A high resolution TOF counter - a way to compete with a RICH detector ?

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representing

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Note: This work was possible because of the Focusing DIRC R&D

Content of this talk

- A bit of history
- TOF detector for Super-B Forward PID
- Timing strategy
- Laser diode measurements
- Lessons from the test beam
- ~~Systematic errors~~ (decided to drop this as it would take an hour)
- Summary

Tom Ypsilantis always liked to end his talks with:

"… and an equivalent performance with a TOF detector would require this σ_{TOF} timing resolution …"

(usually << 1 psec for a RICH detector with n = n_{gas})

However, it is possible to start competing if n is larger:

1) For n ~ 1.03, the required σ_{TOF} ~ 5-10 psec & Lpath ~ 2m
2) For n ~ 1.47, the required σ_{TOF} ~ 15-20 psec & Lpath ~ 2m

A bit of history as I know it

- **~35 years ago:**

  Helmuth Spieler of LBL (private communication):

  - 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 (lecture on the TOF technique at SLAC 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 HEP applications. Instead, Pestov spark counters were mentioned as a way to progress towards a resolution of σ ~ 30-50 ps for large areas.

- **~ 4 years ago:**

  Henry Frisch of Univ. of Chicago (**the 1-st proposal for a 1 ps timing** with a MCP-PMTs coupled to a 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/.

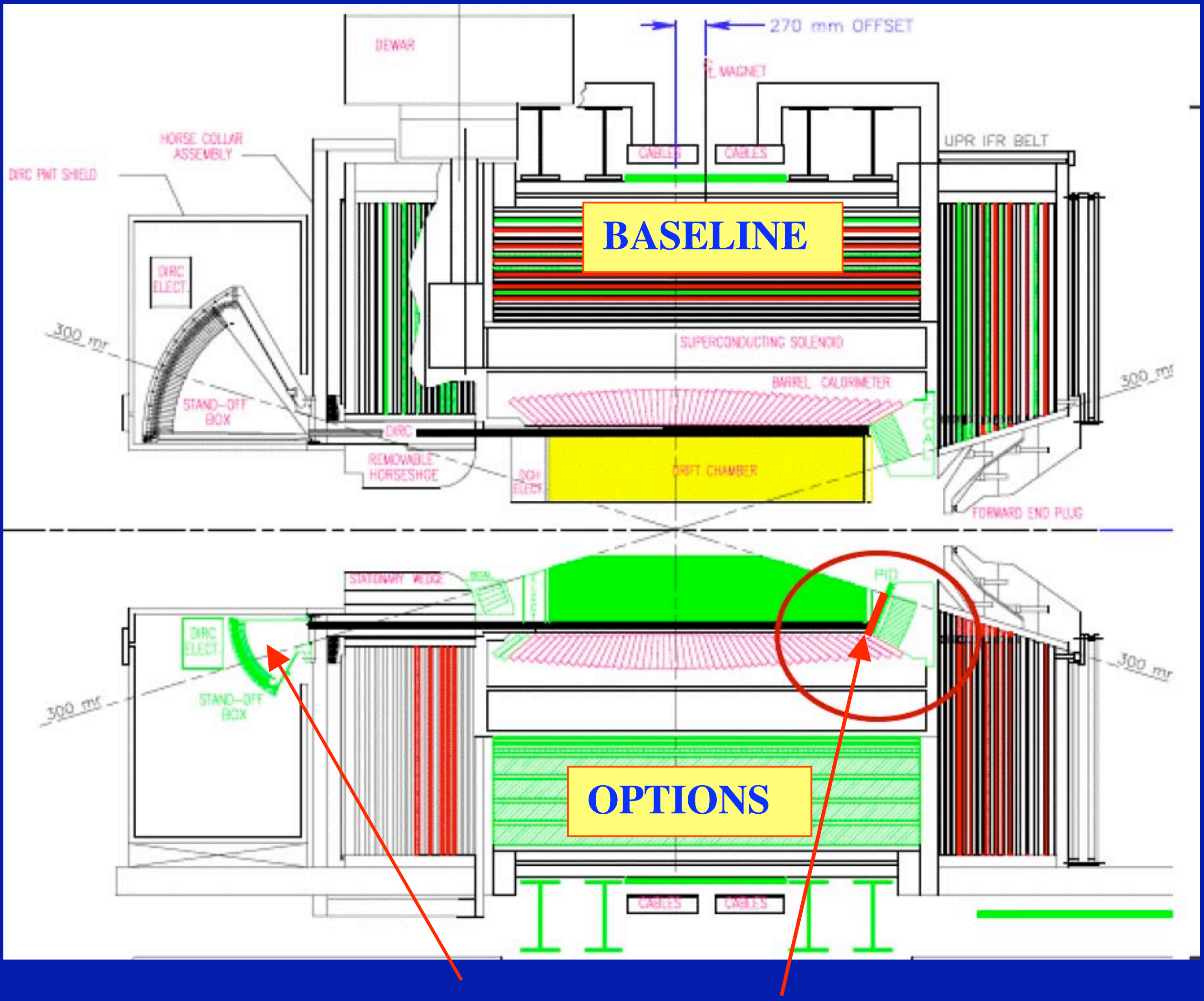
What are the reasons to push the TOF technique towards the new limits ?

- Fast Cherenkov light rather than a scintillation
- New detectors with small transit time spread $\sigma_{TTS} < 30ps$
- Fast electronics
- New fast laser diodes for testing

Forward PID with TOF detector at Super B

(in Italy)

PID systems in Super-B

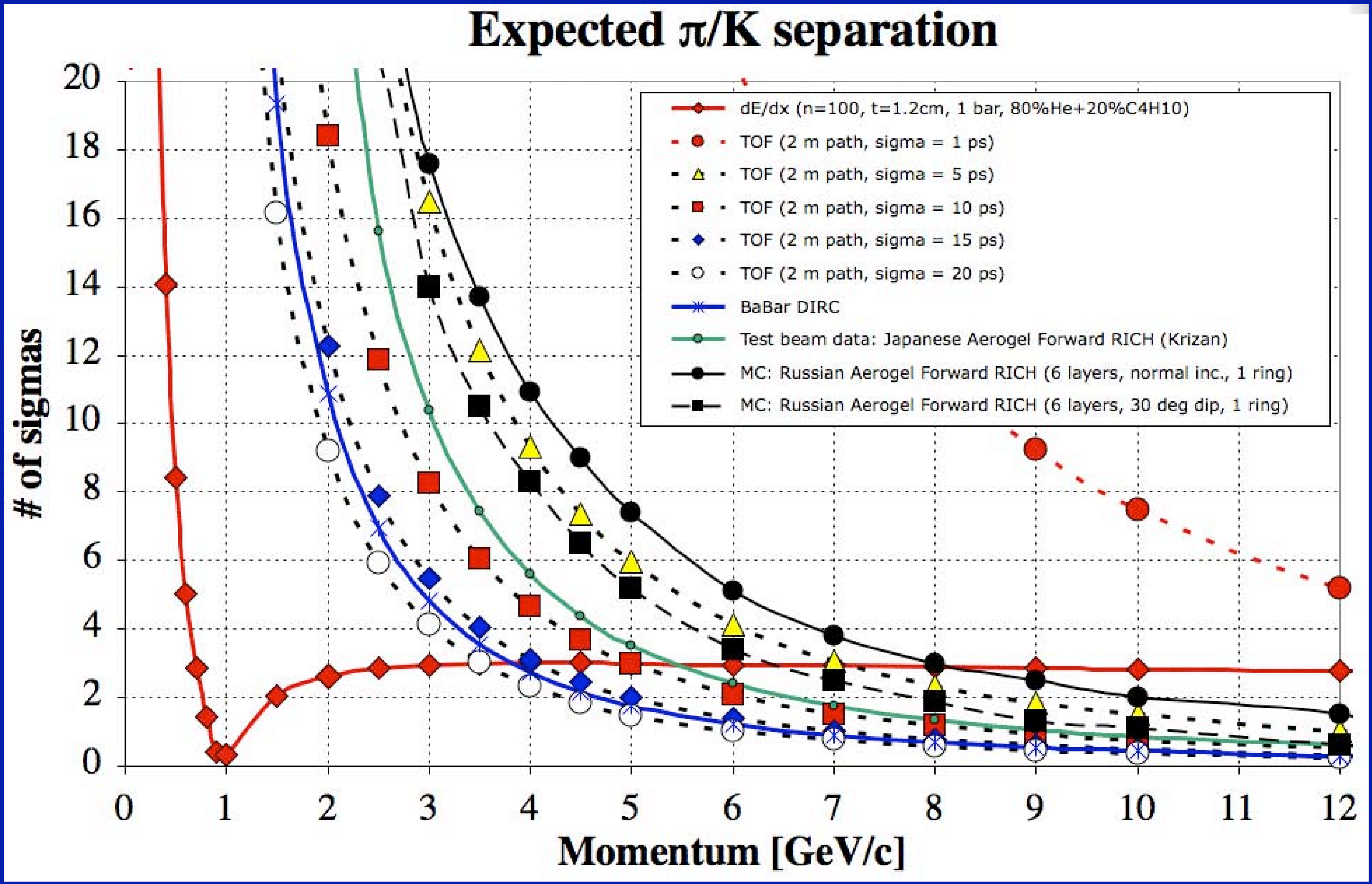


- Two PID systems: **Barrel DIRC & Forward TOF**

Timing at a level of σ ~15-20 ps can start competing with the RICH techniques

Example of various Super-B factory PID designs:

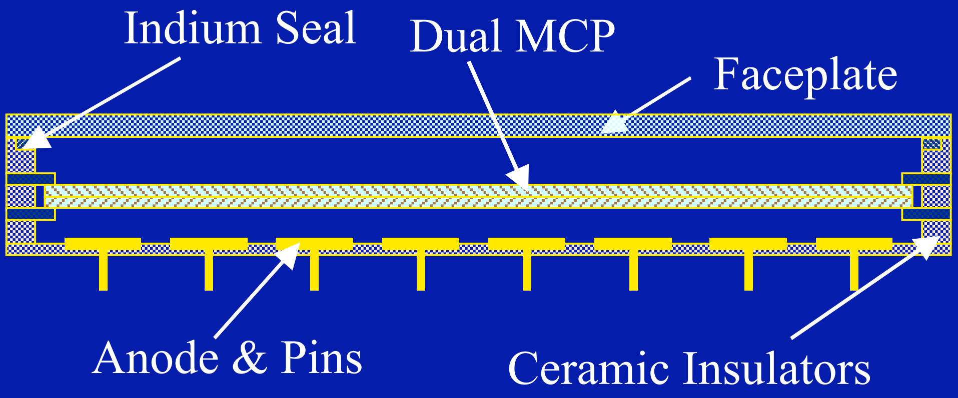
Calculation done for a flight path length: 2 m



