be the essential feature for our R&D effort).
- TAC circuit is based on Burr-Brown Sample/Hold SHC5320 chip.
- 32-channel/board, VME-based, 12 bit ADC, controlled by FPGA logical array. TAC/ADC system gives 25ps/count.

Timing studies in MaPMT and MCP-PMT

Hamamatsu Flat Panel H8500 PMT:

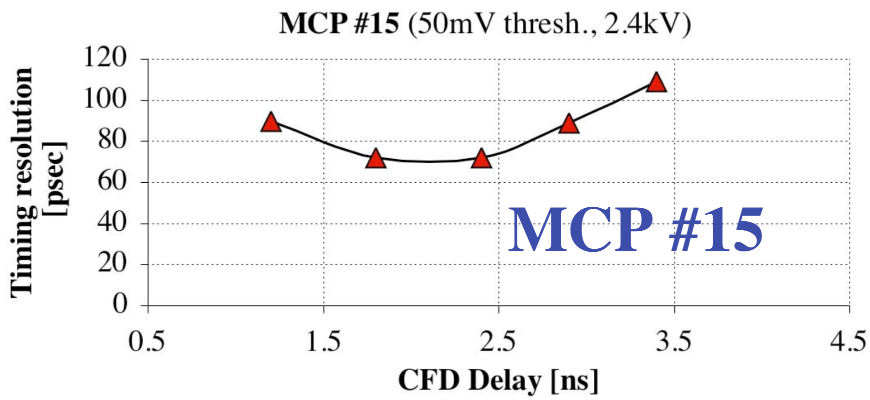


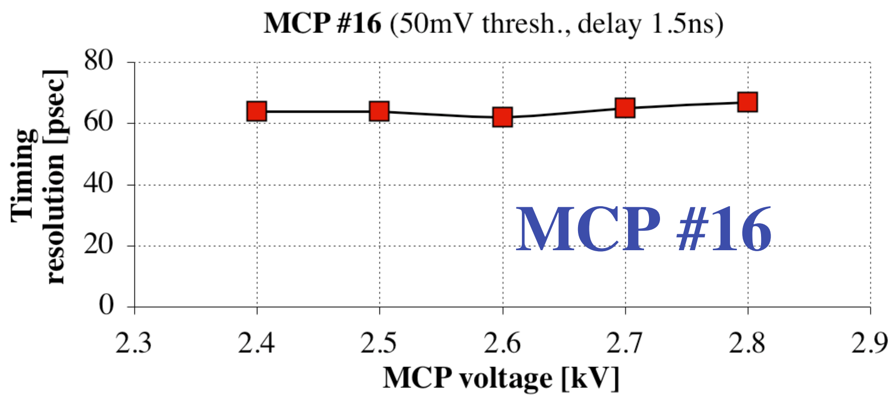
Burle 85011-501 MCP-PMT:

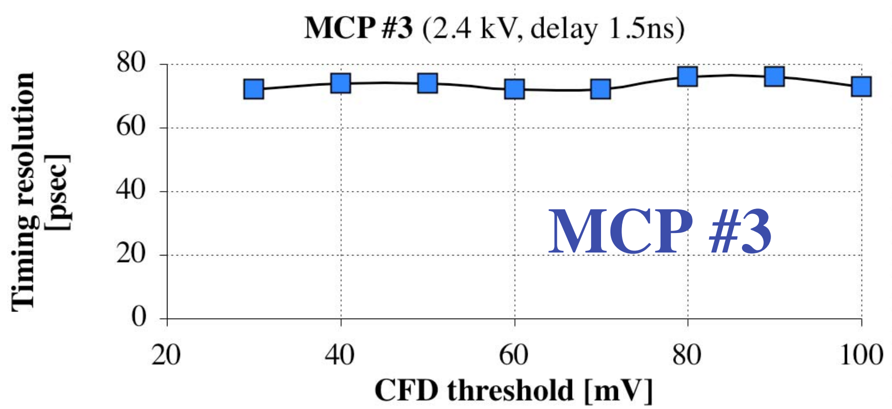


- Double Gaussian fit
- **Hamamatsu Flat Panel MaPMT resolution is good enough to correct the chromatic error.**
- **Burle MCP-PMT #3 has a very long tail due to recoil electrons from the MCP top surface (the tail contains ~20% of all events !!!). The MCP-to-cathode distance is 6mm.**
- Electronics chain used in this test: Final SLAC amplifier, final SLAC CFD providing the analog output to LeCroy 2228A TDC (25ps/count).
- Light source: Use the 635nm PiLas laser diode in single photoelectron mode.

