Detector R&D for SuperB and Other Future Applications

J. Va'vra, SLAC

Light travels 300μm in one ps

A highly selective history of high resolution timing

- **~35 years ago:**

  Helmuth Spieler of LBL: Built, as a part of his Ph.D. thesis work, a TOF system using MCPs for an experiment detecting heavy ions. **He routinely achieved a timing resolution of σ ~ 20-30 ps**.

- **~ 27 years ago:**

  Bill Attwood of SLAC (SLAC lecture on the TOF techniques in 1980):

  The lecture series did not even mention MCP-PMTs. The technology clearly existed at that time, but was either not affordable or obtainable or simply ignored for large scale applications.

- **~10 years ago:**

  Crispin Williams of CERN proposes a TOF detector for ALICE based on multi-gap glass-based RPC chambers; test beam results indicate resolution of **σ ~ 40-50 ps/track.** Presently he is trying to push the timing to a resolution towards σ ~ 10ps.

- **~ 6 years ago:**

  Our group started R&D on FDIRC using fast timing at a level of better than σ ~100ps / single photon

  B. Ratcliff, NIM A502(2003)211, J.Va'vra, NIM A502(2003)172, NIM A572(2007)459, C. Field et al., NIM A553(2005)96.

- **~ 4 years ago:**

  Henry Frisch of Univ. of Chicago (the 1-st proposal for a **1 ps timing** with a MCP-PMTs & Cherenkov radiator). Aspen talk in 2003, and Credo et al., IEEE Nucl. Sci. Symp., Conf. Records, Vol. 1 (2004).

- **~2 years ago:**

  Takayoshi Ohshima's group in University of Nagoya (reached a **σ ~ 6.2 ps** in the test beam)

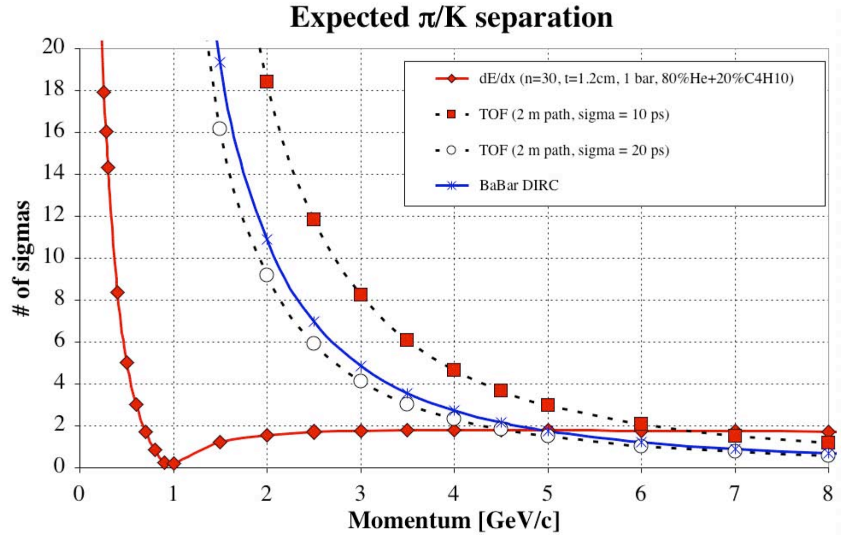
  "The Pico-Sec Timing Workshop," 18 Nov 2005, U. of Chicago, http://hep.uchicago.edu/psec/.

A ps timing community in US

- **U. of Chicago**: **~40 GSa/sec waveform electronics, simulation, detectors**
  - Henry Frisch + 4-5 students
  - Engineers: Jean-Francois Genat + Fukun Tang
- **Argonne lab**: **FPGA electronics, new detector structures**
  - Karen Byrum, Ed May + 1 student (Camden Ertley)
  - Engineers: Gary Drake + John Anderson
- **Fermilab**: **Test beam instrumentation, SiPMTs**
  - Erik Ramberg + Anatoly Ronzhin
- **FP420 collaboration for LHC**: **Detectors, tests**
  - M. Albrow + Andrew Brandt + students
- **U. of Hawaii**: **~10 GSa/sec waveform electronics**
  - Gary Varner + 1 student (Larry Ruckman)
- **SLAC**: **Detectors, tests, simulation**
  - J. Va’vra, J. Schwiening, D. Leith, B. Ratcliff + visiting student from Argonne (Camden Ertley)

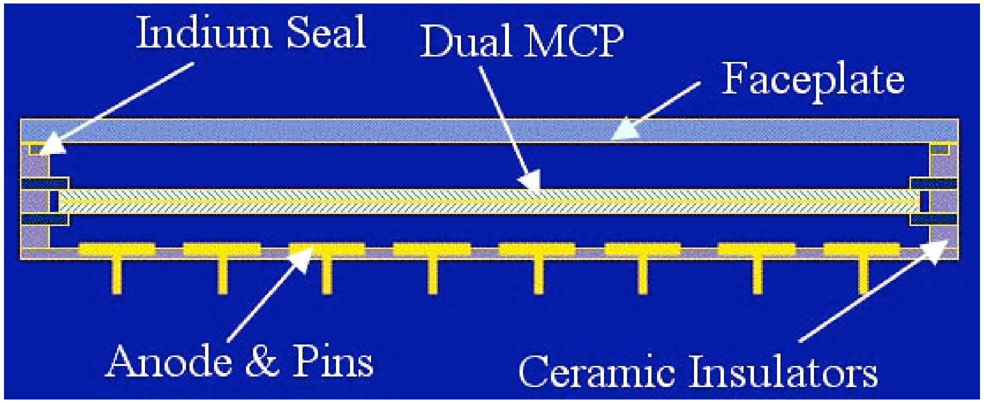
Fast timing at a level of σ ~15 ps can start competing with the RICH techniques for PID

Example of various Super-B factory PID designs:

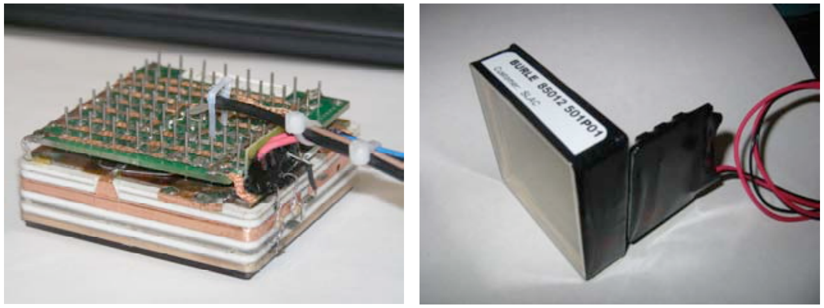


Calculation done for Flight Path Length = 2m

Method to achieve it:

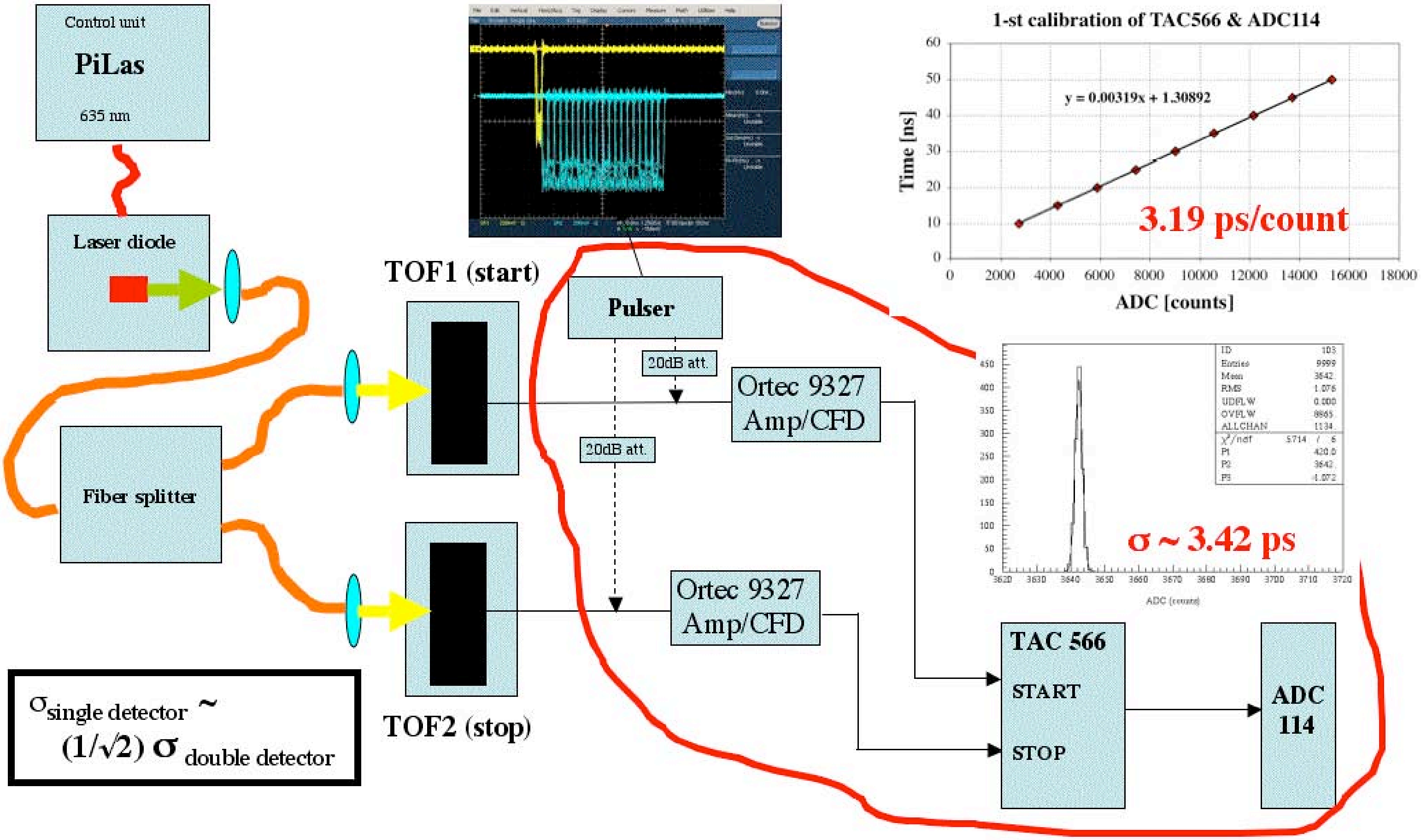


A real device:



Laser setup & calibration of the electronics

J.V., MCP-PMT log book 4, page 29, 2007

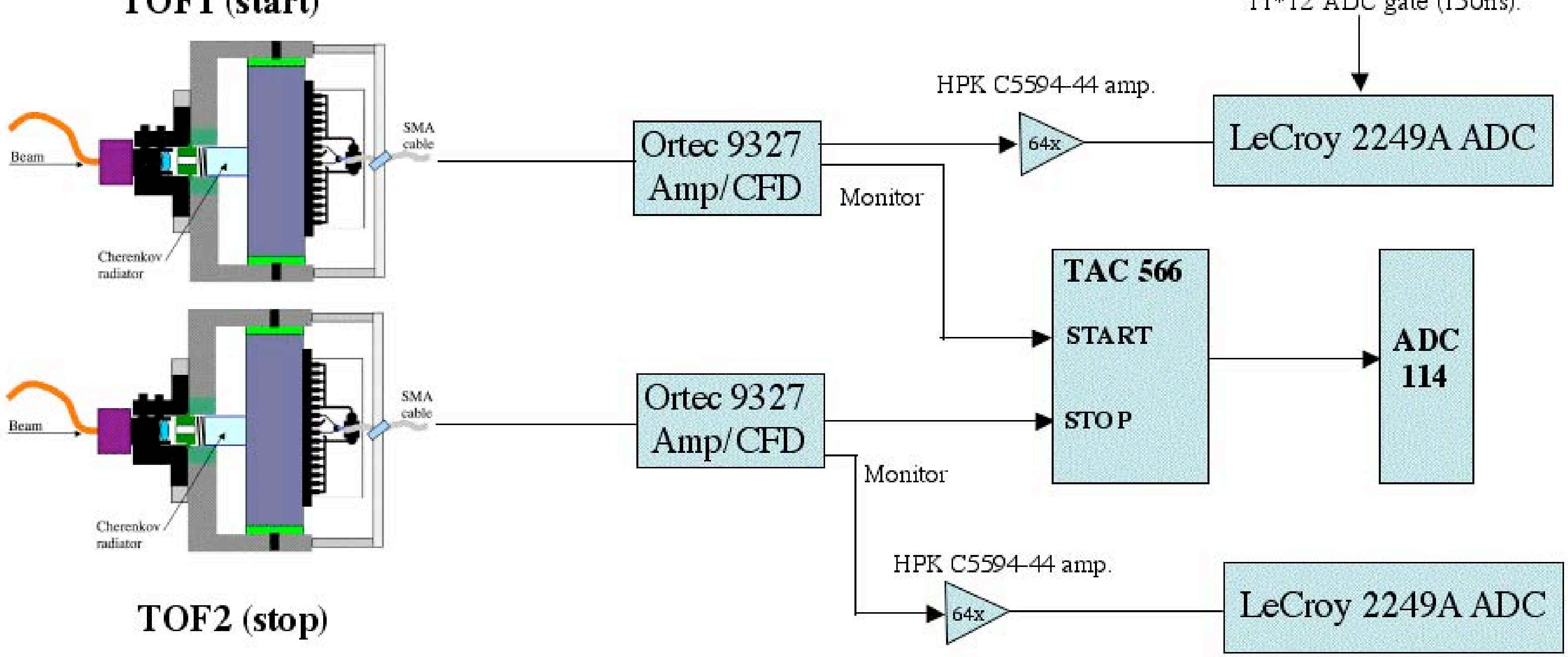


$\sigma_{\text{single detector}} \sim (1/\sqrt{2})\,\sigma_{\text{double detector}}$

* <u>This is the best electronics noise performance in this type of timing.</u>

Beam electronics with two MCP-PMTs

$$\sigma_{\text{single detector}} \sim (1/\sqrt{2})\, \sigma_{\text{double detector}}$$



TOF1 (start)

TOF2 (stop)

Ortec 9327 Amp/CFD

Ortec 9327 Amp/CFD

HPK C5594-44 amp.

HPK C5594-44 amp.