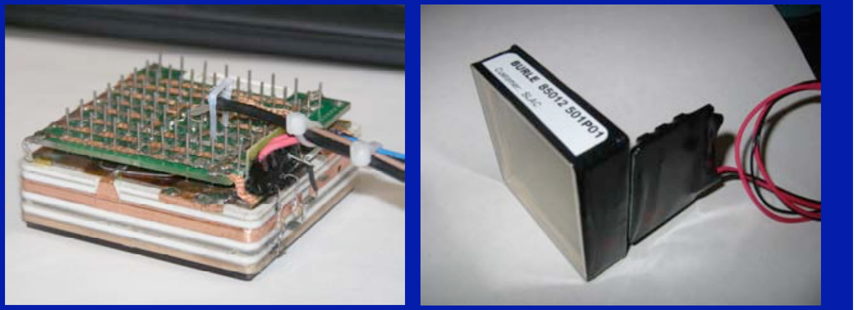
Present detector choice for the TOF application

Burle/Photonis MCP-PMT

Burle/Photonis data



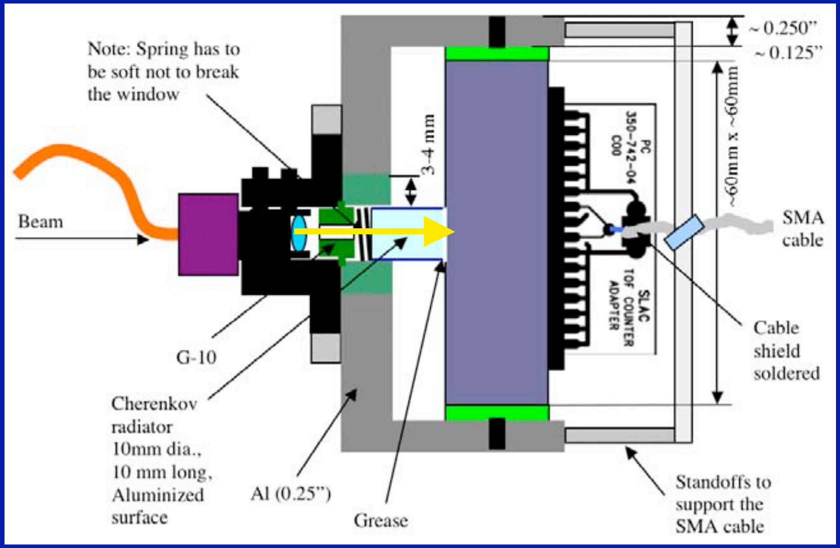
A real device:



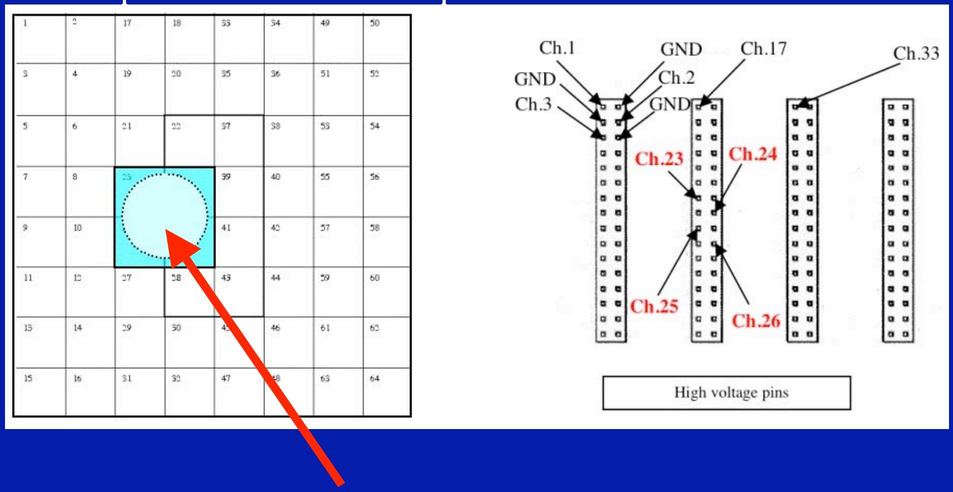
Parameter	Value
Photocathode: Bi-alkali QE at 420nm	**28 - 32%**
Number of MCPs/PMT	**2**
Total average gain @ -2.4kV & B = 0 kG	**~5 x 10^5**
Geometrical collection efficiency of the 1-st MCP	**70 - 80% ***
Geometrical packing efficiency	**85 - 90% ***
PDE = Total fraction of “in time” photoelectrons detected (for Bi-alkali QE)	**17 - 23% ***
Fraction of photoelectrons arriving “in time”	**70 - 80%**
σ_{TTS} - single electron transit time spread (for 10 μm dia. pores)	**27 ps**
Matrix of pixels	**2x2, 8 x 8, 16x16 or 32 x 32**
Number of pixels	**4, 64, 256 or 1024**
Pixel size (8x8 & 32x32 matrix)	**5.94 x 5.94 or ~1 x 1 [mm^2]**

*** Higher number is a future improvement**

A TOF counter prototype



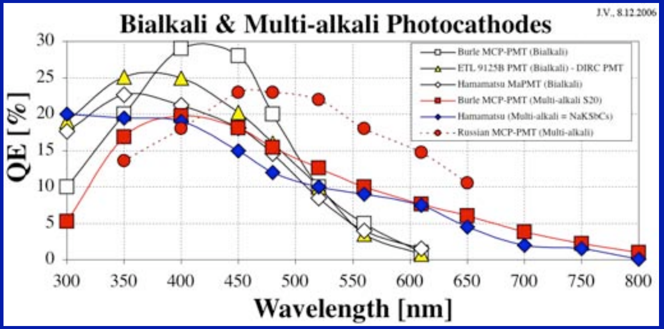
Four pads connected via equal-time traces:



- **Burle/Photonis MCP-PMTs with 10 µm MCP holes.**
- **Short together 4 pads to get a signal; all the rest of pads grounded.**
- **A 10mm-long, 10mm dia, quartz radiator, Al-coating on cylinder sides.**
- **Ortec 1GHz BW 9327Amp/CFD & TAC566 & 14 bit ADC114.**
- Calculation: 10mm long quartz radiator & a window should give Npe ~ 50 pe/track.
- Laser diode light adjusted to provide typically Npe ~ 50 pe.
- The laser spot size: ~1mm dia.; beam spot size typically σ ~1-2mm

What resolution do we expect to get ?

- A calculation indicates **N_{pe} ~50** for 1 cm-long Fused Silica radiator & Burle/Photonis Bialkali photocathode:



- **Expected resolution:**

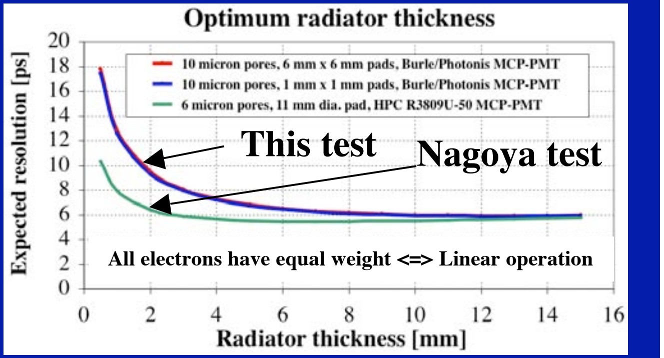
  a) Beam (Radiator length = 10 mm + window): →

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

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

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

$$\sim \sqrt{[3.5^2 + 3.3^2 + 0.75^2 + 3.42^2]} \sim \mathbf{5.9\ ps}$$

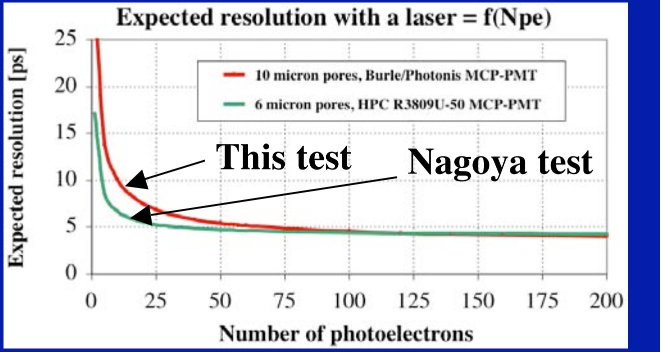


  b) Laser (N_{pe} ~ 50 pe^-): →

$$\sigma \sim \sqrt{[\sigma^2_{\text{MCP-PMT}} + \sigma^2_{\text{Laser}} + \sigma^2_{\text{Electronics}} + \ldots]} =$$

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

$$\sim \sqrt{[3.8^2 + 1.8^2 + 3.42^2]} \sim \mathbf{5.4\ ps}$$



This test: σ_{TTS} **(Burle MCP-PMT, 10µm) = 27 ps**

Nagoya test: σ_{TTS} **(HPC R3809U-50, 6µm) = 10-11 ps**

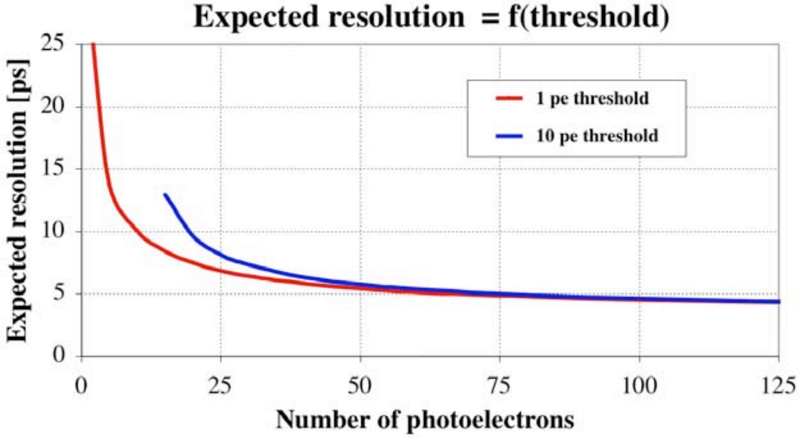
Timing strategy

(this is the hardest part of the problem)