Examples of tuning of some CFD variables





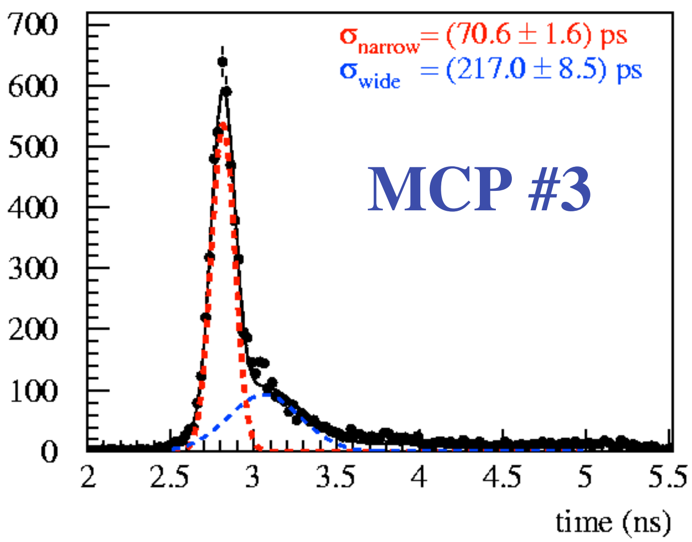


- **CFD delay seems to be the most sensitive variable in this group of tunes.**
- Display only a σ_1 (narrow one) from a double Gaussian fit.
- Detector: MCP-PMT 85011, 8x8 = 64 pads.
- Electronics chain used in this test:
  A final SLAC amplifier, a final SLAC CFD providing the analog output to the LeCroy 2228A TDC (25ps/count).
- Light source: PiLas laser diode in a single photoelectron mode (635nm).

Dependence on the MCP PMT design

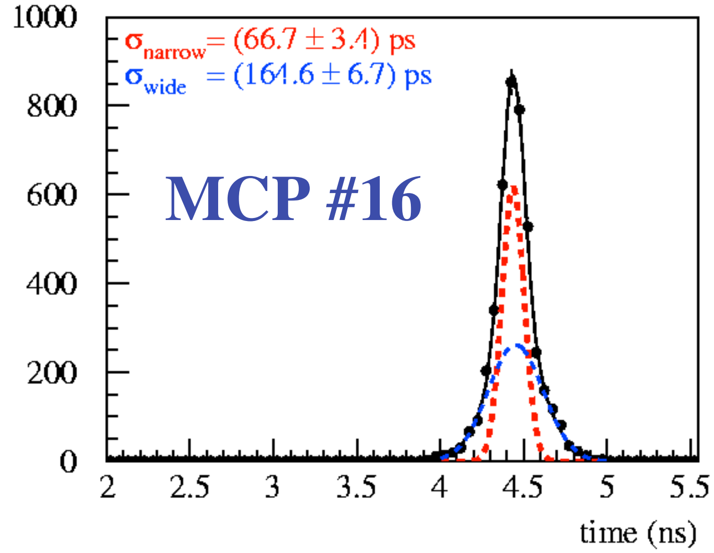
Old design (85011-501):

MCP-to-Cathode distance = 6 mm



New design (85011-430):

MCP-to-Cathode distance = 0.75 mm

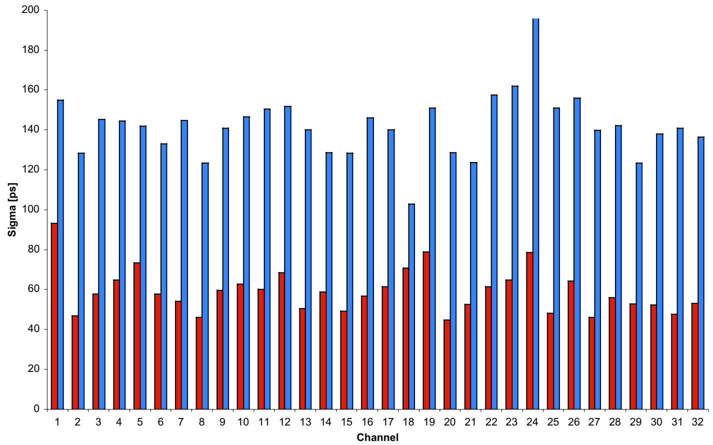


- Double Gaussian fit
- **The reduction of the MCP-to-Cathode distance to 0.75mm limits the rate of recoiling photoelectrons from the MCP surface, which reduces the tail in the timing spectrum. These electrons are, however, lost from the detection efficiency, but the spectrum is more Gaussian.**
- Electronics chain used in this test: Final SLAC amplifier, final SLAC CFD providing the analog output to LeCroy 2228A TDC (25ps/count).
- Detectors in this test: MCP-PMT #3 (old design) & #16 (new design), 8x8 pads, one pads selected.
- Light source: PiLas laser diode in the single photoelectron mode (635nm).

