Exploring the time domain frontier with MCP-PMTs

J. Va'vra, SLAC

Light travels 300μm in one ps

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- What detectors are available ?
- Examples of timing applications
- Tools one needs to make any progress in this filed
- **Our experience, wish list, what needs to fixed, etc.**
- Photoelectron detection efficiency (Detected QE), Photocathode and Gain characteristics.
- Timing strategies
- Timing measurements for various timing strategies as a function of number of photoelectrons.
- Future plans for detector design and electronics
- Bad effects: Charge sharing, cross-talk, coherent oscillation effects, magnetic field, aging, etc.
- **Examples of applications**
- Focusing DIRC prototype for Super B factory PID - the 1st RICH detector capable of correcting the chromatic error in the Cherenkov angle
- TOF detector R&D for Super B factory PID - road to reach σ ~10-15ps per min. ion. track

Transit Time Spread σ_{TTS} of photon detectors

(σ_{TTS} refers to the **single** electron Transition Time Spread)

Manufacturer	Name	Type/Feature	σ_{TTS} [ps]
Photonis	**Quantacon**	XP2020/UR	**~ 150**
Hamamatsu	**HAPD**	HPD+Multi-cell APD	**~ 90**
Hamamatsu	**Flat-panel**	H-8500	**~ 140***
Hamamatsu	**Multi-mesh**	R-6135	**~ 80**
Hamamatsu	**MCP-PMT***	**6 μm** hole dia.	**< 30**
Burle/Photonis	**MCP-PMT****	**10 μm** hole dia.	**< 26***
Sopko/Prague	**G-APD**	Single-cell APD	**~ 38***
Dolgoshein	**G-APD/SiPMT**	Multi-cell APD	**~ 60**

*** ~ 12 mm dia, small single pad detector**

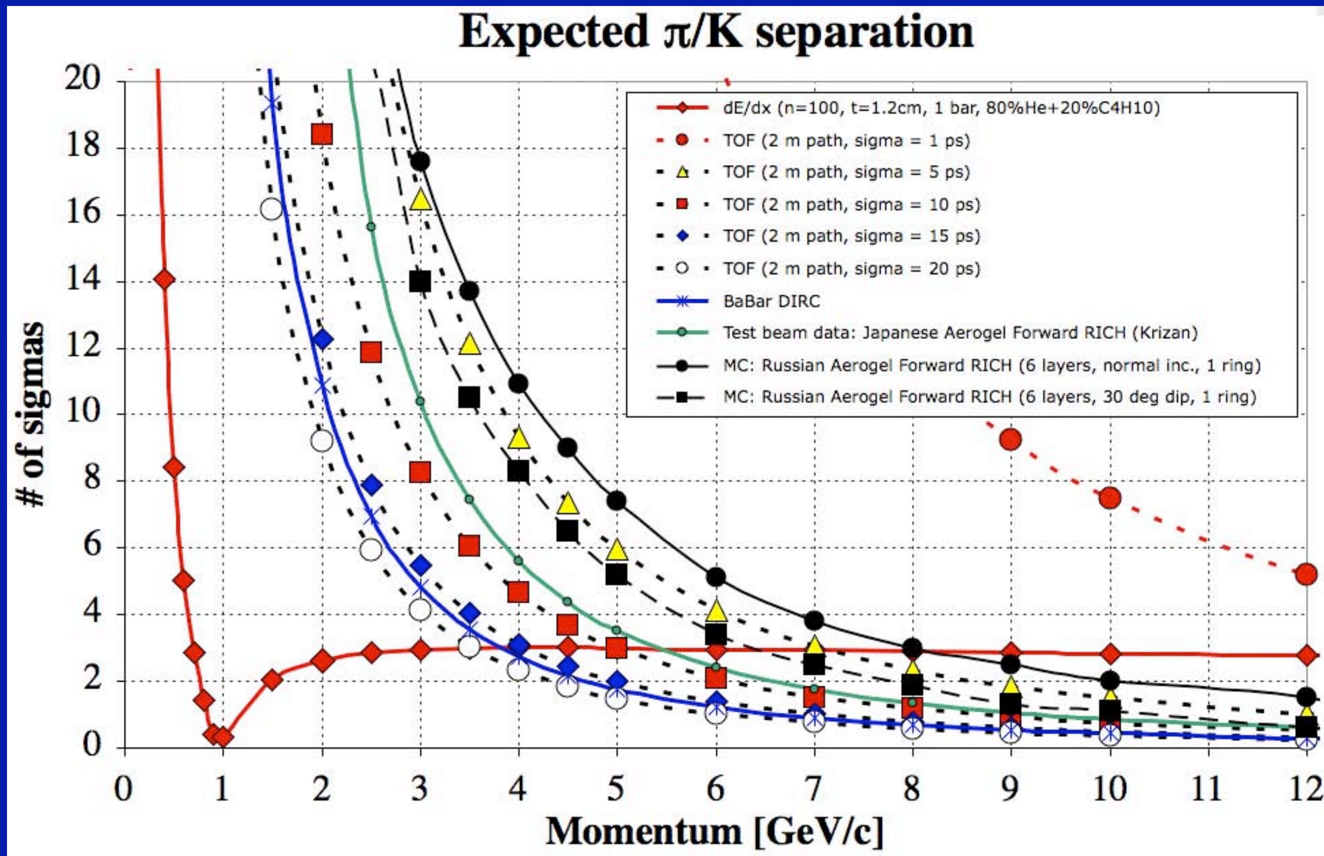
**** ~ 2" x 2", 64 pads detector, all pads grounded except one**

*** measured by speaker**

Example #1: Timing at a level of σ <15ps can start competing with the RICH techniques

Example of various Super-B factory PID designs:

Calculation done for Flight Path Length = 2m



- **Recent progress in the TOF technique is driven by these advances:**

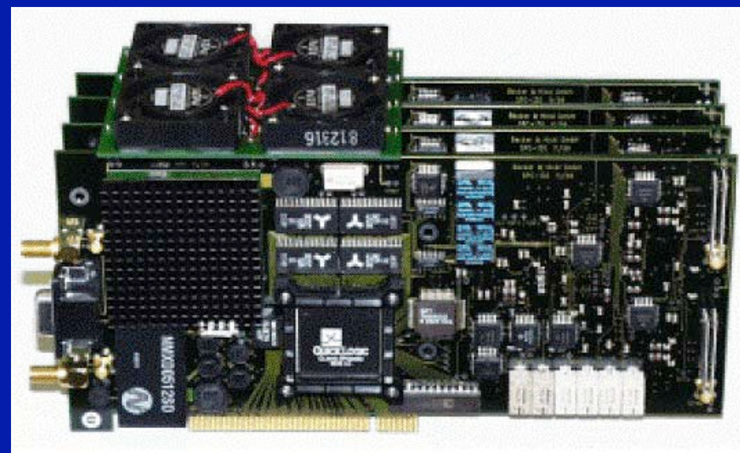
  (a) a fast Cherenkov light rather than a scintillation, (b) new detectors with small transit time spread σ_{TTS}, (c) fast electronics, and (d) new fast laser diodes for testing.

Super-B Belle: Status of Japanese competition

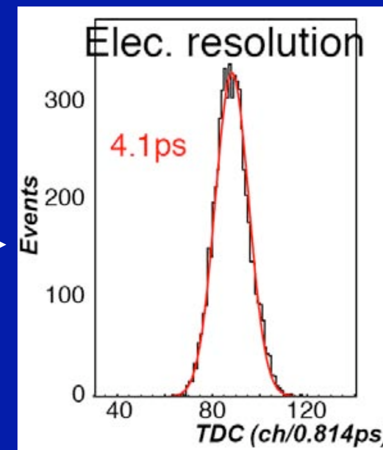
K.Inami et al., Nagoya Univ., Japan - SNIC conference, SLAC, April 2006

MCP-PMT:

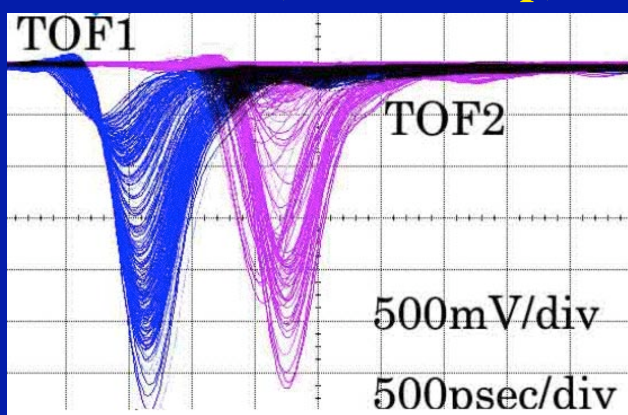
TDC:



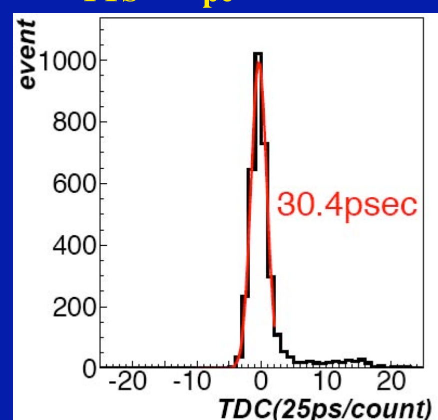
Electronics resolution:



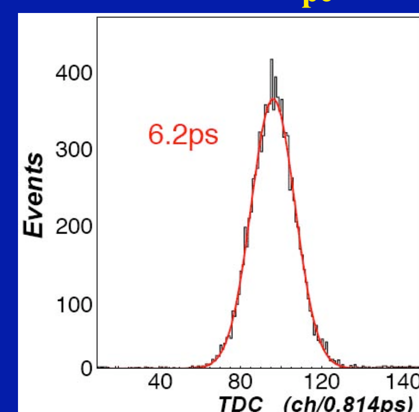
Use two identical TOF detectors in the beam (Start & Stop):