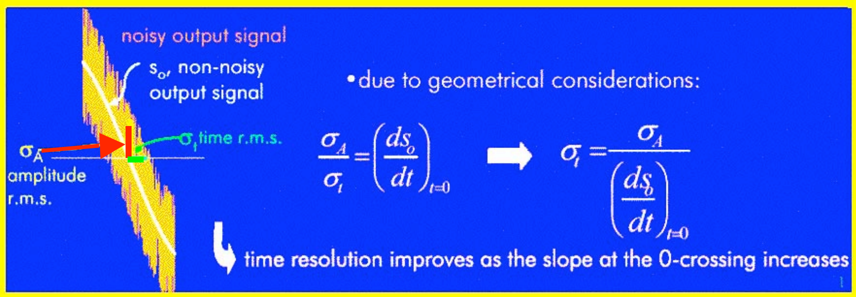
Timing strategy

- **Work with the detector & amplifier gain to be sensitive to a single photoelectron:**
  - => a better resolution at lower Npe
  - => can use thinner radiator
  - => **however, expect worse aging effects**
- **Reduce the amplification gain to be sensitive to larger threshold:**
  - => worse resolution at lower Npe limit,
  - => **more linear operation**
  - => **may need a bit thicker radiator**

I see this type of dependency in data:



- **What speed of amplifier does one need ?**
  - => It needs to be fast enough to follow MCP (this means ≥1 GHz BW for 10μm MCP)
  - => A deciding factor is a rise-time & noise:



- 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

- **CFD, or time-over-threshold timing with ADC correction, or waveform sampling ?**
  - => **I am leaning towards the third option.**

Two laser diode setups

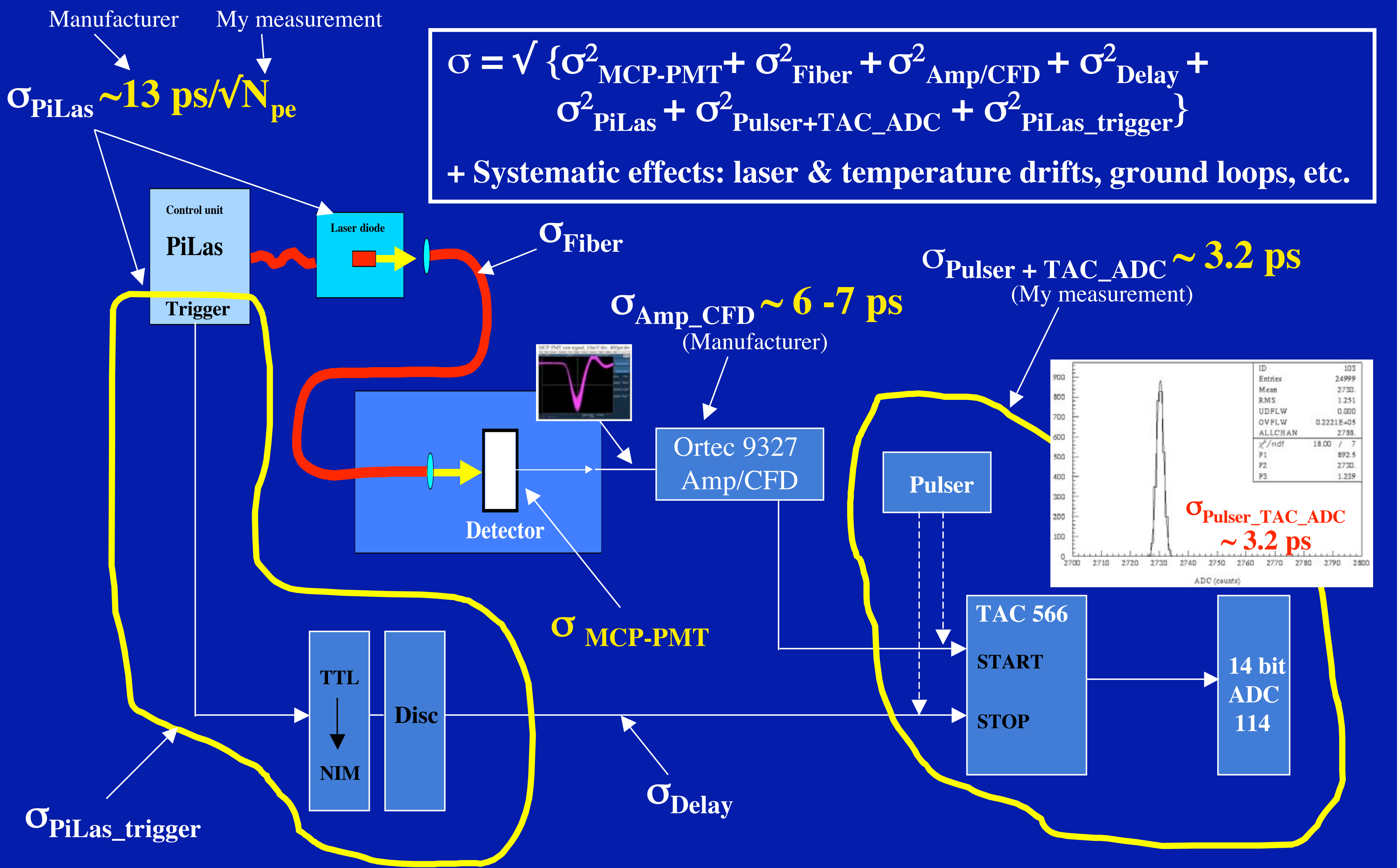
- Single MCP-PMT providing a TDC start, and the laser diode PiLas electronics provides a TDC stop.
- Two identical MCP-PMTs providing a TDC start & stop. The light is split by a fiber splitter.

Single MCP-PMT measurements

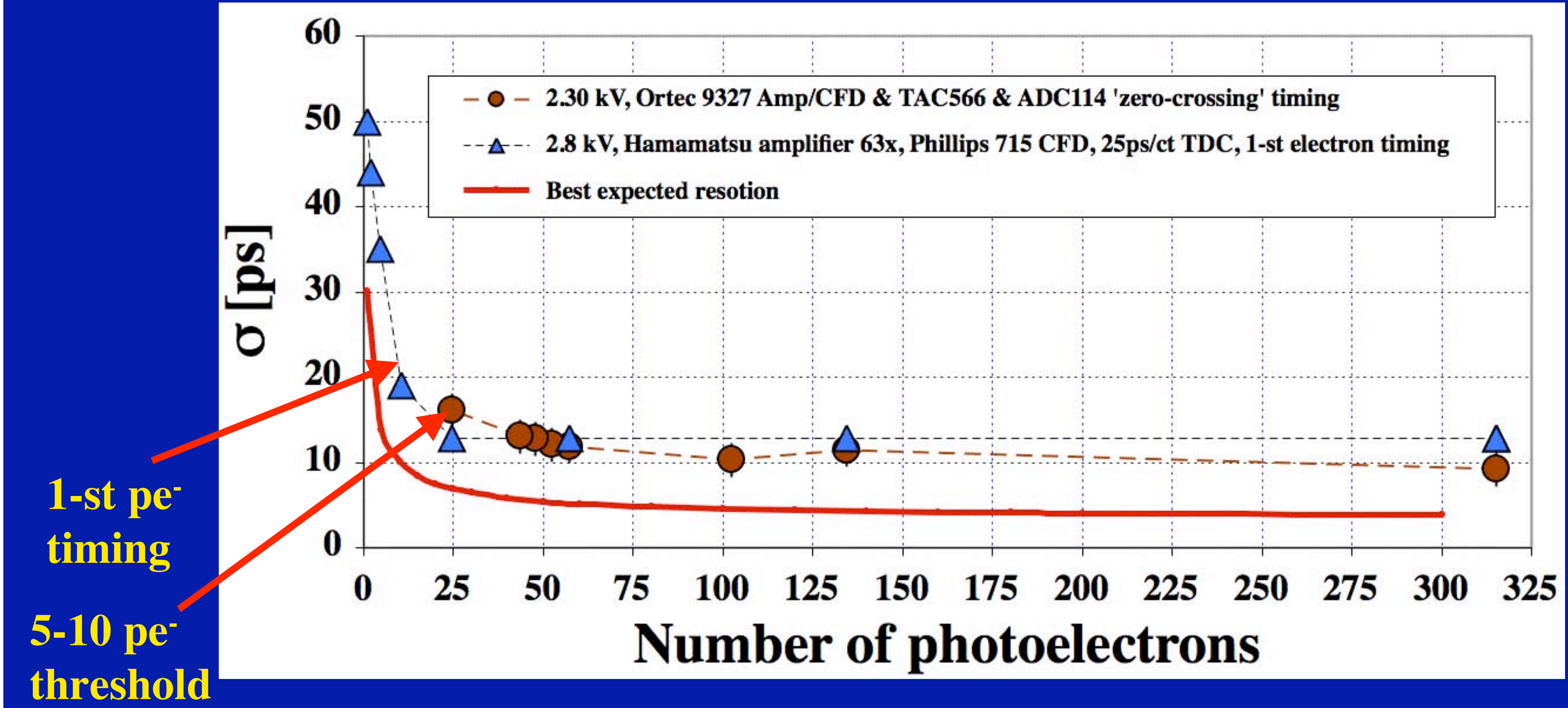
Timing resolution with PiLas laser diode

$$\sigma = \surd \{\sigma^2_{\text{MCP-PMT}} + \sigma^2_{\text{Fiber}} + \sigma^2_{\text{Amp/CFD}} + \sigma^2_{\text{Delay}} + \sigma^2_{\text{PiLas}} + \sigma^2_{\text{Pulser+TAC\_ADC}} + \sigma^2_{\text{PiLas\_trigger}}\}$$

+ Systematic effects: laser & temperature drifts, ground loops, etc.