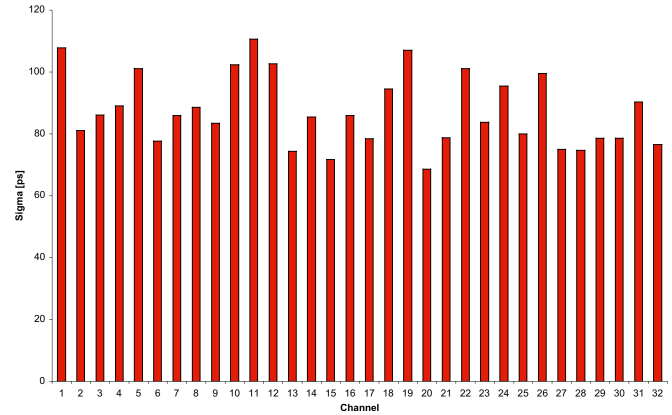
SLAC Constant Fraction Discriminator

CFD#2, MCP #16

Double-Gaussian fits:

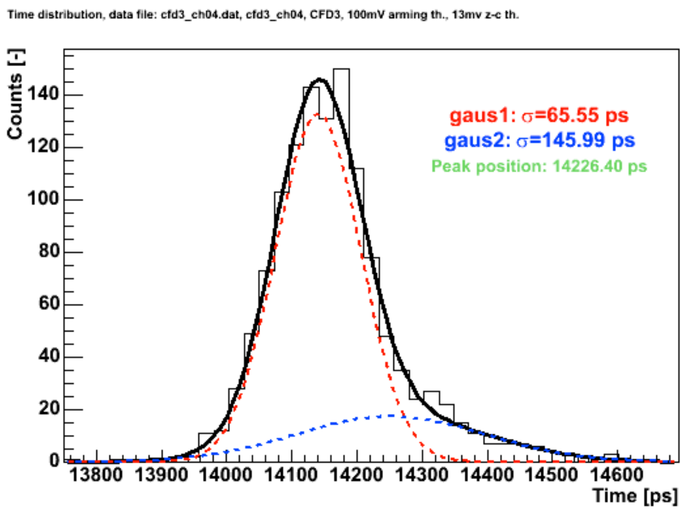


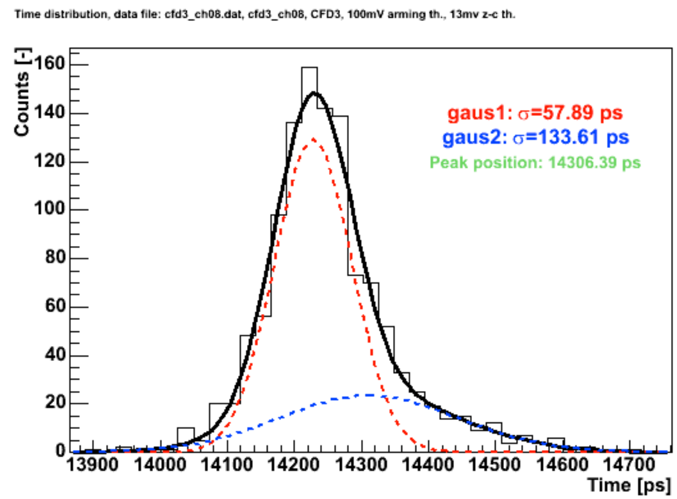
Single-Gaussian fits:



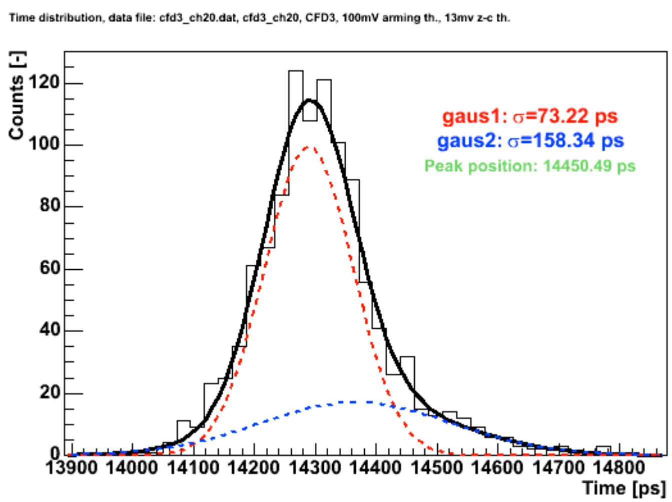
- **Typical result with a double-Gaussian fit: σ_{narrow} = 50-80ps, σ_{wide} = 120-160ps. With a single Gaussian fit, we get typically σ = 90-110ps.**
- Electronics chain used in this test: Final SLAC amplifier, final SLAC 32-channel CFD providing the analog output to LeCroy 2228A TDC (25ps/count), CFD threshold: 100mV.
- Detector in this test: MCP-PMT #16 with MCP-to-Cathode distance of 750μm, 2.6kV.
- Light source in this test: PiLas laser diode in the single photoelectron mode (635nm).