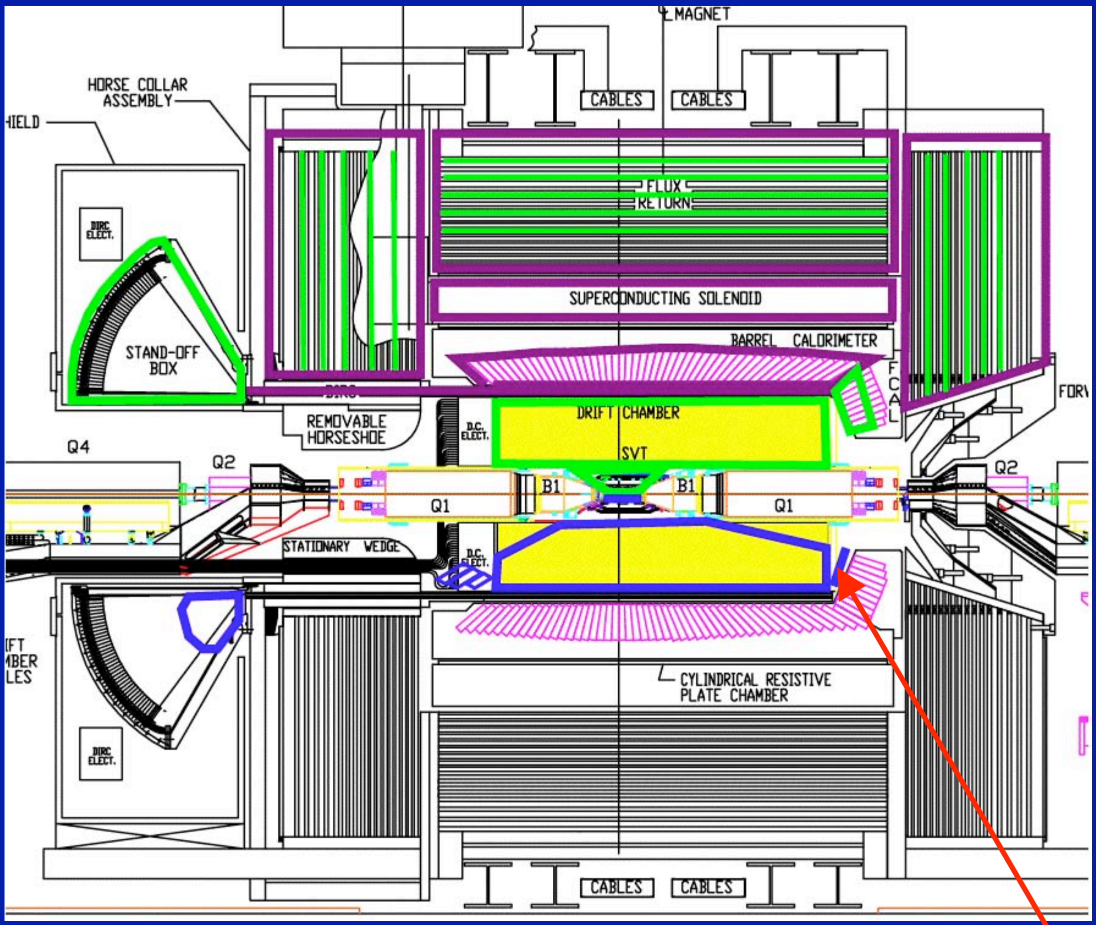
Single photon resolution = σ_{TTS} (N_{pe}~ 1):



Beam resolution with qtz. radiator (N_{pe}~ 180):

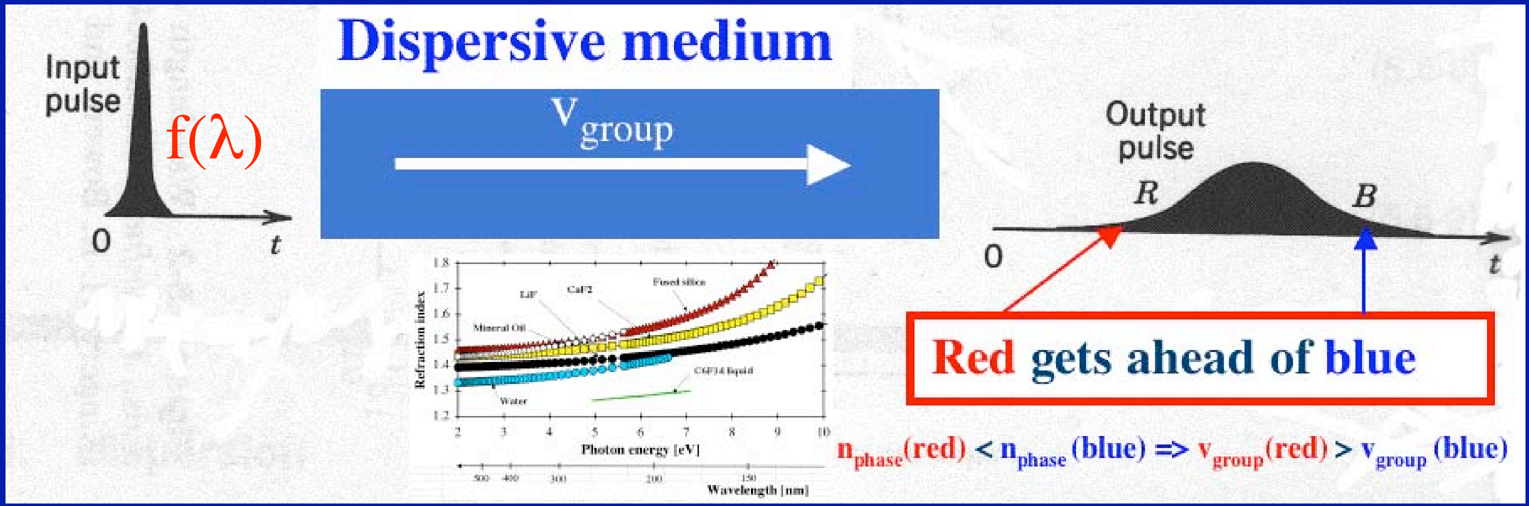


Super-B detector options



- **TOF detector with σ ~ 15ps is one option**

Example #2: Color tagging by measurement of photon propagation time



$$v_{group} = c_0 / n_{group} = c_0 / [n_{phase} - \lambda * dn_{phase}/d\lambda]$$

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

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

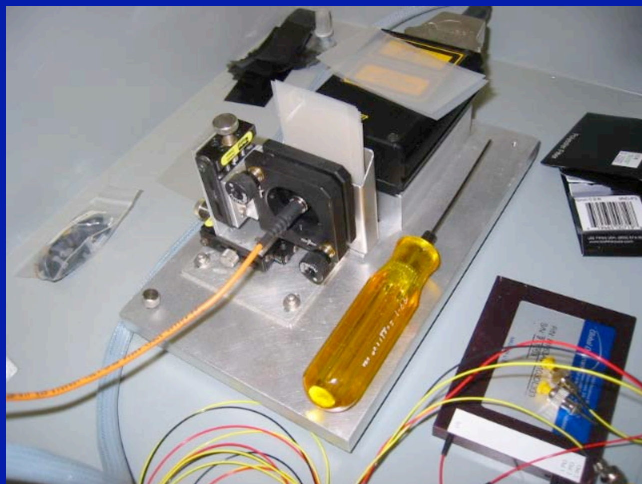
dt is pulse dispersion in time, length **L**, wavelength bandwidth **dλ**, refraction index **n(λ)**