Monitor

Monitor

T1*T2 ADC gate (150ns).

LeCroy 2249A ADC

LeCroy 2249A ADC

TAC 566

START

STOP

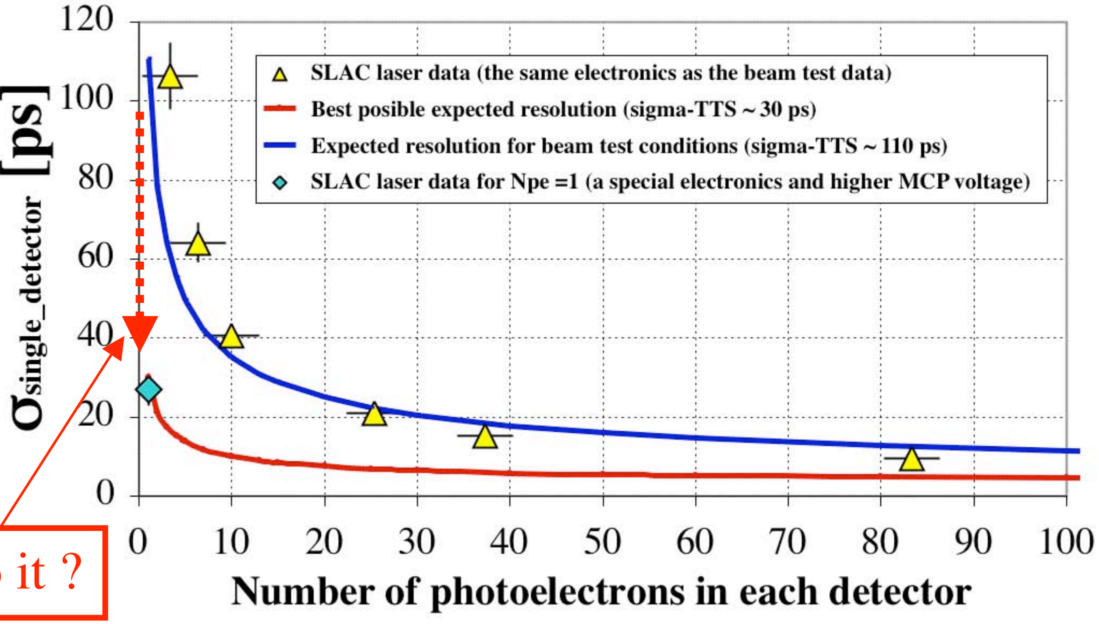
ADC 114

- * **Aim of this particular electronics: be linear in a region of Npe = 30-50.**
- * **The electronics is NOT sensitive to single photoelectrons (pe).**
- * The setup uses standard fast electronics.
- * An attempt is made to correct the CFD timing with an ADC.

A laser-based result with the beam electronics

J.V., MCP-PMT log books 3 & 5, 2006 & 2008

Run with a linear operation of the electronics for Npe ~ 30 - 50 pe, i.e., not very sensitive to single pe !!!



How to do it ?

Two different electronics setups, and two different MCP conditions were used in two laser tests

* **Present level of understanding of the laser diode data (blue curve):**

$$\sigma_{prediction} \sim \sqrt{[\sigma^2_{MCP-PMT} + \sigma^2_{Laser} + \sigma^2_{Electronics}]} \sim$$

$\sim \sqrt{[(\sigma_{TTS}/\sqrt{N_{pe}})^2 + ((FWHM_{Laser}/2.35)/\sqrt{N_{pe}})^2 + (3.42\ ps)^2]} \sim$

$\sim \sqrt{[(\sigma_{TTS}/\sqrt{N_{pe}})^2 + (13ps/\sqrt{N_{pe}})^2 + 3.42^2]}$ **~ 18.1 ps**, where I assumed **σ_{TTS} ~ 110 ps & Npe = 35**

=> This indicates that the measured data are consistent with a simple model.

* **Red curve represents running with a good single pe sensitivity (σ_{TTS} ~ 30 ps).**

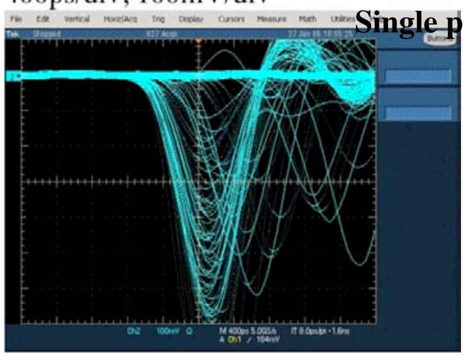
Burle MCP-PMT transit time spread limit

J.V., MCP-PMT log book #3, page 28, 11.16.2006, and NIM A572(2007)459

With a good single pe sensitivity, this type of detector will give $\sigma_{TTS} \sim 30$ ps.

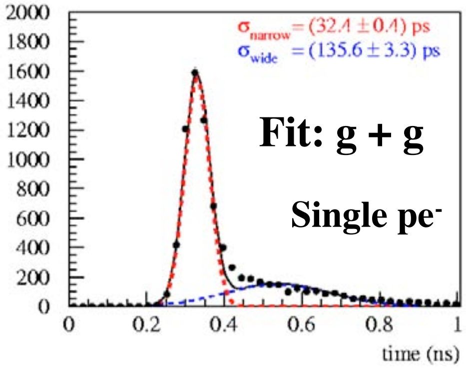
Single pe MCP pulses with HPK amplifier:

400ps/div, 100mV/div



Single pad

Single pe timing spectrum:



- * **10 μm MCP hole diameter, a fast low noise amplifier, 2.8 kV on MCP**
- * **PiLas red laser diode (635 nm):**