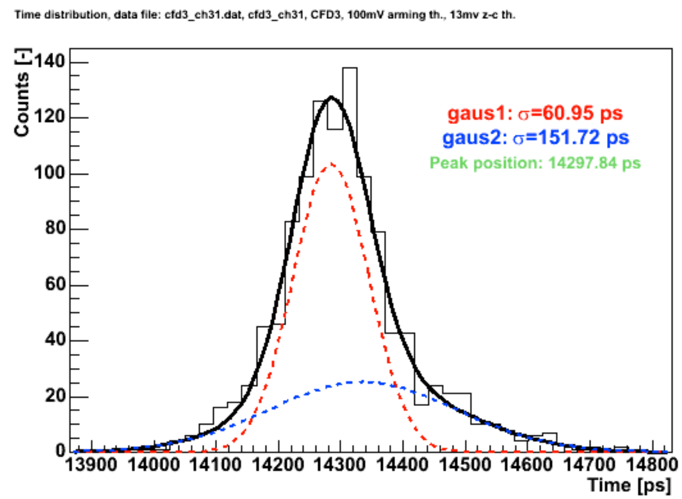
Examples of double Gaussian fits





MCP #16
CFD#3

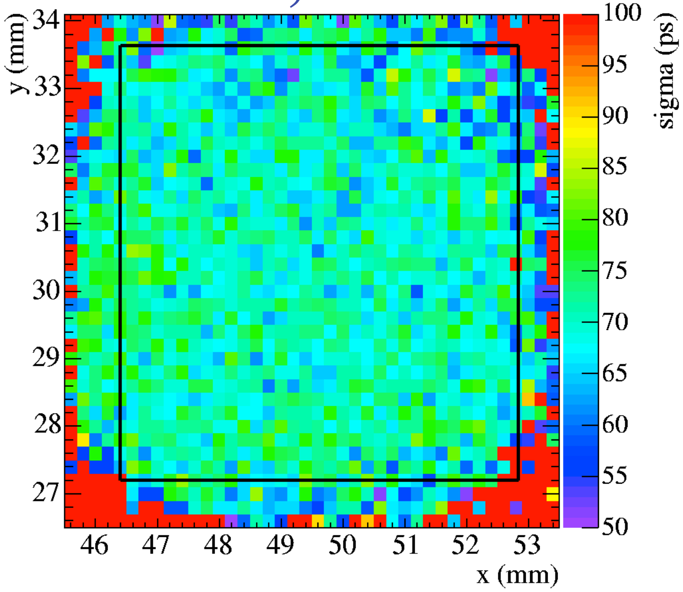




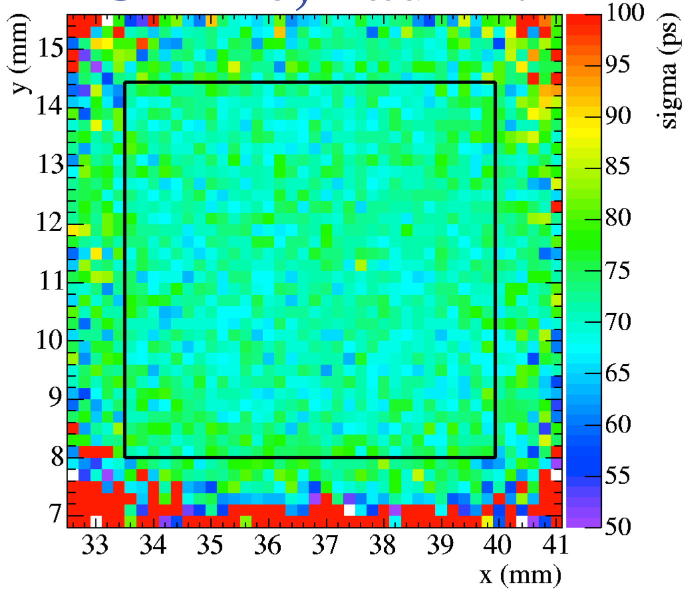
- Electronics chain used in this test: Final SLAC amplifier, final SLAC 32-channel CFD providing the analog output to LeCroy 2228 TDC (25ps/count), CFD threshold: 100mV.