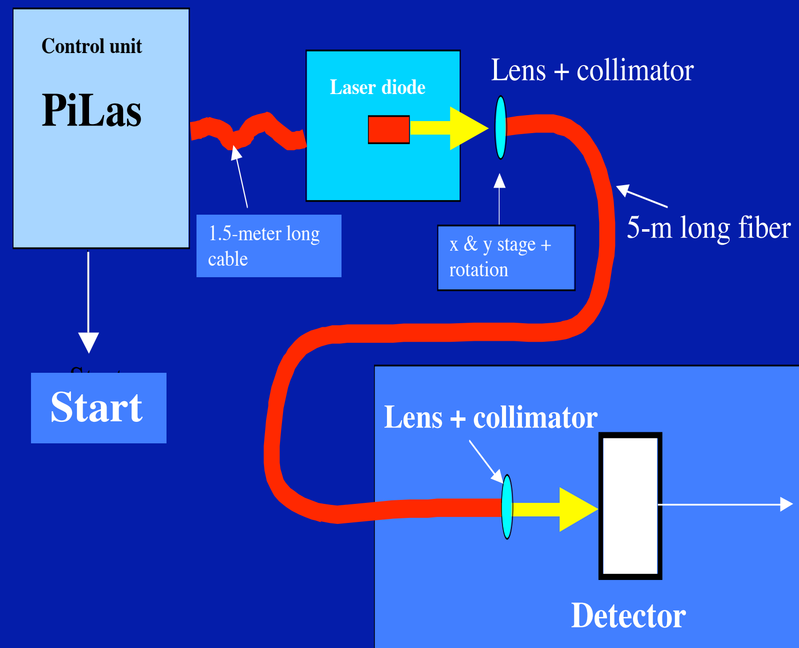
- The Focusing DIRC determined (Fused Silica): **dt/L = dTOP/L ~ 40ps/meter**.
- **<u>Our goal is to measure the color of the Cherenkov photon by timing !</u>**

A laser diode setup to measure timing

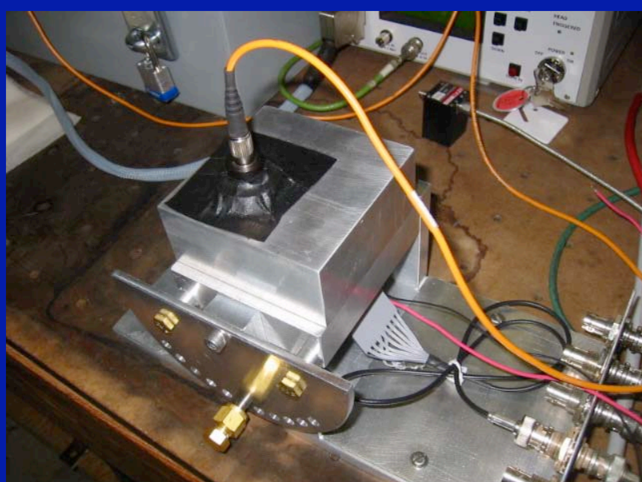
Timing measurement setup in trailer 233 at SLAC

PiLas laser head:





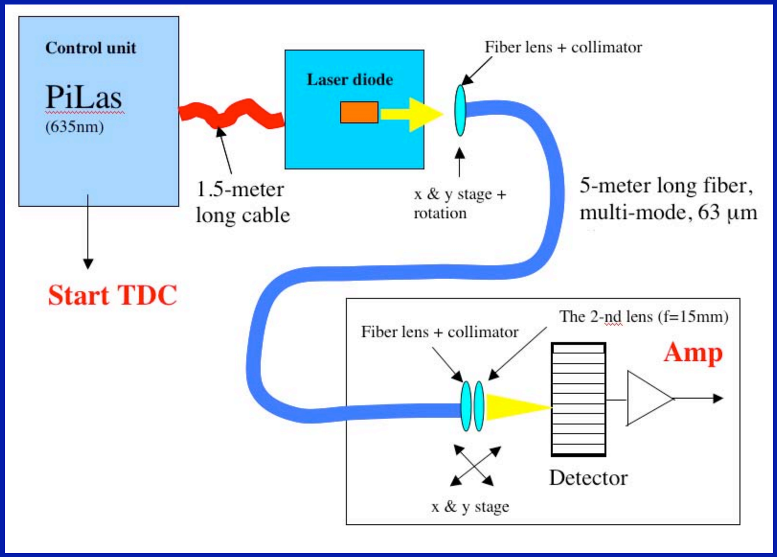
Calibration of a fast detector:

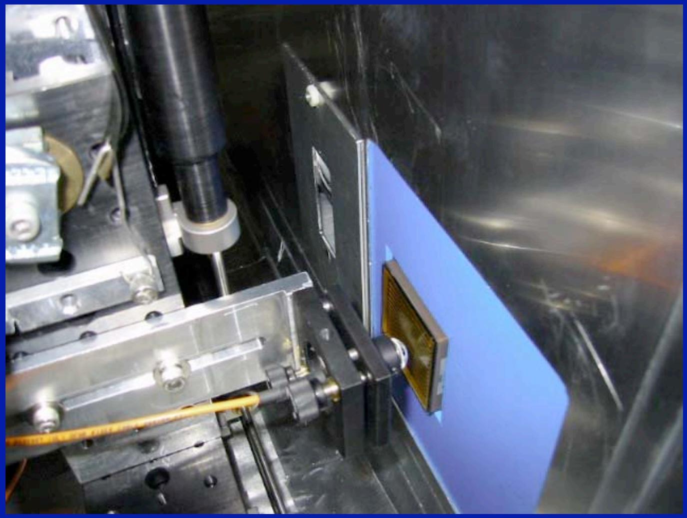


Parameter	SLAC tests
Laser diode source	PiLas
Wavelength	635 nm
FWHM light spread	~ 35 ps
Fiber size	62.5 μm