σ_{TTS} (Npe = 1) ~ $\sqrt{}$ (32^2-13^2-11^2) = 27 ps

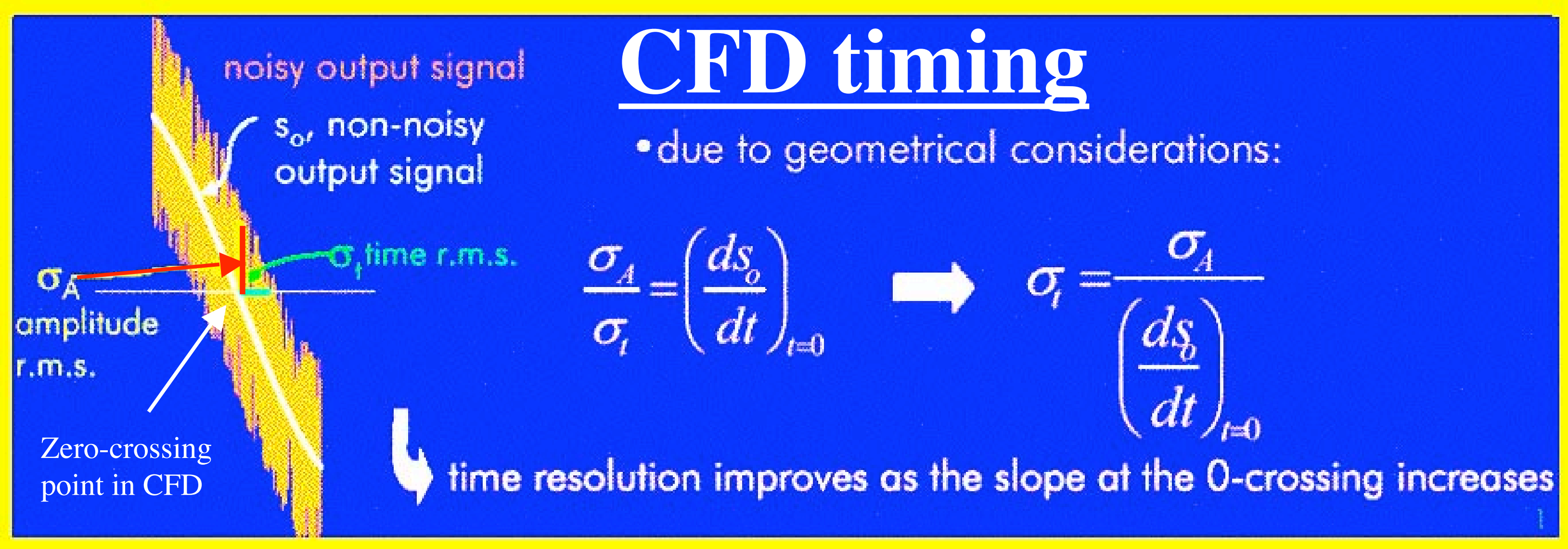
PiLas laser diode
contribution

Electronics contribution
during this particular test (TDC mainly)

- What is a recipe to obtain a "good" single pe timing resolution ?

What is the secret of good timing ?

- **Speed of amplifier:**
  - It needs to be fast enough to follow MCP
  - **A deciding factor is the ratio of noise and rise-time:**



CFD timing

- due to geometrical considerations:

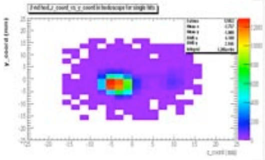
$$\frac{\sigma_A}{\sigma_t} = \left(\frac{ds_o}{dt}\right)_{t=0} \Rightarrow \sigma_t = \frac{\sigma_A}{\left(\frac{ds_o}{dt}\right)_{t=0}}$$

↳ time resolution improves as the slope at the 0-crossing increases

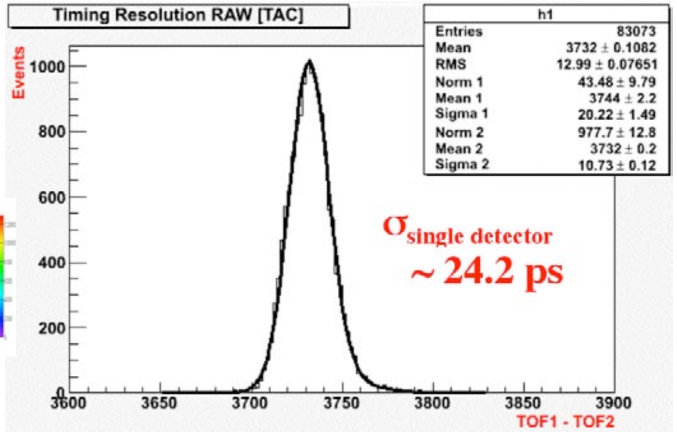
- **In addition, one needs a fast discriminator, one needs to correct variation in pulse height, a high enough resolution TDC (~14 bits), high enough voltage on the MCP-PMT, etc.**
- A reference J. Va'vra et al., NIM A572(2007)459 shows a comparative study of several fast amplifiers from point of view of "single pe" or "multi-pe" timing. **Not all solutions work, especially if one wants to push the limits !**

SLAC & Fermilab Beam Test Results

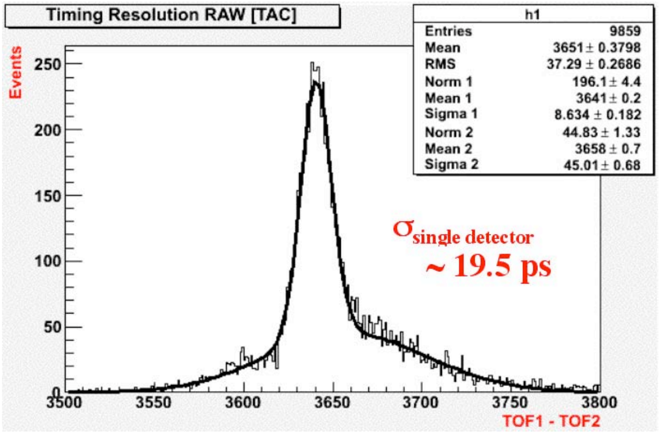
SLAC
Beam spot
(σ ~2-3mm):



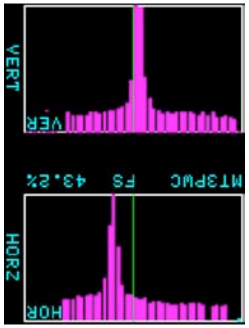
SLAC tests (10 GeV electrons):



Fermilab tests (120 GeV protons):



Fermilab beam spot
(σ ~7mm + halo):

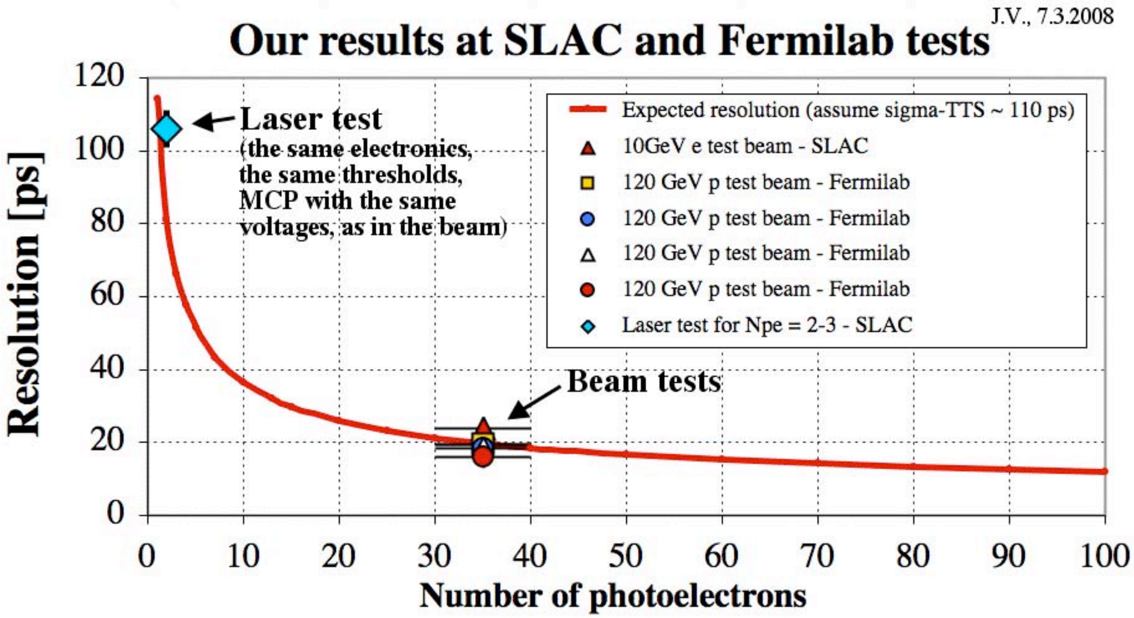


* 1-st test at SLAC: typical resolution results: $\sigma_{\text{single detector}}$ ~23-24 ps

* 2-nd test at Fermilab: typical resolution results: $\sigma_{\text{single detector}}$ ~17-20 ps

Are the beam results consistent with expectations ?