σ = f(Npe) - with amplifier, timing with a CFD



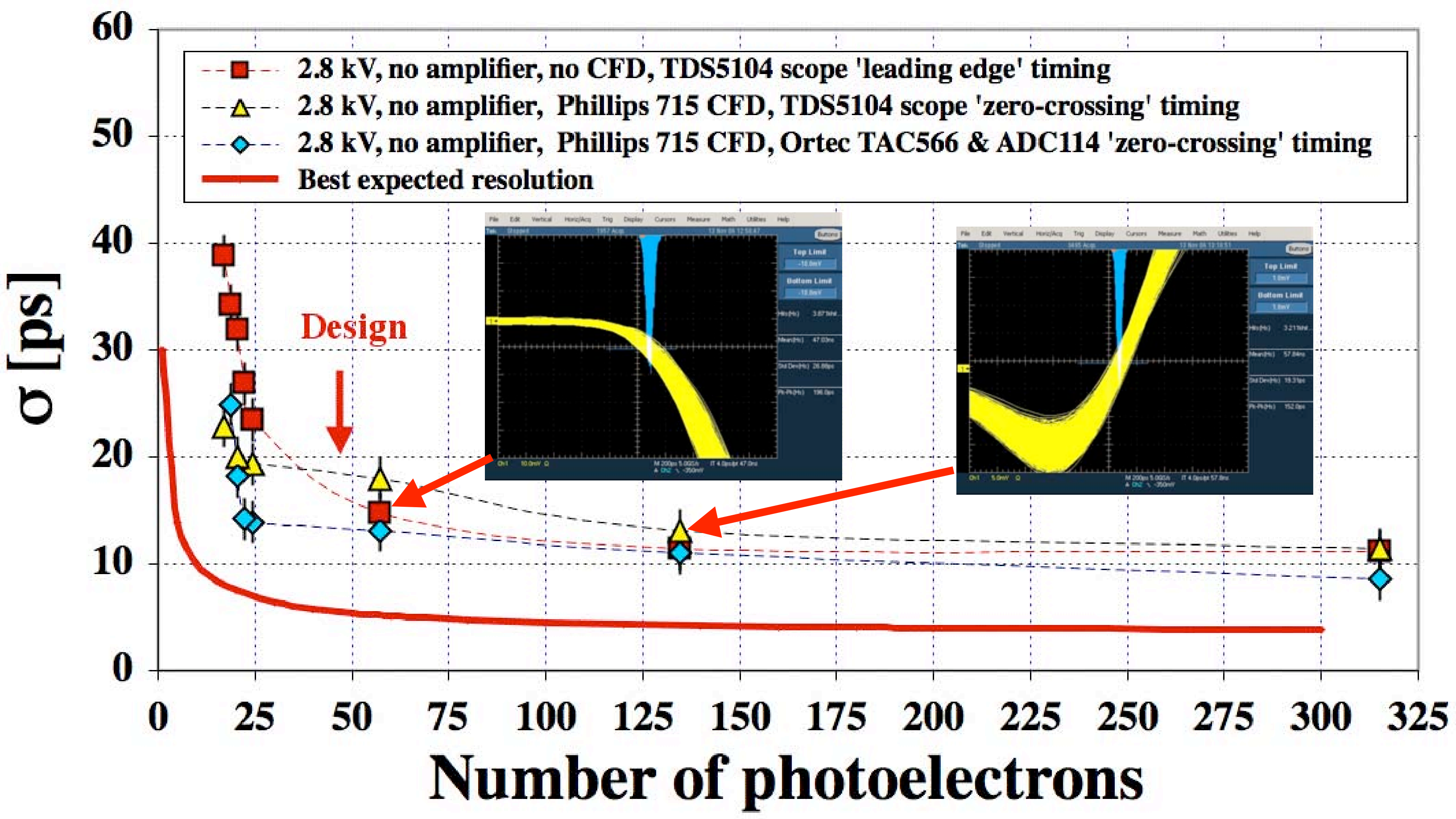
1-st pe$^-$ timing

5-10 pe$^-$ threshold

- One Burle/Photonis MCP-PMTs with 10 µm MCP holes ; red laser wavelength (635 nm).

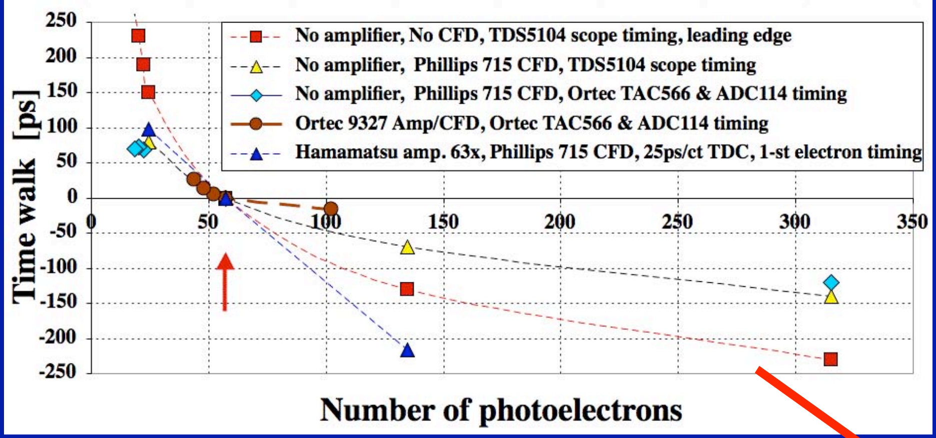
- **The 1-st pe$^-$ timing mode can reach a σ ~ 12 ps resolution even for Npe ~ 25, which corresponds to a 5mm long quartz radiator; a higher threshold leads to a requirement of larger Npe, and thus thicker radiator.**

σ_{RMS} = f(Npe) - no amplifier, timing with a 1GHz BWscope

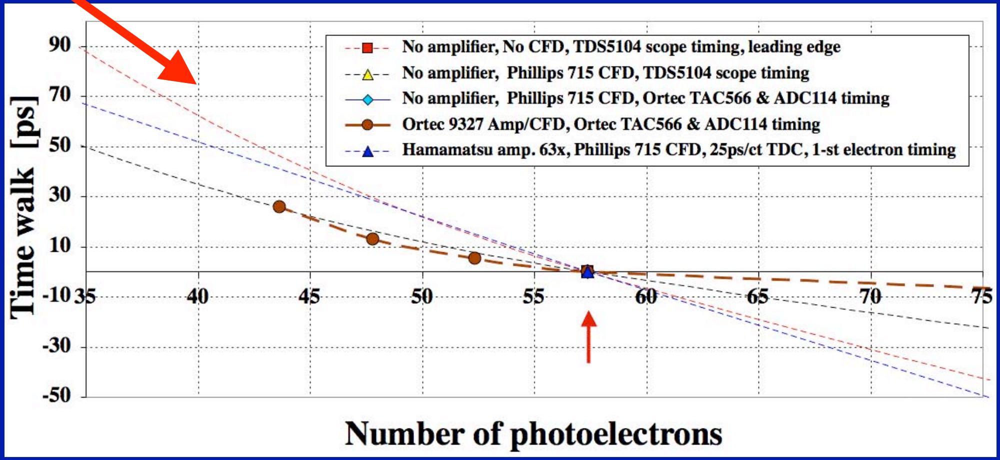


- **No amplifier** => MCP voltage rather high to see small Npe; threshold: 15-20 pe.
- The scope-based timing resolution are worse, probably due to scope triggering noise.

Time-walk = f(Npe) for all methods so far



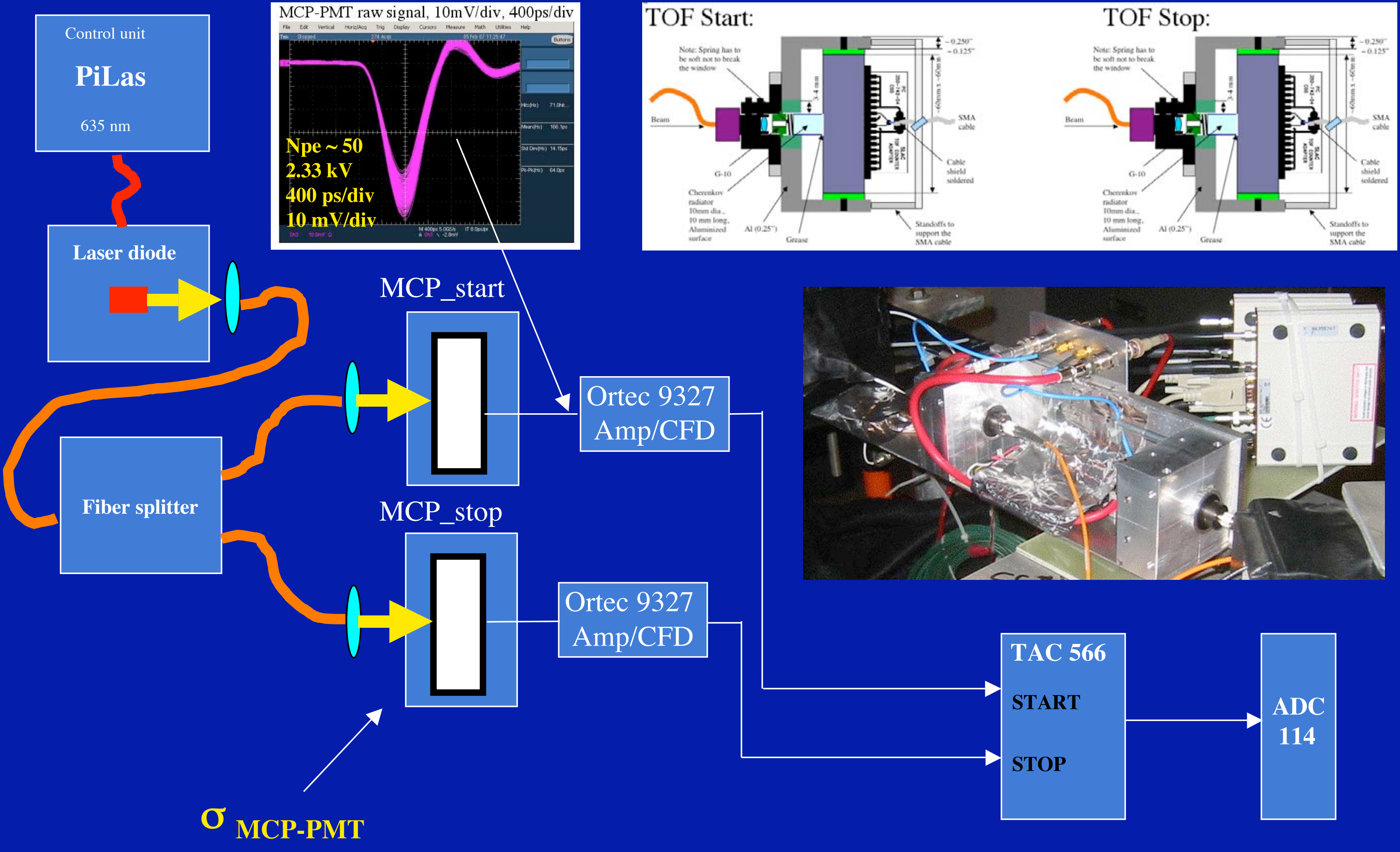
Zoom into a more likely range of variation in Npe:



- Time-walk needs to be corrected with ADC - for all methods !
- Ortec 9327 Amp/CFD time-walk is the smallest, but still significant !
- So, why to use a CFD discriminator at all ?