Scanning setup to measure a spatial response

Scanning setup in bldg 403 at SLAC





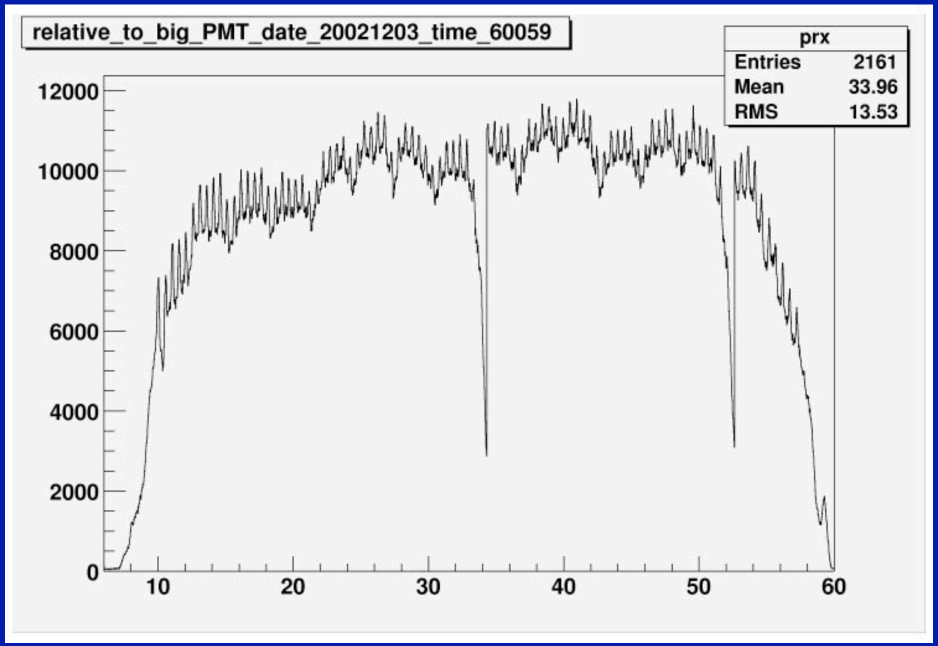
- **x&y stage for the fiber final focus :**
  Stepper motor moves the end of the fiber with **typical steps:** $\Delta x \sim 100\mu m$ & $\Delta y \sim 1mm$.
- **Light source:**
  - PiLas laser diode operating in single photoelectron mode.
  - **410nm** & **635** & **430nm** (was on loan).
  - Fiber is 63µm dia. multi-mode fiber, equipped with lenses at both ends, plus additional lens, resulting in the **spot size of ~150 µm**.
- **Analysis:**
  - A hit is accepted into the efficiency definition if it is within a time window, and it is on the same pad as the laser head is pointing to.
  - **To get a relative efficiency we normalize to the 2 inch dia. Photonis XP 2262B PMT** (or the DIRC PMT, ETL 9125FLB17).
  - DAQ trigger rate: up to **20kHz**.

Resolution of the scanning system

Scanning setup in bldg 403 at SLAC

Micro-structure of the dynode electrodes:

Hamamatsu Flat Panel H8500 MaPMT:



- **Spatial resolution of the system is less than 150 µm, for a step size of 25µm.**

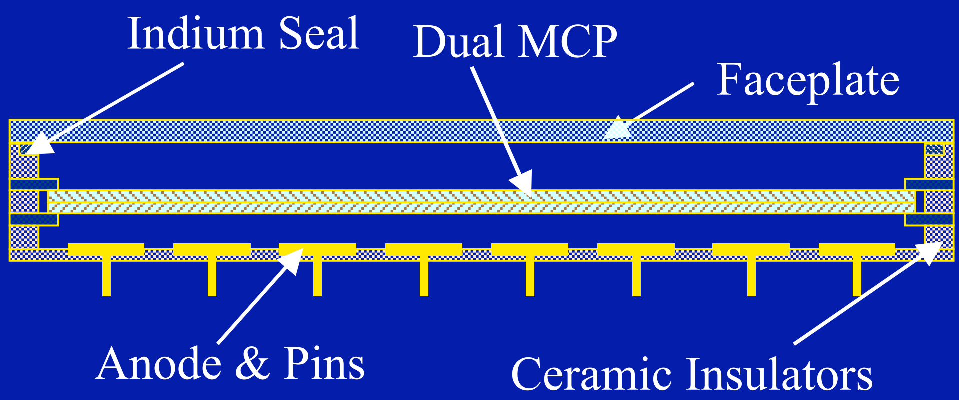
- Electronics chain used in this test:
  Final SLAC amplifier, LeCroy 4413 discriminators with 100mV threshold, LeCroy 3377 TDCs with 0.5ns/count.

MCP-PMT and MaPMT Detectors

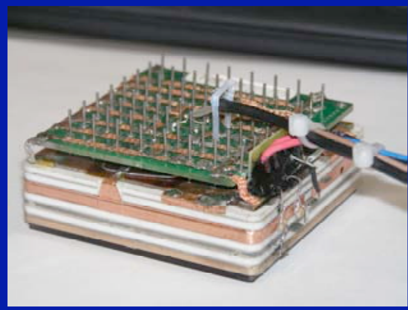
- Detection efficiency, pixelization, edge effects, etc.