Compare timing distribution on two different pads with the Phillips 7186 TDC

MCP #16, Pad 14:



MCP #16, Pad 24:

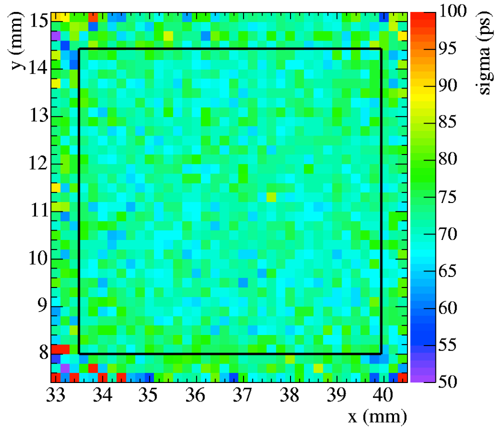


- **Single Gaussian fit** to the timing distribution generated in each laser head location.
- **Measure typically σ = 70-80ps in the central pad region, slightly worse near the boundary.**
- Worse timing resolution around edges is due to the charge sharing, causing lower pulse height, and possibly a cross-talk from hits in neighboring pads.
- <u>Electronics chain in this test:</u> final SLAC amplifier, final SLAC 32-channel CFD providing the analog output to Phillips 7186 TDC (25ps/count).
- <u>Detector in this test:</u> MCP-PMT #16 with MCP-to-Cathode distance of 750μm, 8x8 pads, 2.6kV.
- <u>Light source in this test:</u> PiLas laser diode in the single photoelectron mode (635nm).

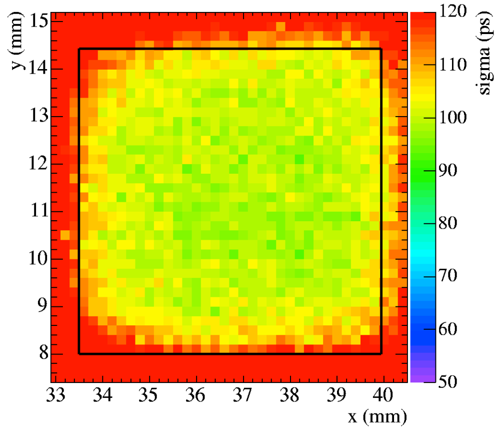
Compare SLAC and Philips TDC timing performance

Phillips 7186 TDC:

Double Gaussian Fit (display σ_{narrow}):



Single Gaussian Fit:

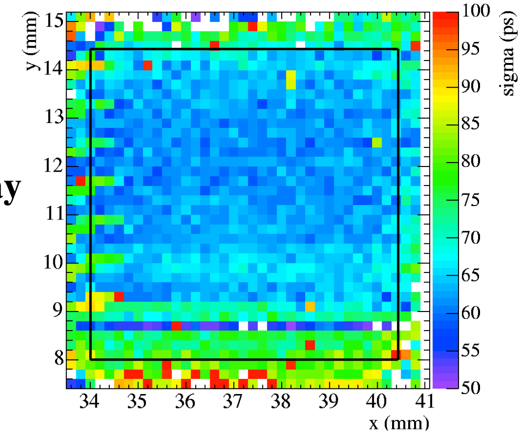


MCP #16
Pad #24

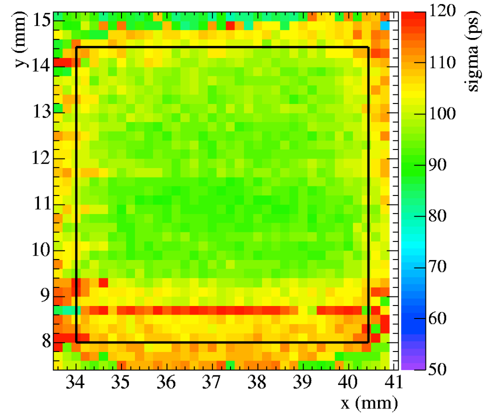
- Electronics chain in this test:
  Final SLAC amplifier, SLAC 32-channel CFD analog output, and Phillips 7186 TDC (25ps/count).
- Detector in this test: MCP-PMT #16 with MCP-to-Cathode distance of 750µm, 8x8 pads, Pad 24 selected, 2.6kV.