Double MCP-PMT measurements

Setup with two MCP-PMTs and a fiber splitter



MCP-PMT raw signal, 10mV/div, 400ps/div

Npe ~ 50
2.33 kV
400 ps/div
10 mV/div

Control unit

PiLas

635 nm

Laser diode

Fiber splitter

MCP_start

MCP_stop

Ortec 9327
Amp/CFD

Ortec 9327
Amp/CFD

TAC 566

START

STOP

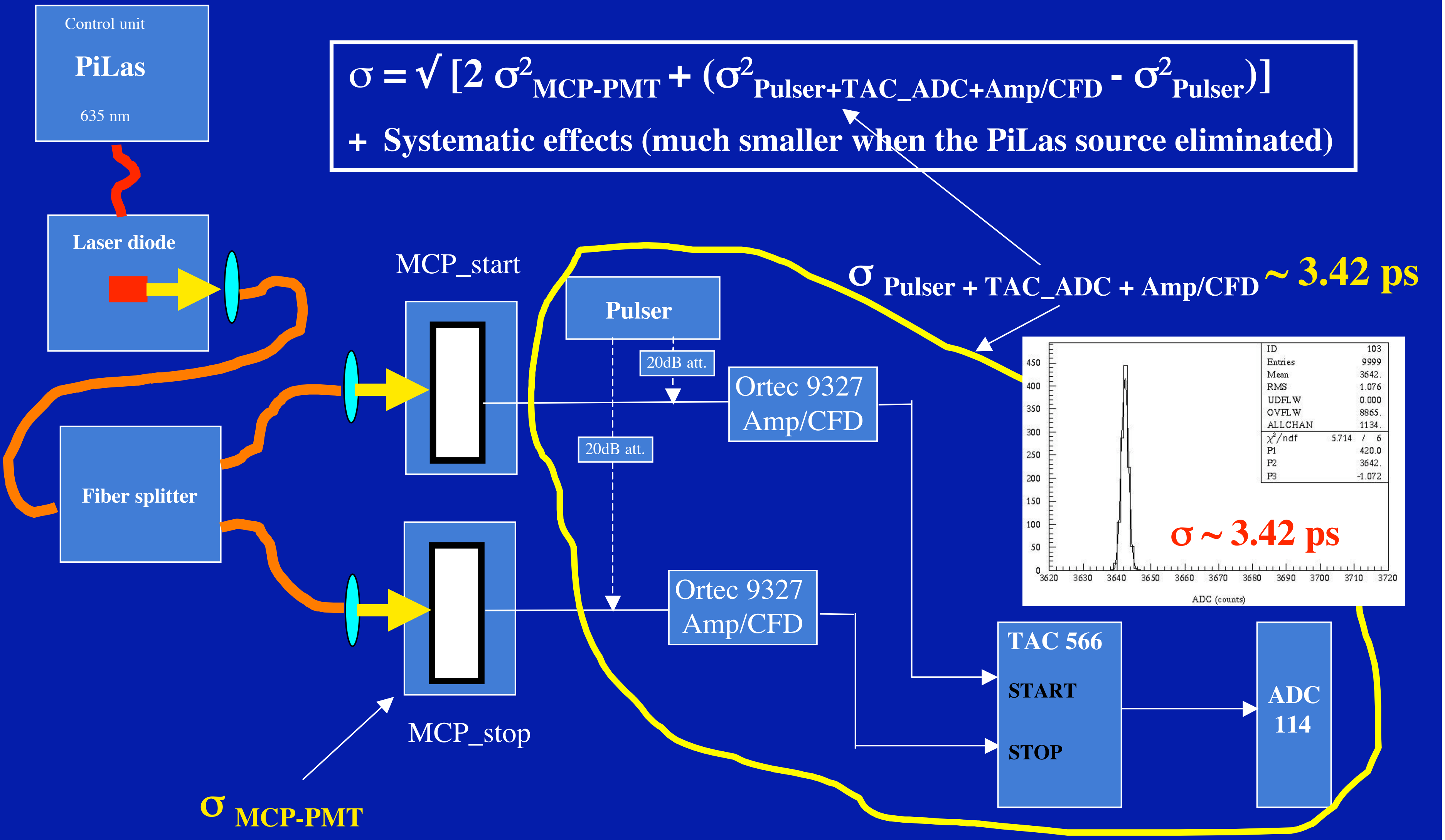
ADC
114

σ MCP-PMT

Calibration of the electronics

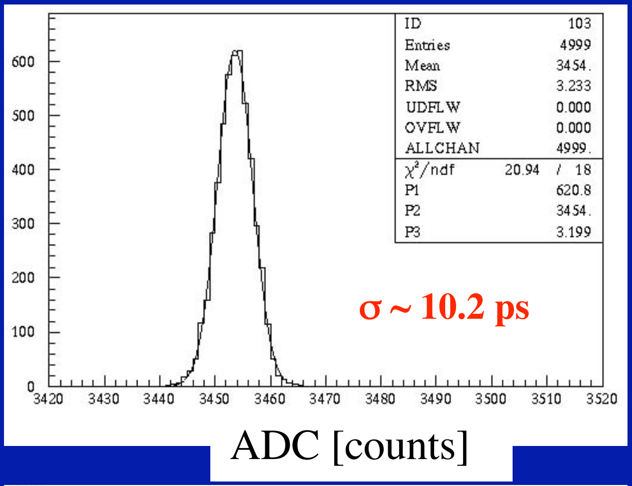
$\sigma = \surd\,[2\,\sigma^2_{\text{MCP-PMT}} + (\sigma^2_{\text{Pulser+TAC\_ADC+Amp/CFD}} - \sigma^2_{\text{Pulser}})]$

+ Systematic effects (much smaller when the PiLas source eliminated)

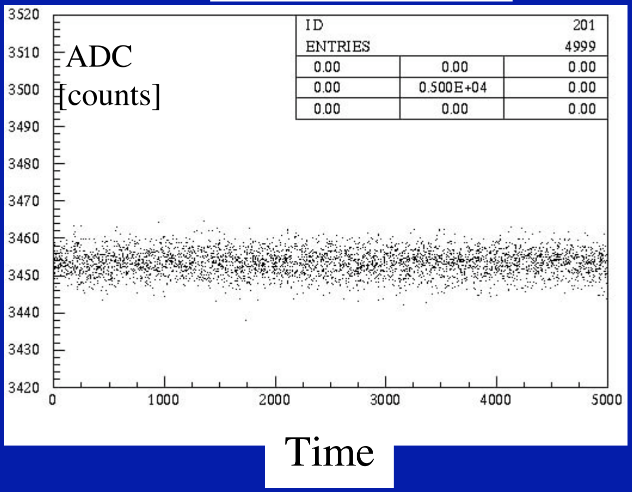


A final result with two TOF counters in tandem

Two detector resolution:



σ ~ 10.2 ps



Each detector has Npe ~ 50 pe$^-$:

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

~ 7.2 ps

Running conditions:

1) Low MCP gain operation ($<10^5$)

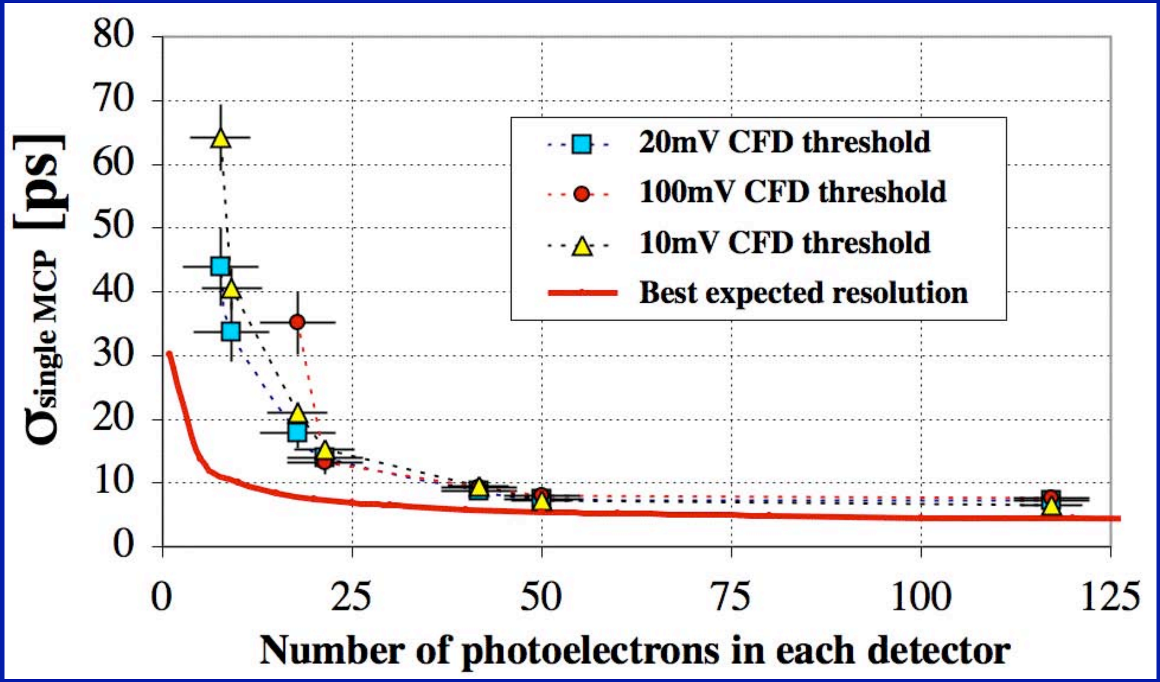
2) Linear operation

3) CFD discriminator

4) No additional ADC correction

- Two Burle/Photonis MCP-PMTs with 10 μm MCP holes operating at 2.27 & 1.88 kV.
- Ortec 9327Amp/CFD (two) with a -10mV threshold and a walk threshold of +5mV & TAC566 & 14 bit ADC114

A single MCP resolution = f(Npe)$_{threshold}$



CFD threshold:

10 mV <=> 2-3 pe

20 mV <=> 3-6 pe

100 mV <=> 15-20 pe

- Two Burle/Photonis MCP-PMTs with 10 μm MCP holes operating at 2.27 & 1.88 kV.
- Ortec 9327Amp/CFD (two) with a walk threshold of +5mV & TAC566 & 14 bit ADC114

- **Can we aim for a 5mm thick radiator (Npe ~25 pe$^-$) ?**

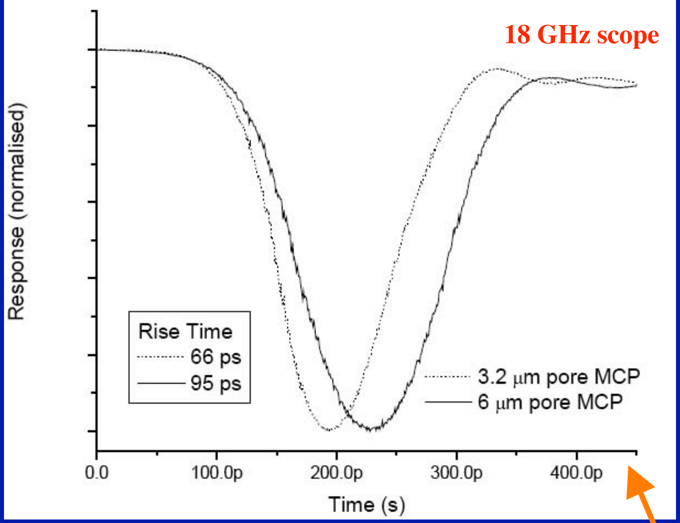
Let’s change the voltage divider to reduce the MCP rise time

(Can we improve the resolution further ?)

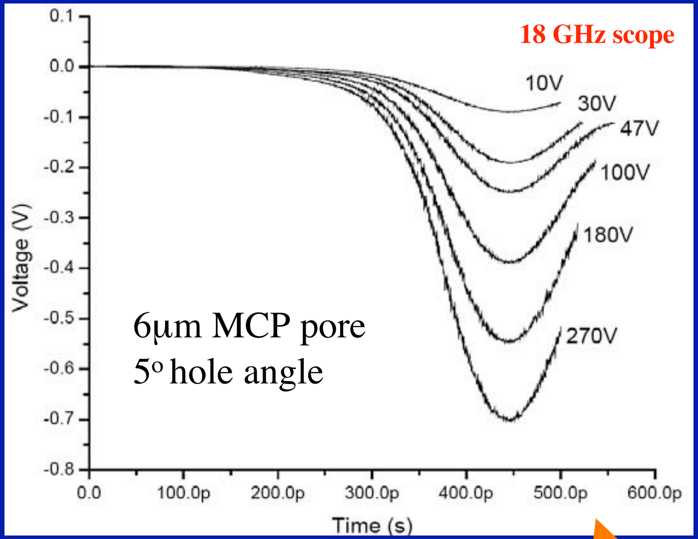
Rise time = f(pore size, $E_{\text{MCP-to-anode}}$, $E_{\text{Cathode-to-MCP}}$)

(Photek Ltd. information)

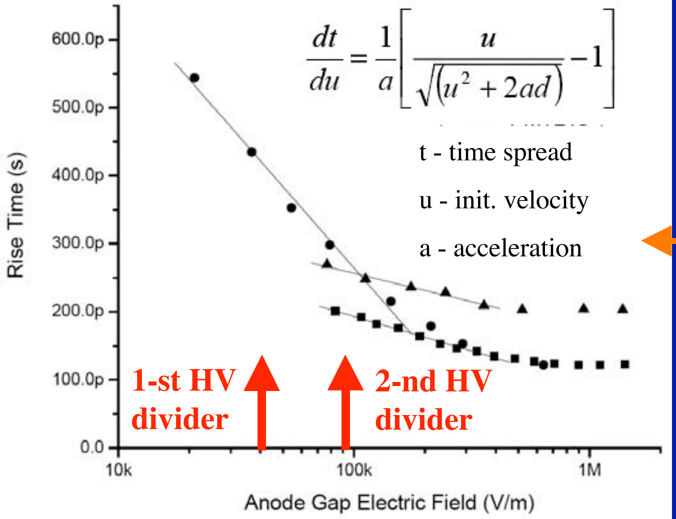
Pore size:



Cathode-to-MCP voltage:



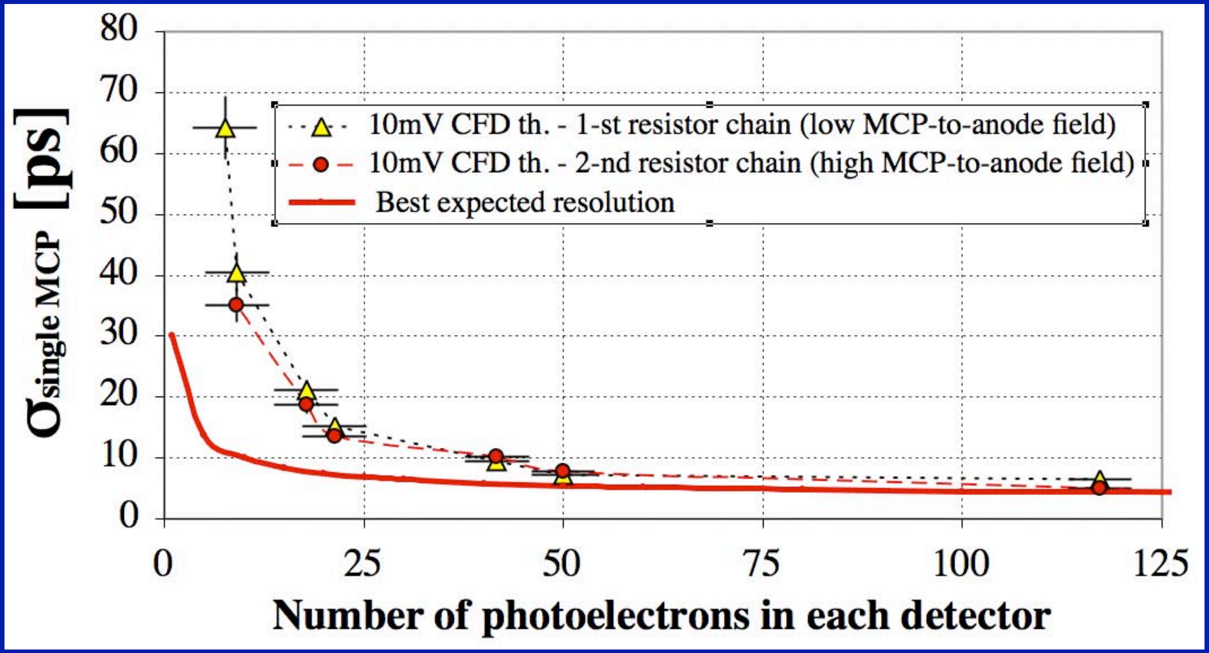
MCP-to-anode electric field:



- **Rise time is determined by:**
  - **- Transit time variation in MCP pores**
    Smaller MCP pore size, faster rise time
  - **- Exit velocity variation from MCP towards anode**
    Larger MCP-to-Anode electric field, faster rise time
  - **- Exit velocity variation from cathode towards MCP**
    Small effect for red wavelengths & Bialkali
    [635 nm <=> ~2 eV => $dt/du|_{max}$ ~ $((2-\phi)/200)*1000$ps],
    ϕ ~1.5-2 eV. **Could be a problem for $\lambda < 300$ nm !!**

A single MCP resolution = f(Npe)$_{\text{MCP-to-anode field}}$

Comparison of two resistor chains:

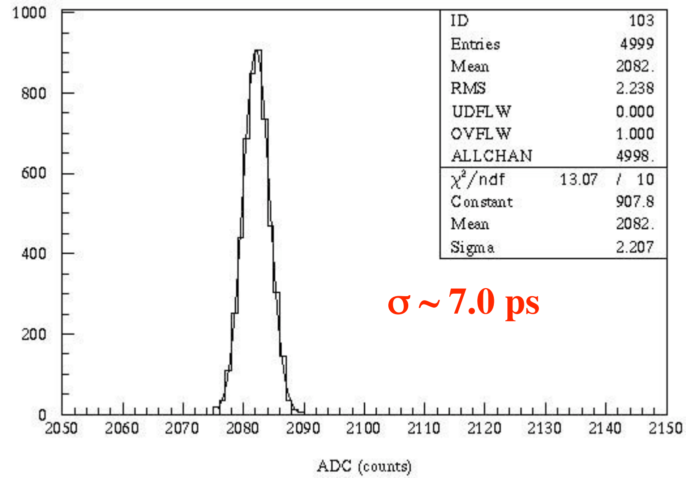


- Two Burle/Photonis MCP-PMTs with 10 μm MCP holes operating at 2.27 & 1.88 kV.
- Ortec 9327Amp/CFD (two) with a -10mV threshold and a walk threshold of +5mV & TAC566 & 14 bit ADC114

- **Some improvement when running a high MCP-to-anode field.**
- **Not worth the risks of a possible damage and reduction of the operating range for the magnetic field application.**

The best result with two TOF counters in tandem

Two detector resolution (resistor chain #2):



Each detector has Npe ~ 115-120 pe$^-$:

$$\sigma_{\text{single detector}} \sim (1/\sqrt{2})\ \sigma_{\text{double detector}}$$
$$\sim 5.0 \text{ ps}$$

Running conditions:

1) Low MCP gain operation ($<10^5$)

2) Linear operation

3) CFD discriminator

4) No additional ADC correction

- Two Burle/Photonis MCP-PMTs with 10 μm MCP holes operating at 2.85 & 2.43 kV.
- Ortec 9327Amp/CFD (two) with a walk th. of +5mV & TAC566 & 14 bit ADC11

Contribution of the MCP-PMT itself to the above single detector resolution:

$$\sigma_{\text{MCP-PMT}} < \sqrt{1/2}\ \{\ \sigma^2 - [\sigma^2_{\text{Pulser+TAC\_ADC+Amp/CFD}} - \sigma^2_{\text{Pulser}}\ ]\} < 4.5 \text{ ps}$$