Beam tests so far:
Run with a linear operation for Npe ~30-50 pe, i.e., not fully sensitive to single pe !!



- **Present level of understanding of obtained data (red curve):**

$$\sigma_{\text{prediction}} \sim \surd\,[\sigma^2_{\text{MCP-PMT}} + \sigma^2_{\text{Radiator}} + \sigma^2_{\text{Pad broadening}} + \sigma^2_{\text{Electronics}}\,] =$$

$$= \surd\,[(\sigma_{\text{TTS}}/\surd N_{\text{pe}})^2 + (((12000\mu\text{m}/\cos\theta_C)/(300\mu\text{m/ps})/n_{\text{group}})/\surd\,(12\text{Npe}))^2 +$$

$$+ ((4*6000\mu\text{m}/300\mu\text{m/ps})/\surd\,(12\text{Npe}))^2 + (3.42\text{ ps})^2\,] \sim$$

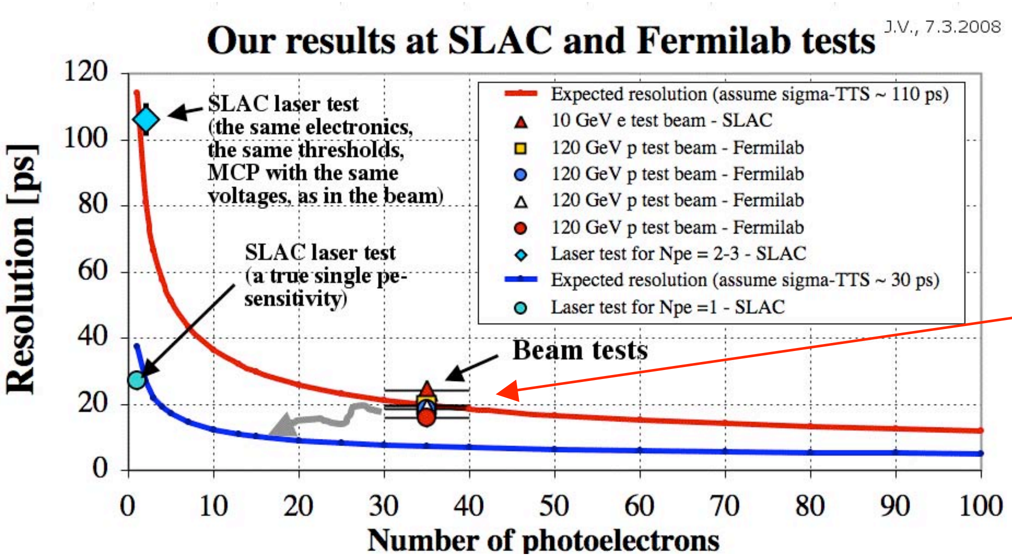
$$\sim \surd\,[\mathbf{20.2}^2 + 4.3^2 + 3.7^2 + 3.42^2\,] \sim 21.3\text{ ps},$$ where I assumed $\sigma_{\text{TTS}} \sim 110$ ps & Npe ~ 35 pe

=> This indicates that data are consistent with a simple model, which ties together laser and beam data.

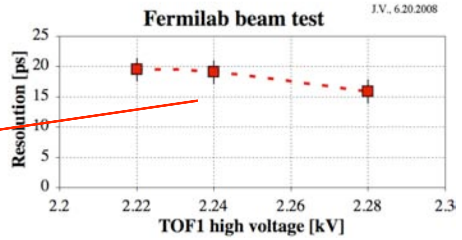
=> We reached the Super-B Forward TOF goal: $\sigma \sim 20$ ps.

What to do next with the present TOF setup ?

Next beam test:
Run with single pe sensitivity



Hint in data:



* **Expected resolution in the beam (blue curve):**

$\sigma_{\text{prediction}} \sim \surd\,[\sigma^2_{\text{MCP-PMT}} + \sigma^2_{\text{Radiator}} + \sigma^2_{\text{Pad broadening}} + \sigma^2_{\text{Electronics}}] =$

$= \surd\,[(\sigma_{TTS}/\surd N_{pe})^2 + (((6000\mu m/\cos\theta_C)/(300\mu m/ps)/n_{group})/\surd\,(12Npe))^2 +$

$+ \; ((4*6000\mu m/300\mu m/ps)/\surd\,(12Npe))^2 + (3.42\ ps)^2\,] \sim$

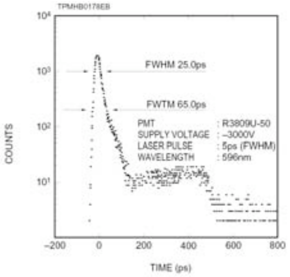
$\sim \surd\,[\mathbf{9.0}^2 + 3.3^2 + 5.2^2 + 3.42^2\,]$ **~ 11.4 ps**, where I assumed σ_{TTS} **~ 30 ps & Npe ~ 15 pe$^-$**

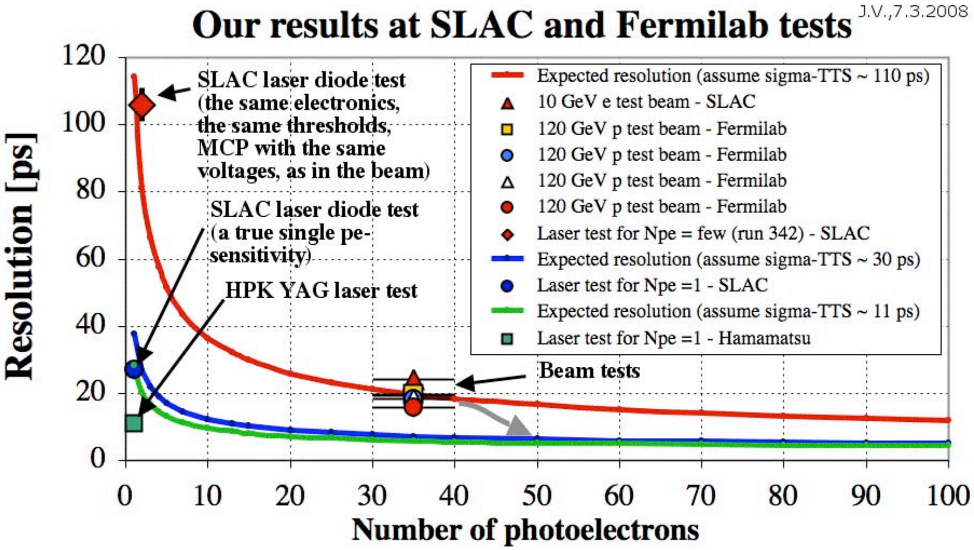
* **There is actually a hint in the test beam data that as one moves towards the good single pe sensitivity by increasing HV, one starts improving timing. However, to increase HV alone is not enough !**

What is the ultimate limit at present ?