Burle/Photonis MCP-PMT

Based on Burle/Photonis data sheet and discussions with P. Hink



A real device:



Parameter	Value
Photocathode	Bialkali or Multi-alkali
Number of MCPs	2
Total average gain @ -2.4kV & B = 0 kG	~ 5 x 10^5
Geometrical collection efficiency of the 1-st MCP	60 - 70% *
Geometrical packing efficiency (plus QE edge effects)	75 - 85% *
Fraction of late photoelectrons arrivals	~ 25%
Total fraction of "in time" photoelectrons detected	33 - 45%
σ_{TTS} - 10 µm & 25 µm MCP hole dia. & B = 0 kG	30-32 & 50-60 ps
Matrix of pixels	2x2, 8 x 8, 16 x 16 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]

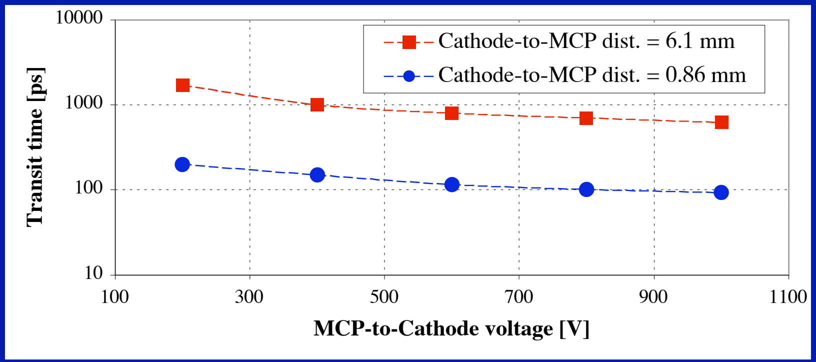
This is a real handicap for RICH → (Total fraction of "in time" photoelectrons detected)

* Higher number is a future improvement

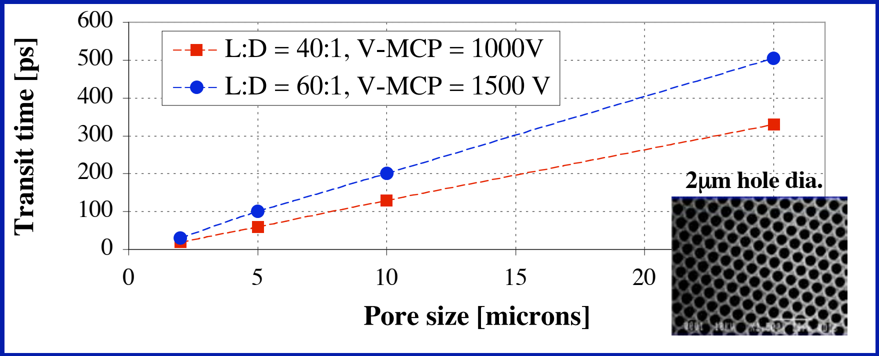
MCP-PMT: transit time & gain

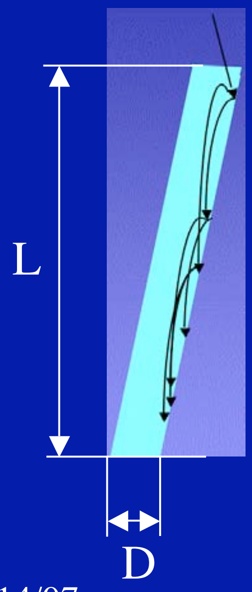
Burle/Photonis information

Transit Time = f($V_{cath\_to\_MCP}$):



Transit Time = f(Pore size)$_{L:D}$:





Transit time spread:

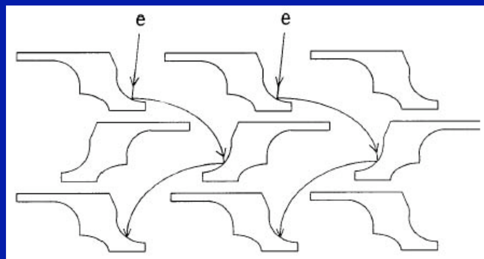
- **Increased voltage or decreased gap can reduce the transit time.**
- **Smaller pore size smaller the transit time.**

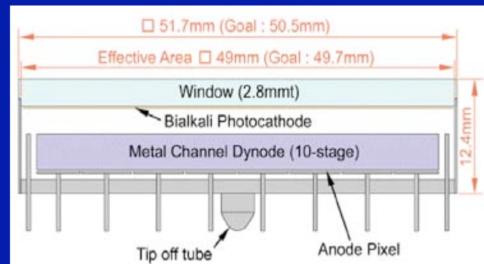
MCP Gain:

- **Typical secondary yield is 2 per each strike of the wall.**
- **L:D = 40:1 seems to be optimum design**; for this ratio there are typically 10 strikes, i.e., Gain ~ 2^{10} ~ 10^3 per single MCP plate; **$G \sim e^{(A*L/D)}$**
- **For 10 µm dia. MCP hole, a ratio of 40:1 cannot be achieved for a 50x50 mm^2 size MCP (too fragile);** therefore, a ratio of 60:1 is used. As a result, such MCP has slightly worse transit time.