7.0 ps

3.42 ps

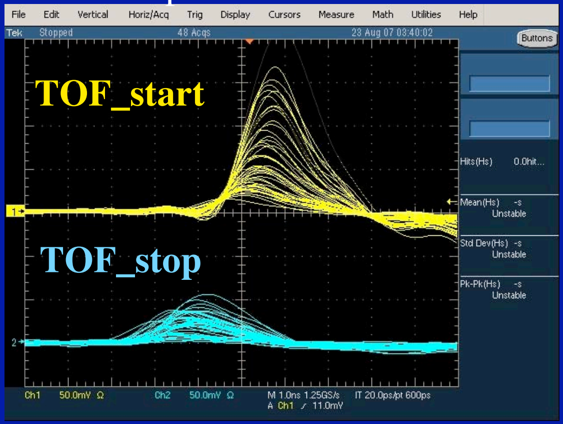
< 2 ps (manufacturer)

Lessons from the test beam

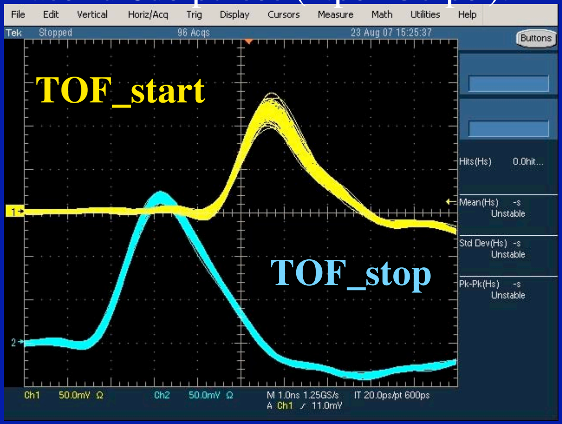
Beam test - problem with the radiators

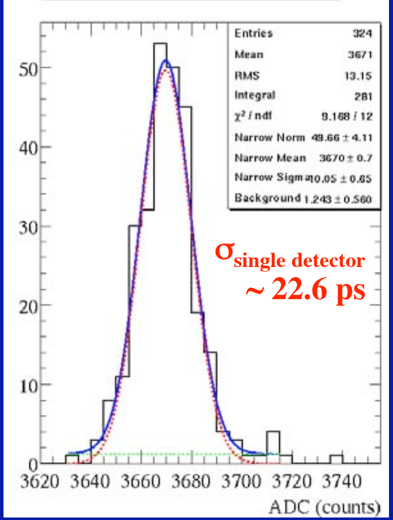
To make these pictures possible, send monitor signals over a long delay cable => rise time is degraded:

Beam test pulses:



Laser diode pulses (Npe ~50 pe$^-$):





$\sigma_{\text{single detector}}$ ~ 22.6 ps

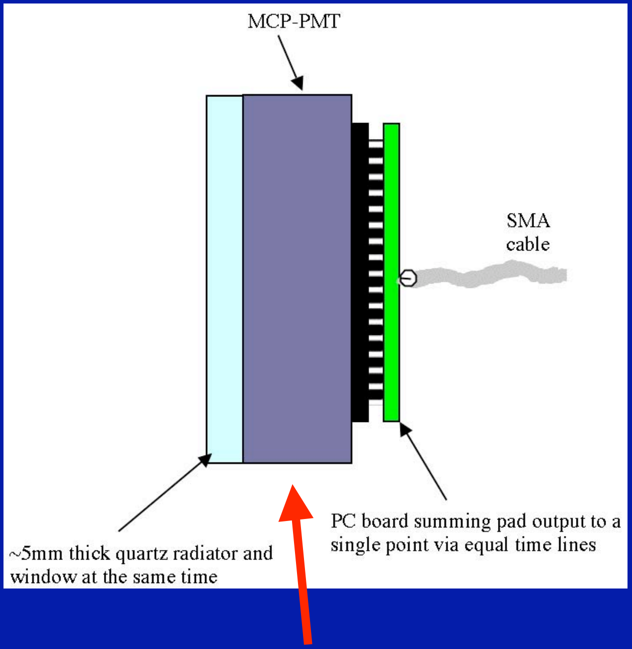
- **A poor reflectivity of radiator's Al coating created a non-uniform number of photoelectrons. The 2-nd radiator's yield is worse than the 1-st one.**
- **One could still correct it if we would have a fast ADC !!**

  (Ortec 9327 Amp/CFD provides a fast bipolar monitor of the amplifier. However, an ordinary ADC, such as LeCroy, would integrate it to a fixed constant. We did not have a better ADC available, which could be used to correct for the pulse height variation. If we would have it, we would get a better result.)

- $\sigma_{\text{single detector}} \sim (1/\sqrt{2})\ \sigma_{\text{double detector}} \sim 22.6$ ps

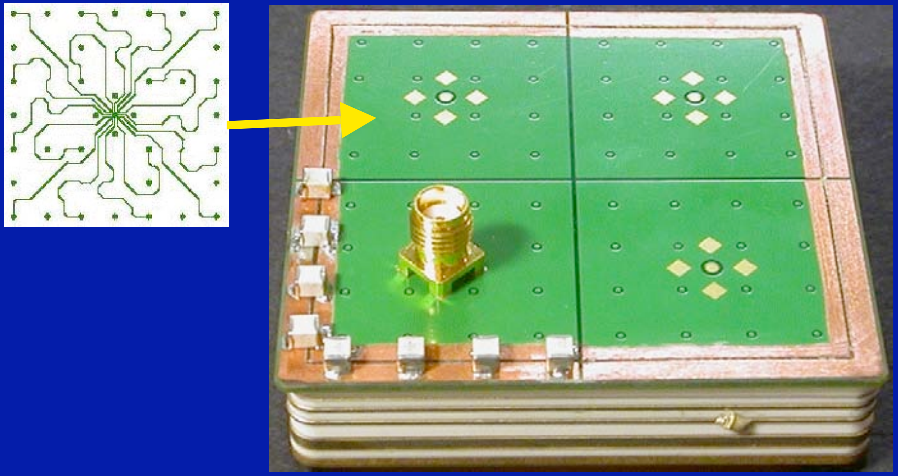
Towards a final design

My initial thoughts:



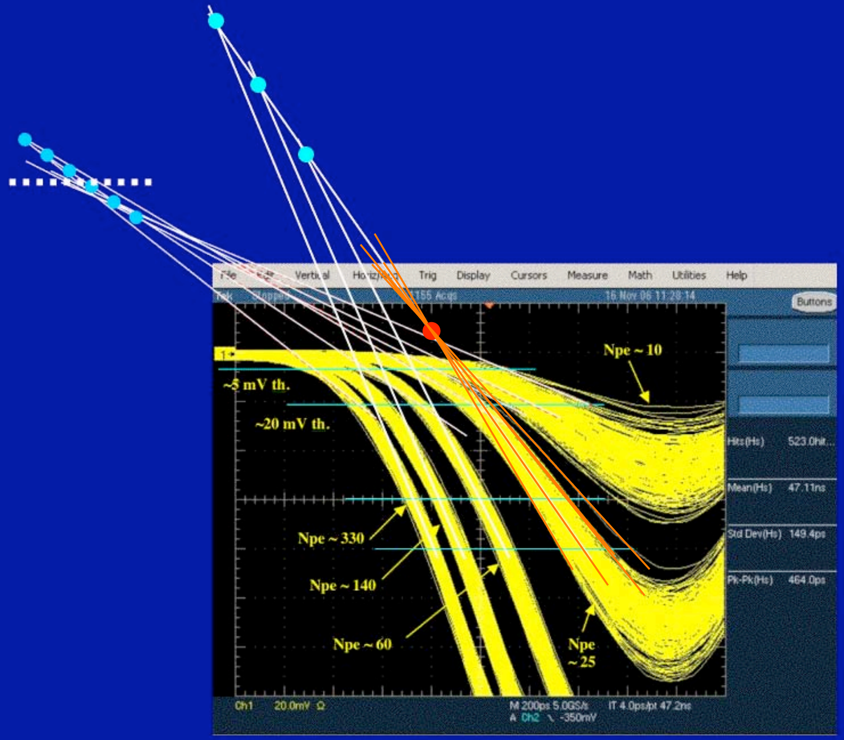
U. of Chicago solution:

Equal-time trace PC board & new ground layout:



- **Starting parameters, which Burle/Photonis is willing to try:**
  - 5 mm quartz window & radiator => ~ 25 pe^-
  - 0.07” cathode-to-MCP distance (this still allows a placement of the getter)
  - 0.02” MCP-to-anode distance
  - 64 pads, 6x6 mm initially

Time-walk in a double threshold method using a 1GHz BW scope



- Burle/Photonis MCP-PMTs with 10 µm MCP holes operating at 2.80kV; no amplifier; red laser (635 nm).
- Tektronix TDS 5104 scope with 1 GHz BW; trigger: PiLas trigger; thresholds 5 & 20 mV; scope: 200ps/div & 10 mV/div.

- **A double-threshold method does not lead to a single intersect point, probably due to a nonlinearity in the amplification process, <u>if one accepts a large variation in Npe</u> ! It may work only over a very small range of variation in Npe.**
- **<u>May have to digitize pulses with 2-4 sampling points on both leading & trailing edges to get best timing and amplitude.</u>**

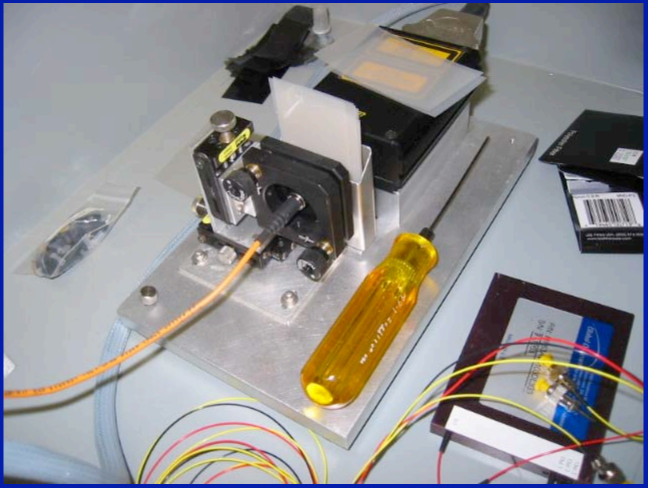
Conclusions

- **Our present best laser diode results:**
  - $\sigma_{\text{single MCP}} \sim 7.2$ ps for Npe ~ 50, expected from a 1cm thick radiator.
  - $\sigma_{\text{TTS}} \sim 27$ ps for Npe ~ 1.
  - Electronics contribution (Amp, CFD, TAC, ADC): $\sigma_{\text{Total\_electronics}} \sim 3.4$ ps.
  - Upper limit on the MCP-PMT resolution: $\sigma_{\text{MCP-PMT}} \sim 4.5$ ps, obtained for a modified resistor chain and Npe ~120.
- **Our present best test beam results:**
  - $\sigma_{\text{single MCP}} \sim 22.5$ ps (believed to be due to a poor radiator Al-coating, and due to not having a fast ADC to correct PH variation).