SLAC TDC (final design):

Double Gaussian Fit (display σ_{narrow}):

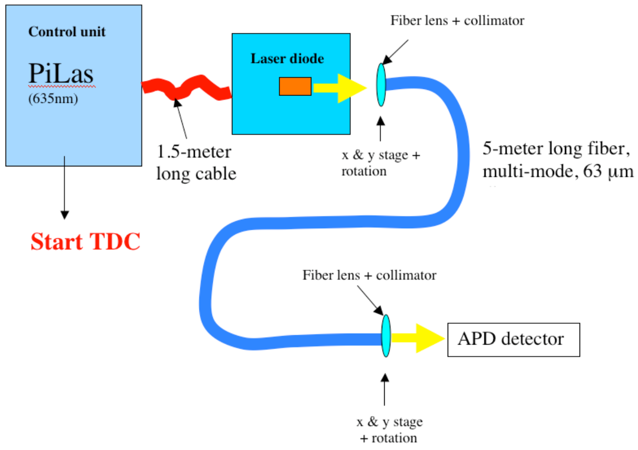


Single Gaussian Fit:

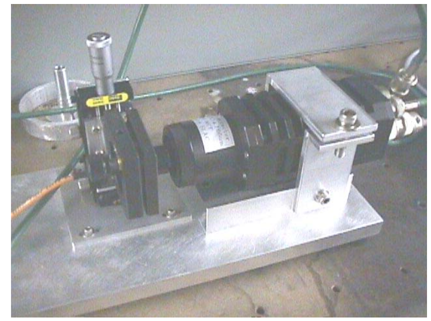


- Electronics chain in this test:
  Final SLAC amplifier, SLAC 32-channel CFD, and SLAC TAC/ADC (25ps/count), **all according to the final design.**
- Detector in this test: MCP-PMT #16 with MCP-to-Cathode distance of 750µm, 8x8 pads, Pad 24 selected, 2.6kV.
- DAQ rate is ~2kHz in this case.

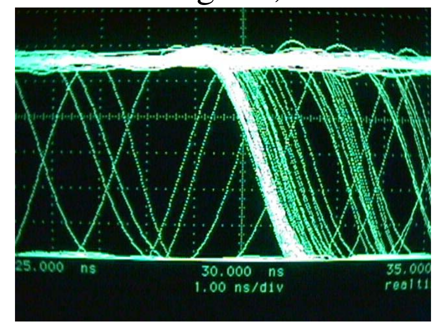
How to verify that the light PiLas laser is tuned properly ?



APD:

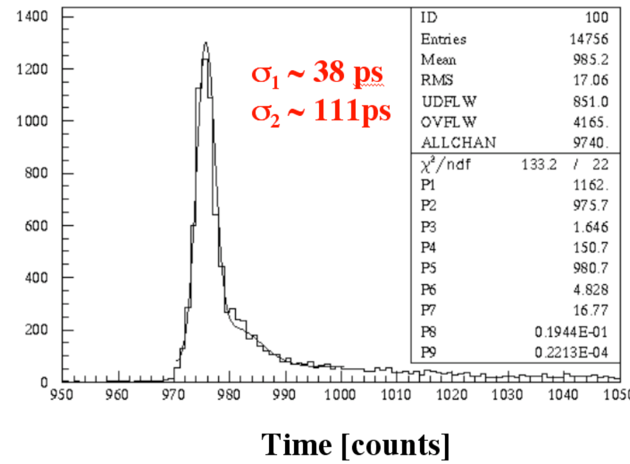


CFD analog out, 1ns/div:



Use this one in this test

Parameter	PiLas 043G	PiLas 063G	Hamamatsu
Wavelength	430 nm	635 nm	394 nm
Tolerance [nm]	± 10	± 5	
Spectral width [nm]	< 7	< 7	
FWHM of light pulse spread	< 60 ps	~35 ps	34 ps
Light pulse jitter relative to trigger	~2 ps	~2 ps	±10 ps
Peak power [mW]	> 140	> 200	