Hamamatsu MaPMTs

Based on Hamamatsu Co. data sheet





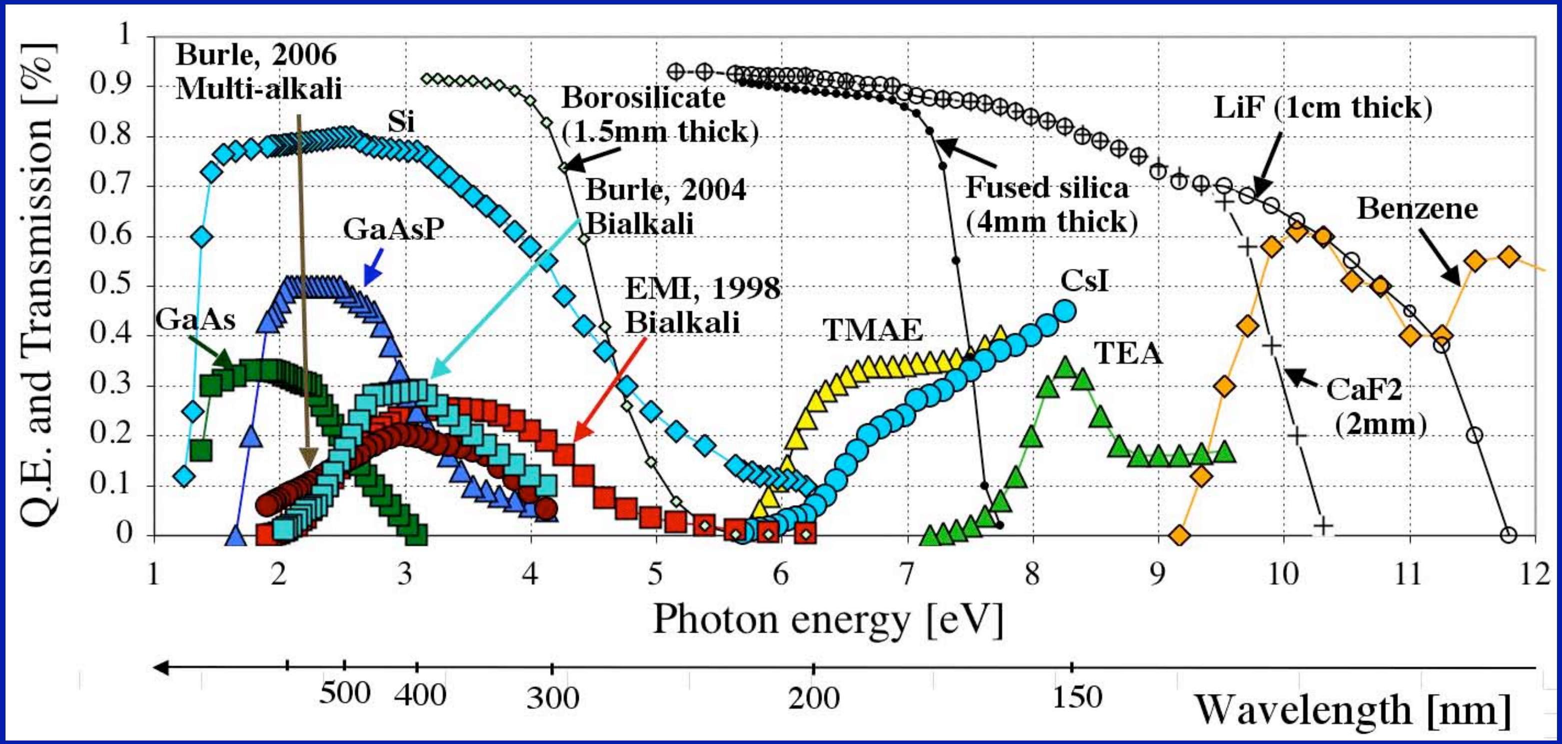
Parameter	Value
Photocathode	Bialkali only at present
Number of dynodes	12
Total average gain @ -1kV	~10^6
Geometrical collection efficiency of the 1-st dynode	70 - 80%
Geometrical packing efficiency (plus QE edge effects !!)	97%
Fraction of late photoelectrons arrivals	~5%
Total fraction of "in time" photoelectrons detected	65 - 75%
σ_{TTS} (SLAC measurement) - H8500	~ 140-150 ps
Matrix of pixels (H8500 & H9500)	8 x 8 & 16 x 16
Number of pixels (H8500 & H9500)	64 & 256
Pixel size (H8500 & H9500)	5.8 x 5.8 & 2.9 x 2.9 [mm^2]

Photocathode

- The Cherenkov application want to have as large QE as possible.