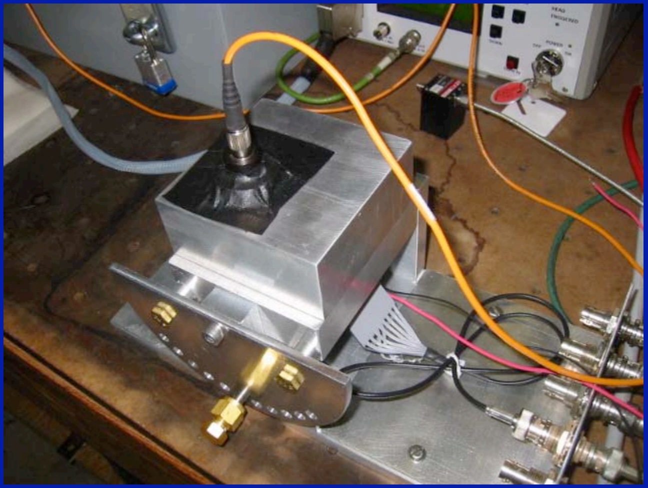
Backup slides

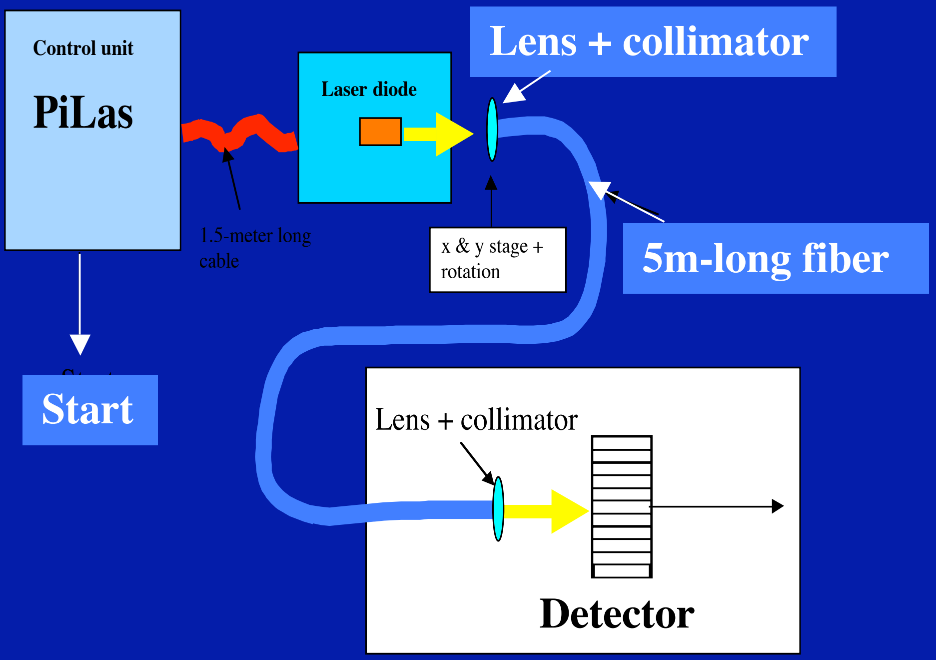
New laser-based testing methods

PiLas laser head:



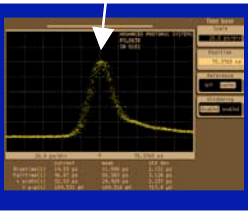
Calibration of a fast detector:





Parameter	**Value**
Laser diode source	PiLas
Wavelength	635 nm
TTS light spread (FWHM)	**~ 30 ps**
Fiber size	62.5 μm

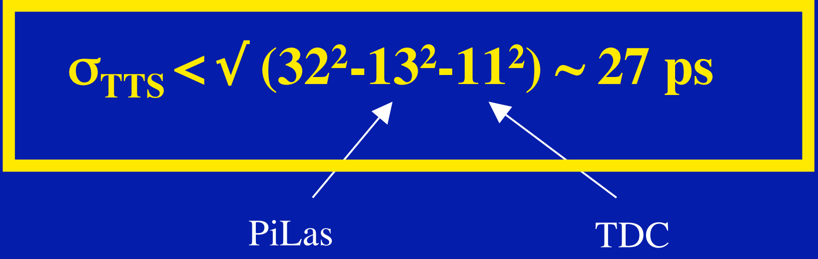
Manufacturer: Ultra-fast Si Detector
or a streak camera :



Single-photon timing resolution - σ_{TTS}

Burle/Photonis MCP-PMT 85012-501 (64 pixels, ground all pads except one)

- **10 μm MCP hole diameter**
- Phillip CFD
- PiLas red laser diode (635 nm):



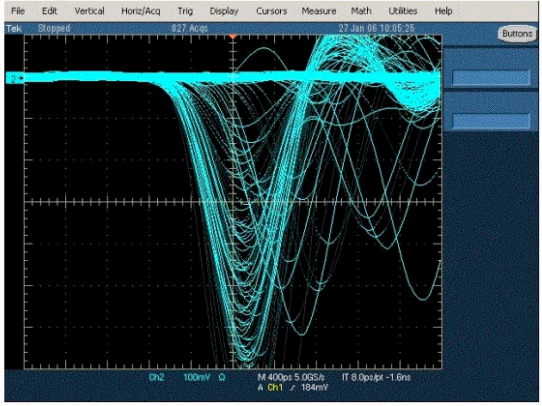
$$\sigma_{TTS} < \sqrt{(32^2-13^2-11^2)} \sim 27 \text{ ps}$$

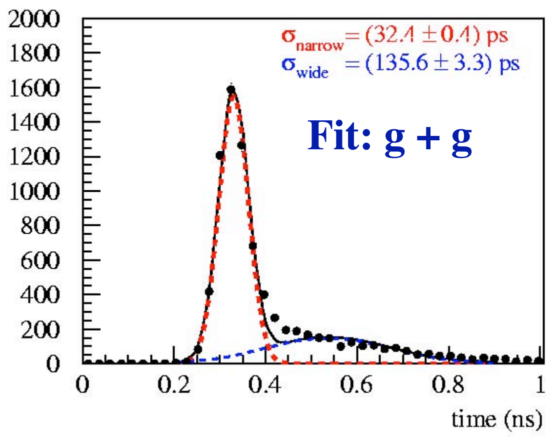
PiLas

TDC

Hamamatsu C5594-44 amplifier

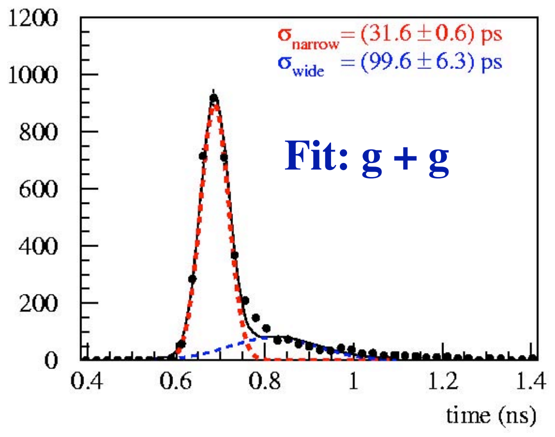
1.5 GHz BW, 63x gain





Ortec VT120A amplifier

~0.4 GHz BW, 200x gain + 6dB



Super-B Belle: Status of Japanese competition

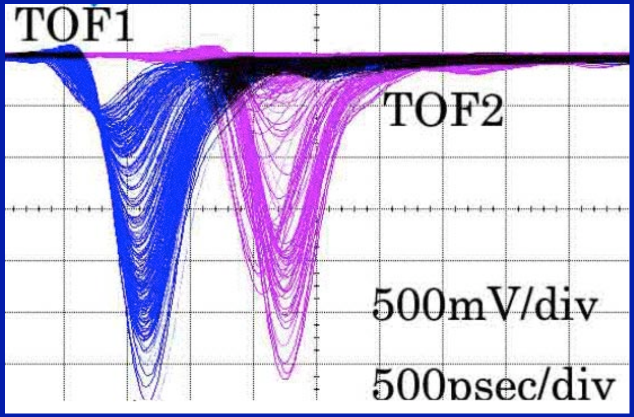
K.Inami et al., Nagoya Univ., Japan - SNIC conference, SLAC, April 2006

MCP-PMT:

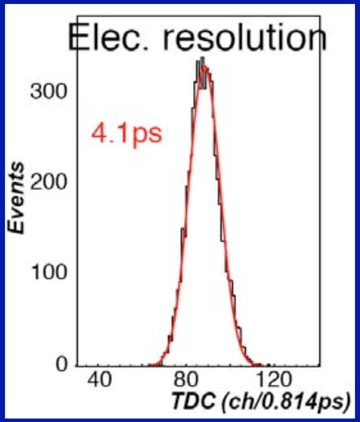
σ_{TTS} = 10-11ps

Amp/CFD/TDC:

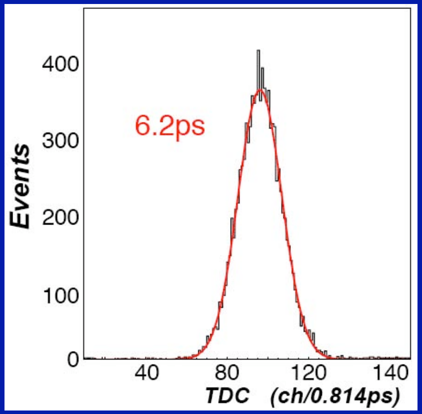
Use two identical TOF detectors in the beam (Start & Stop):



Electronics resolution:



Beam resolution with qtz. radiator (N_{pe}~ 50):



Systematic errors

(They will ultimately decide what will be a final performance)

Systematic errors when doing timing at a level of σ~10-20ps

- Laser diode start up instability
- Laser diode temperature stability
- Noise
- TDC linearity stability
- “Sleep-wake up” ADC effect
- Non-uniform MCP gain response
- Deflection of MCP front window
- Cross-talk, ringing
- Vertexing, track length
- START time
- Aging
- Magnetic field