MCP-PMT R3809U-50:

$\sigma_{TTS} \sim 11$ ps:

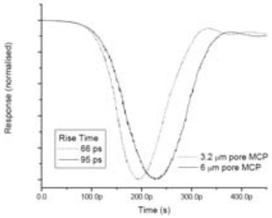



Our results at SLAC and Fermilab tests

J.V.,7.3.2008

Photek MCP:

Rise time <100ps:



* <u>Hamamatsu</u>: a special Nd-YAQ laser setup to do this timing measurement (laser diode too slow for this) - <u>this is where one starts spending money !</u>

* Best possible expected resolution in the beam (green curve):

$$\sigma_{\text{prediction}} \sim \sqrt{}\,[\sigma^2_{\text{MCP-PMT}} + \sigma^2_{\text{Radiator}} + \sigma^2_{\text{Pad broadenibng}} + \sigma^2_{\text{Electronics}}] =$$

$$= \sqrt{}\,[(\sigma_{TTS}/\sqrt{}N_{pe})^2 + (((12000\mu m/\cos\theta_C)/(300\mu m/ps)/n_{group})/\sqrt{}\,(12Npe))^2 +$$

$$+ ((6000\mu m/300\mu m/ps)/\sqrt{}\,(12Npe))^2 + (3.42\ ps)^2\,] \sim$$

$$\sim \sqrt{}\,[1.6^2 + \mathbf{3.6}^2 + 0.74^2 + 3.42^2\,] \sim 5.3\ ps,$$ where I assumed $\sigma_{TTS} \sim 11$ ps & Npe ~ 50 pe^-

* Challenge: Can we achieve a "$\sigma_{TTS} \sim 11$ ps performance" with our electronics ?

Examples of timing applications

Goals:

- **CMS and Atlas** TOF detector for FP420 experiments at LHC: **$\sigma \sim$ 10-15 ps**
- TOF for **ALICE** PID: **$\sigma \sim$ 40-50 ps** ✓
- TOF for **Super-B Forward** PID: **$\sigma \sim$ 20 ps** ✓
- → FDIRC for **Super-B** PID to tag Cherenkov photon **color**: **$\sigma \sim$ 150 ps** ✓
- TOP DIRC for **Super-KEKb** PID to measure θ_c with **time imaging**: **$\sigma \sim$ 50 ps** ✓
- Liquid water TPC ?: **$\sigma \sim$ few ps**
- Add a TOF capability to the **PET** machines in **medicine**: **$\sigma \sim$ 100-300 ps**
- The **astrophysics** detectors such as **MAGIC**: **$\sigma \sim$ 100-200 ps**
- Generally for a particle with $\beta = 1$: **$\sigma_{\text{time}} \sim$ 10 ps means $\sigma_{\text{position}} \sim$ 3 mm !!**
- Applications in **Homeland security ?** **:**

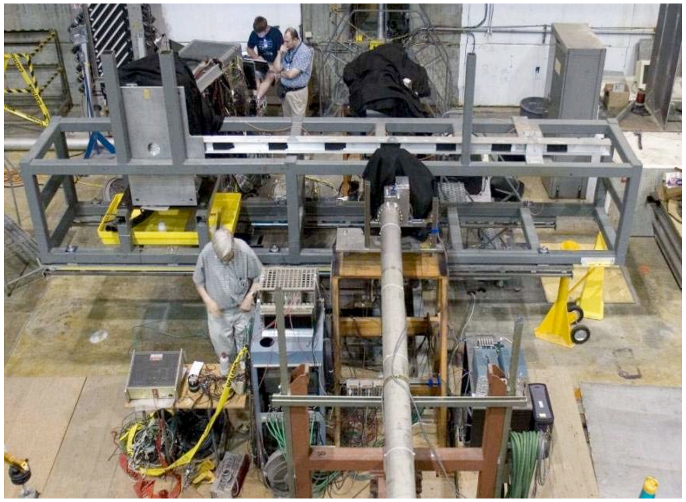
  (Can such timing be used for a localization of suspect items using a pulsed neutron source ???)

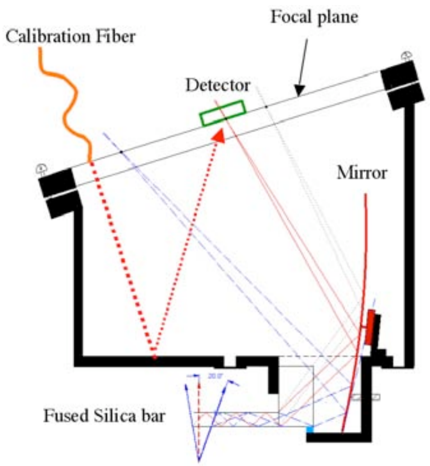
Chromatic correction by timing

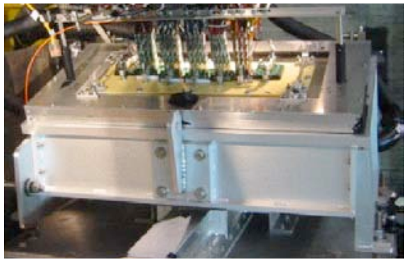
A ~10x better timing resolution than BaBar DIRC allows a measurement of **a photon color**, and this allows the **chromatic error correction of θ_c**.

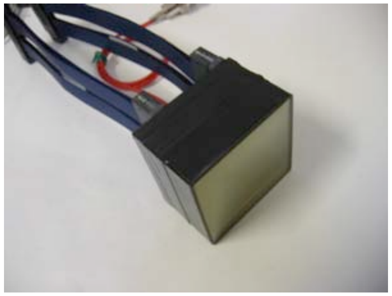
A new concept in Cherenkov Detectors !!!

FDIRC and TOF detectors in the ESA test beam:









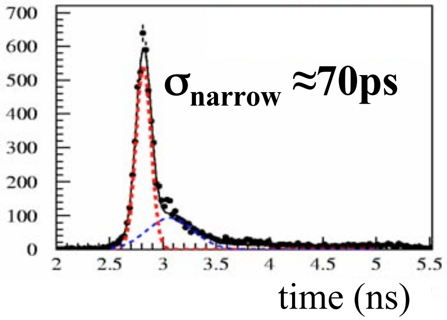
- **Beam instrumentation:**
  - 2 x-y scintillating fiber hodoscopes
  - START Quartz counter to monitor flux
  - Time start from the LINAC RF signal, but correctable with a local START counter
  - Lead glass to monitor beam multiplicity (very important in the SLAC's beam)

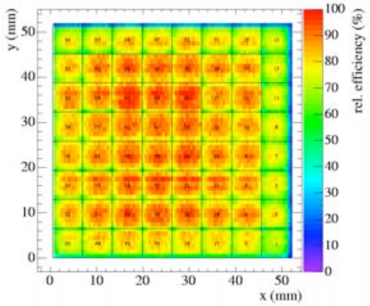
- **Radiator:**
  - 1.7 cm x 3.5 cm x 3.7 m long bar (three 1.22 m long bars).
- **Optical expansion region:**
  - filled with a mineral oil.
  - include optical fiber for the electronics calibration.
- **Focusing optics:**
  - a spherical mirror (available from CRID detector).