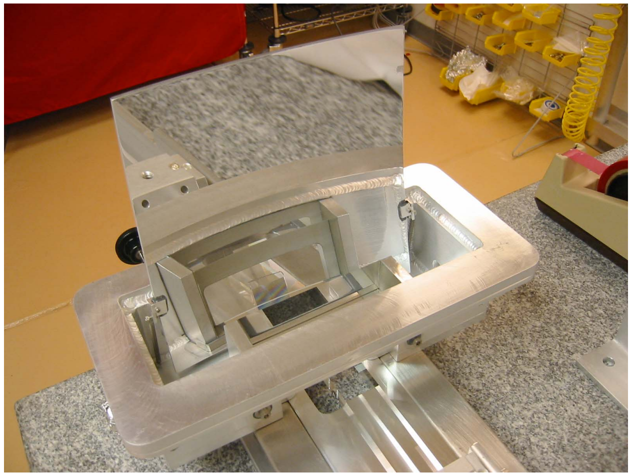


- **To check that the PiLas laser diode works as advertised, and see the limit of the SLAC CFD design.**
- **This also proves that the analog part of the SLAC CFD design performs well.**
- Detector: 100 μm dia. GaP APD operating in a Geiger mode with active quenching. APD developed by Sopko & Prochazka, CVUT Prague. The authors quote this timing resolution: σ_{diode} ~ (FWHM = 58/2.35) ~ 25 ps for the single photoelectron regime. Therefore, we expect: $\sigma_{PiLas} \sim \mathrm{sqrt}(\sigma_{result}^2 - \sigma_{APD}^2 - \sigma_{electronics}^2) \sim \mathrm{sqrt}(38^2 - 25^2 - 17^2)$ **~23 ps**; PiLas data sheet quotes: (35/2.35) **~15ps**)

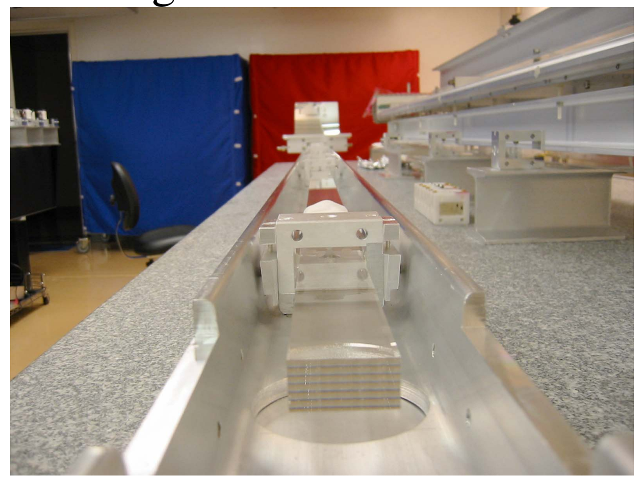
  - a small inconsistency due to some systematic error (for examle,the PiLas power set to ~11% might be too low).
- Electronics chain in this test: SLAC CFD, 30mV threshold, CFD analog output to the LeCroy 2228ATDC (25ps/count).

Construction of the Focusing DIRC prototype

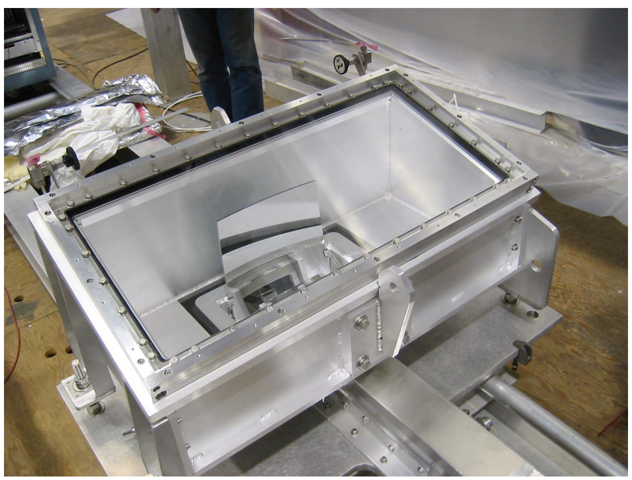
Mirror:



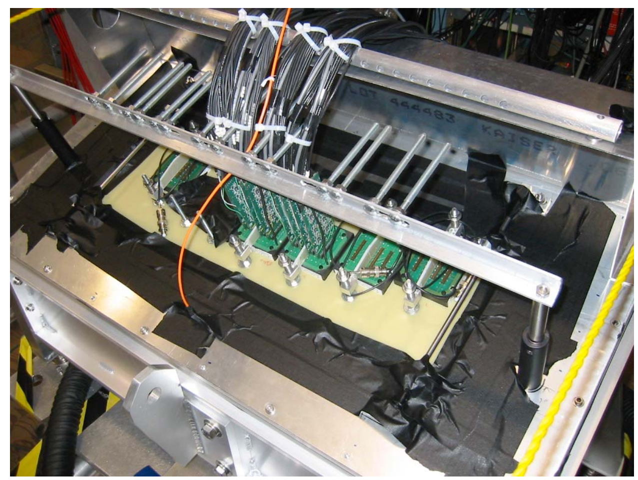
4m-long fused silica DIRC bar:



Detector filled with KamLand oil:

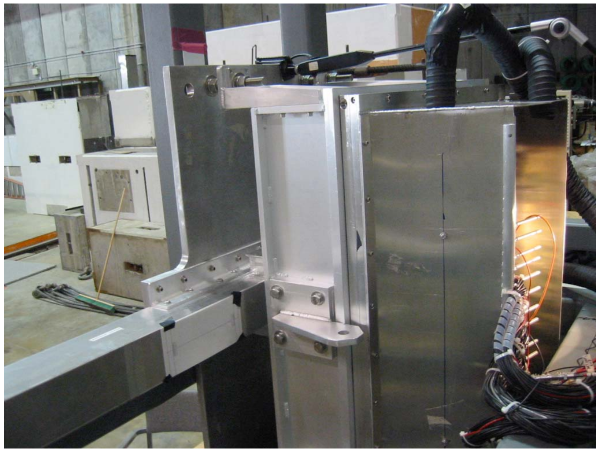


Photon detectors placed in the focal plane:

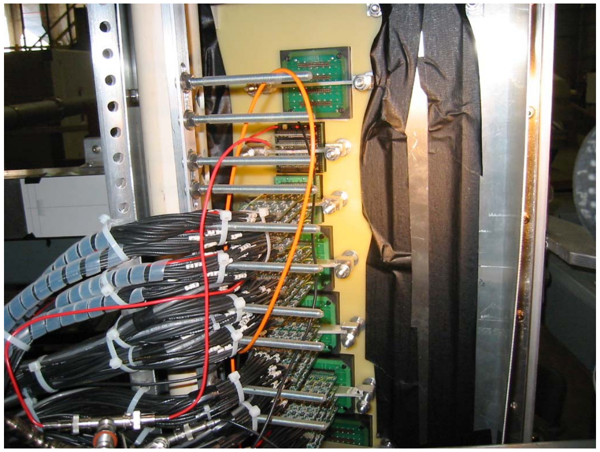


The Focusing DIRC prototype test beam setup

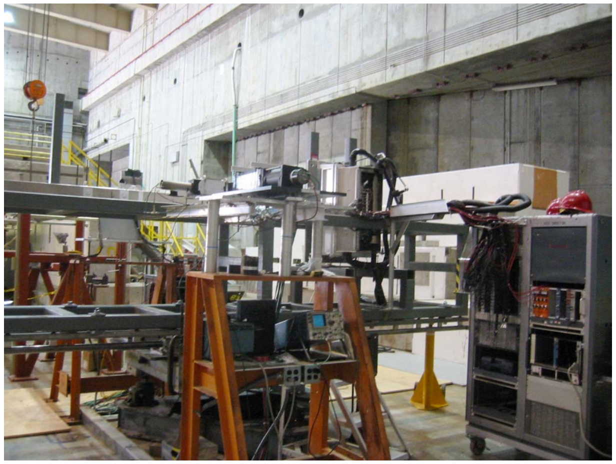
4m-long bar + Photon detector:



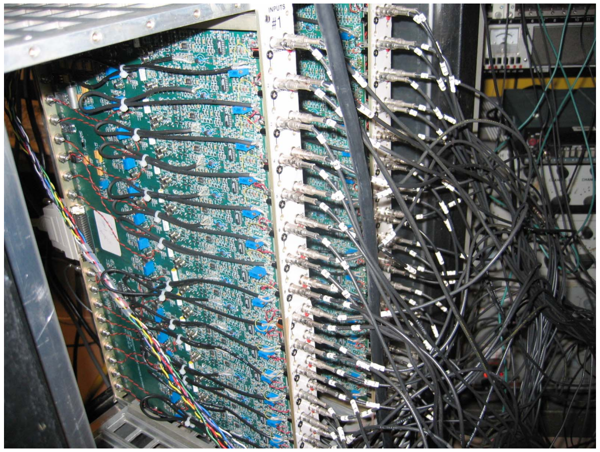
3 MCP-PMTs and 2 MaPMTs: 320 ch.



Prototype on test beam:



32-channel SLAC CFD/TAC board:



Conclusions

- We are excited to prove experimentally that the chromatic error contribution can be corrected out by high precision timing of each Cherenkov photon.
- We have developed a considerable experience with the Hamamatsu Flat Panel MaPMT and the Burle MCP-PMT photon detectors.
- We have developed the new electronics capable of measuring the single photon resolution to ~100ps. The new development includes the amplifier, the constant-fraction discriminator (CFD), and the TAC/ADC system capable of delivering 25ps/count. The system has ~300 channels.
- At this point we are confident that the SLAC amplifier and the analog part of the SLAC CFD performs well. The TAC/ADC part of the system is still being tuned presently.
- It is a considerable non-trivial effort to develop such a system with this level of performance, even on a scale of a few hundred channels.
- If a new large B-factory detector is to be built based on the Focusing DIRC idea, one would have to develop a new highly integrated electronics.
- **The Focusing DIRC prototype is in the test beam at SLAC.**