FDIRC prototype photon detectors

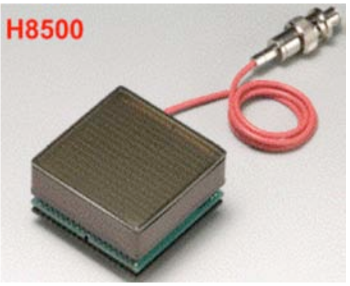
Nucl.Inst.&Meth., A 553 (2005) 96

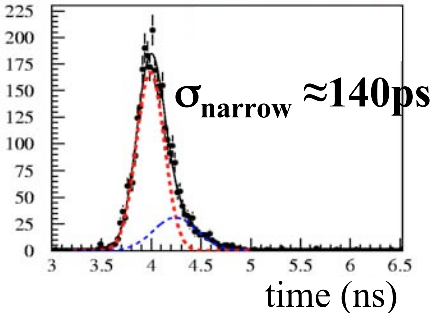
1) Burle 85011-501 MCP-PMT (64 pixels, 6x6mm pad, σ_{TTS} ~50-70ps)

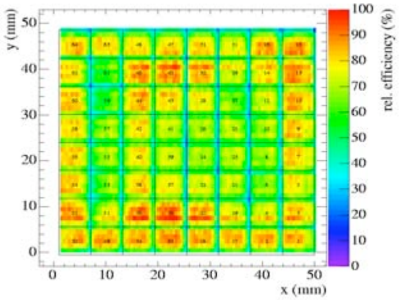




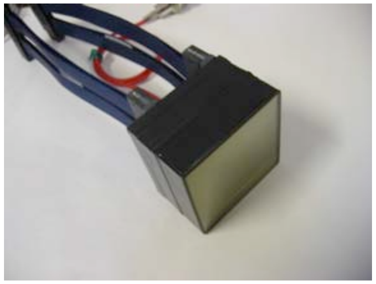
2) Hamamatsu H-8500 MaPMT (64 pixels, 6x6mm pad, σ_{TTS} ~140ps)

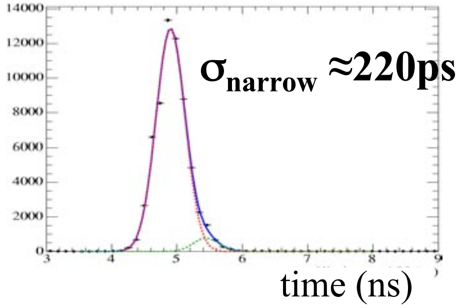


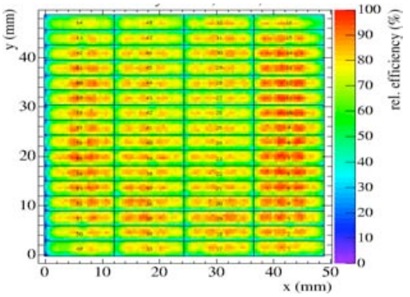




3) Hamamatsu H-9500 MaPMT (256 pixels, 3x12mm pad, σ_{TTS} ~220ps)







* **Timing resolutions were obtained using a fast laser diode in bench tests with single photons on pad center.**

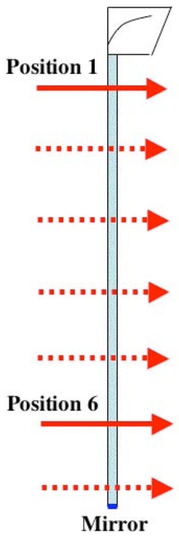
In the FDIRC prototype test we gang four pixels together to be able to use our 64 channel amplifier electronics.

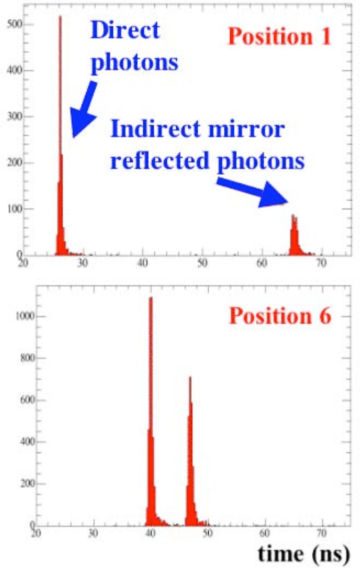
Cherenkov Photons in Time and Pixel domains

J.Va'vra et al., SLAC-PUB-12803

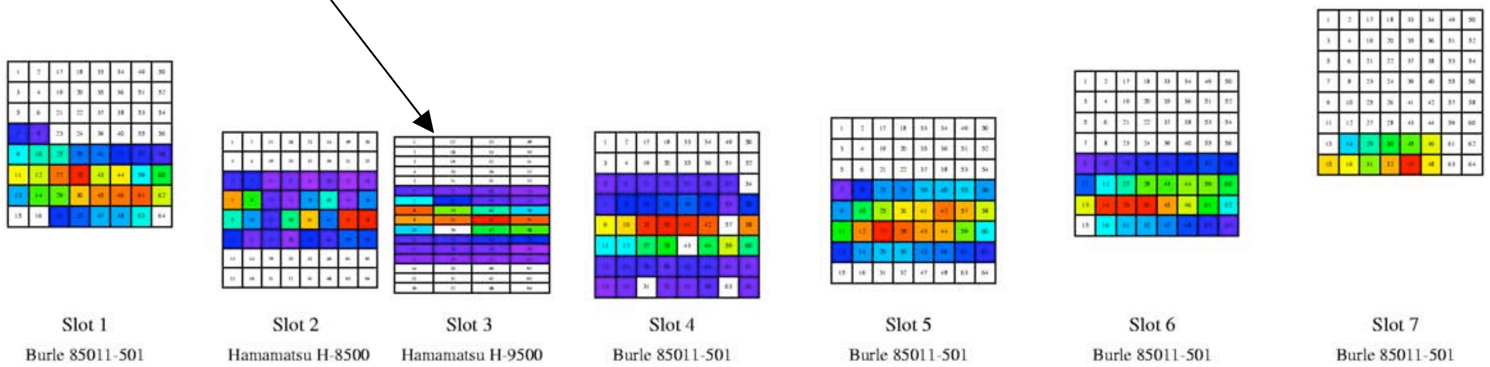
- * ~ 200 pixels instrumented with SLAC electronics & 16 with the Hawaii electronics.
- * Ring image is most narrow in the 3 x 12 mm pixel detector.

Cherenkov photons in time domain:





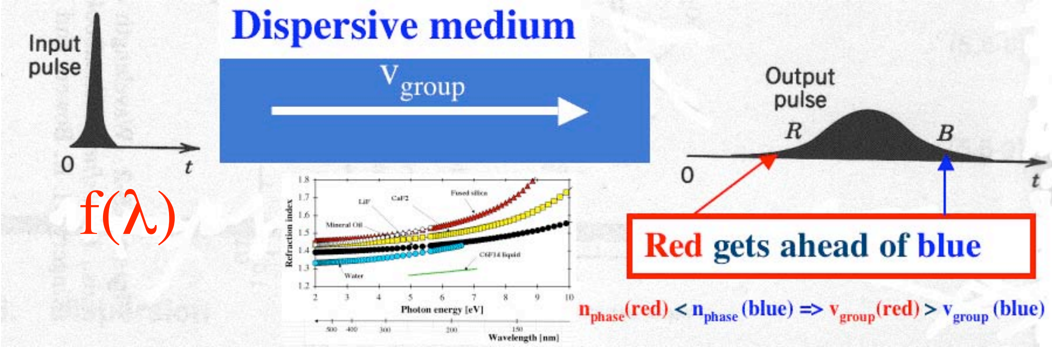
Cherenkov ring in pixel domain:



Chromatic correction by timing in FDIRC

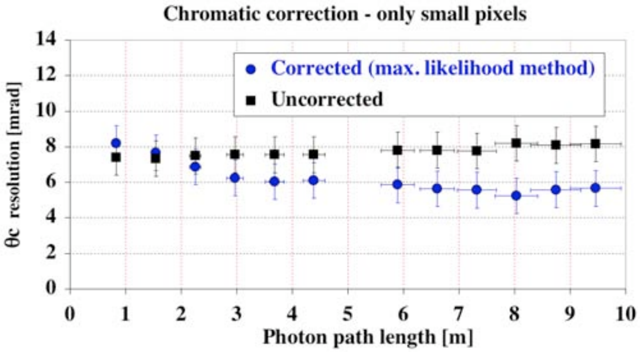
J.Va'vra et al., SLAC-PUB-12803

Time dispersion in fused silica bar:

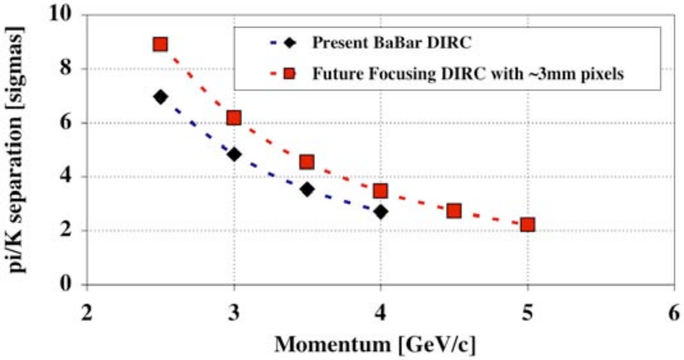


$n_{phase}(\text{red}) < n_{phase}(\text{blue}) \Rightarrow v_{group}(\text{red}) > v_{group}(\text{blue})$

For 3mm pixels:

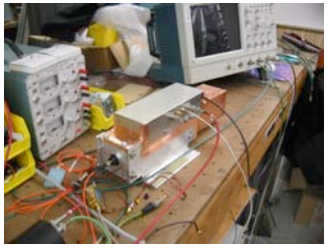


PID performance prediction based on our prototype results:

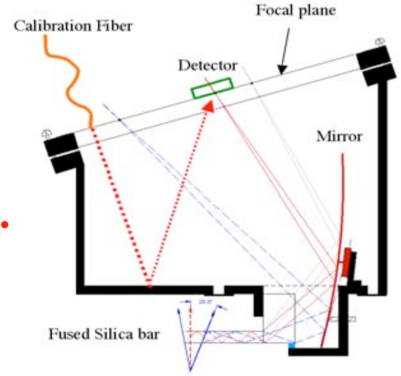


- * **The chromatic correction and smaller pixel size (3mm) helped to improve the Cherenkov angle resolution.**
- * **Better timing also means better rejection of the background.**
- * **This is the first RICH detector to do it !!**

Conclusions



* TOF:
    - Test beam results at SLAC & Fermilab: $\sigma_{\text{single detector}} \sim$ 16-24 ps
    - SLAC Laser tests result for the same condition: $\sigma_{\text{single detector}} \sim$ 18 ps
    - Results are consistent with a simple model.
    - Using this model, we predict that to make a further improvement in the timing resolution with the present setup, one needs to improve the single pe timing.
    - Using this model, we also predict an "ultimate" timing resolution limit using present "best" MCP-PMT detectors: $\sigma_{\text{single detector}} \sim$ 5 ps.
    - We have reached a Super-B goal: $\sigma \sim$ 20ps

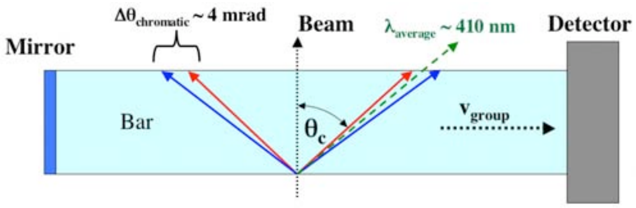


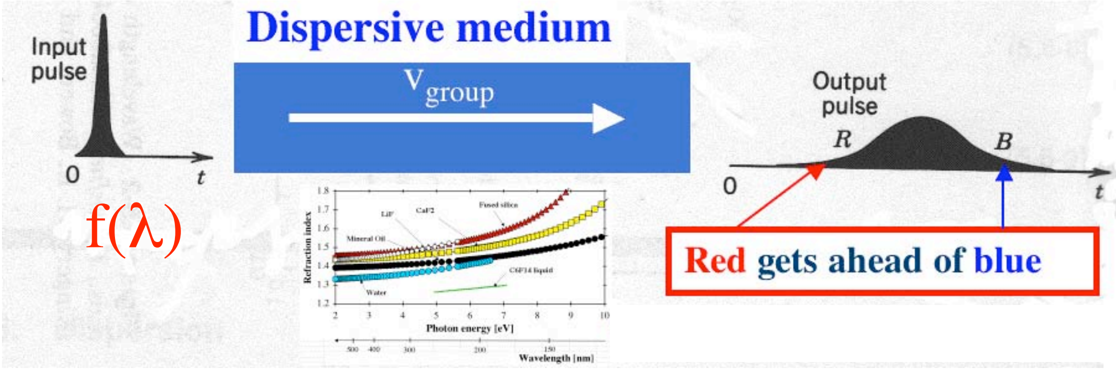
* FDIRC:
    - The first RICH detector to correct the chromatic error by timing.
* Future steps on timing:
    - Aging & rate tests => iterate with MCP-PMT manufacturers.
    - Switch to the waveform sampling electronics.
    - Understand the systematics of the ps timing.
    - Detector simulation at much more advanced level to get to $\sigma_{\text{single detector}} \sim$ 5ps.
* **We need frequent access to a test beam !**

Backup slides

Time dispersion in fused silica bar

J.Va'vra et al., SLAC-PUB-12803





Cherenkov angle production controlled by n_{phase} ($\cos\theta_c = 1/(n_{phase}\,\beta)$): θ_c (red) < θ_c (blue)
Propagation of photons is controlled by n_{group} ($v_{group} = c_0/n_{group} = c_0/[n_{phase} - \lambda * dn_{phase}/d\lambda]$): v_{group}(red) > v_{group} (blue)

$$t = TOP = L / v_{group} = L\,[n_{phase} - \lambda * dn_{phase}/d\lambda] / c_0 \quad = \text{Time-Of-Propagation}$$

$$dt/L = dTOP/L = \lambda \; d\lambda * | - d^2n/d\lambda^2 | / c_0$$

dt is pulse dispersion in time, length **L**, wavelength bandwidth **dλ** , refraction index **n(λ), dt/L = dTOP/L ~ 40 ps/meter in quartz**

* **A single photon timing resolution at a level of ~150ps for >3 meters of propagation in the fused silica can start correcting the Cherenkov angle chromatic broadening.**