Compilation of various Photocathodes

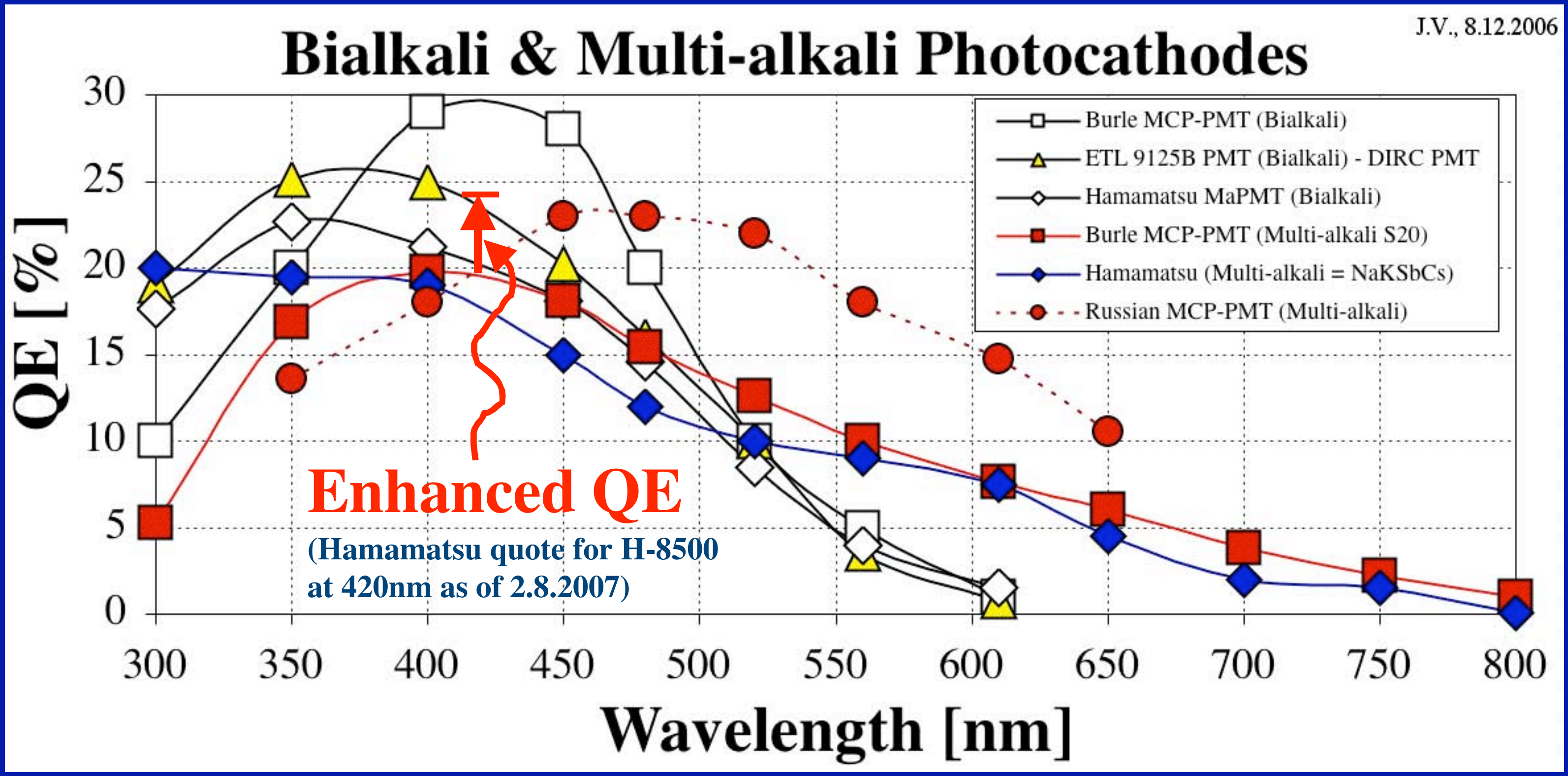
Compilation of data by J. Va'vra, SLAC



- **In the past 20 years, there was a steady push to develop photocathodes operating in the visible wavelength range.** The main reasons: (a) The radiators are very chromatic in the UV region, (b) Materials are less transparent, expensive, (c) Mirrors are difficult to make, expensive, (d) The far UV region is difficult to work in (cleanliness, outgasing pollution, etc).
- **Benzene** was used by HRS, **TMAE** by DELPHI, SLD, OMEGA, CERES, JETSET and CAPRICE; **TEA** by CLEO, **CsI** by ALICE, COMPASS, HADES; **Bialkali** by HERA-B, DIRC, HERMES, Belle, CELEX, **Multi-alkali by** LHC-b, and **GaAsP, GaAs or Si** will be pushed by new detectors.
- **QE in TMAE, TEA and Benzene measured in the gas.**

QE depends on the manufacturer

Compilation of data by J. Va'vra, SLAC



- **Would like to have either the enhanced Bialkali QE or S-25 multi-alkali QE.**
- **Moving towards the red wavelength range reduces the chromatic time dispersion effects. Therefore, in the TOF detector I would like to have the S-25 photo-cathode.**

MCP-PMT spatial response

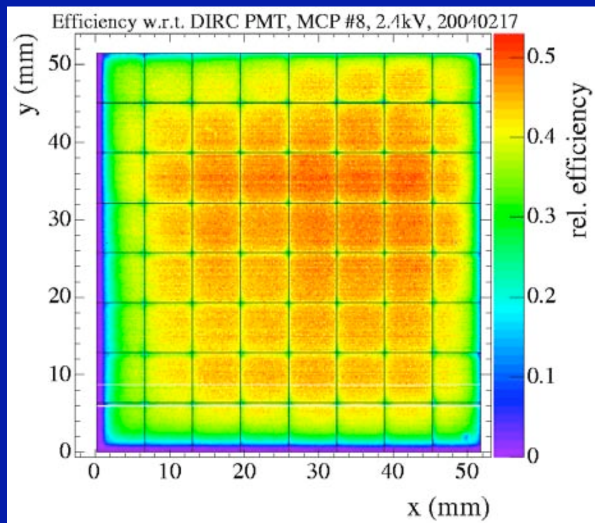
- Overall uniformity issues, edge effects.
- The charge sharing we will discuss later

Burle MCP-PMT #8 relative detection efficiency

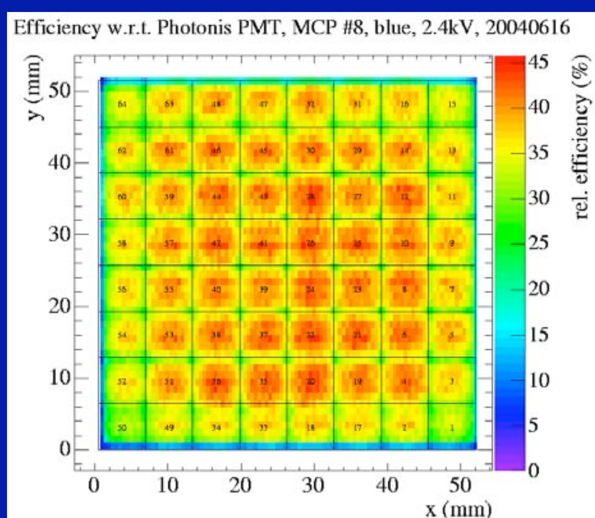
Scanning setup in bldg 403 at SLAC

Normalized to the Photonis XP 2262B PMT

635nm:



430nm:



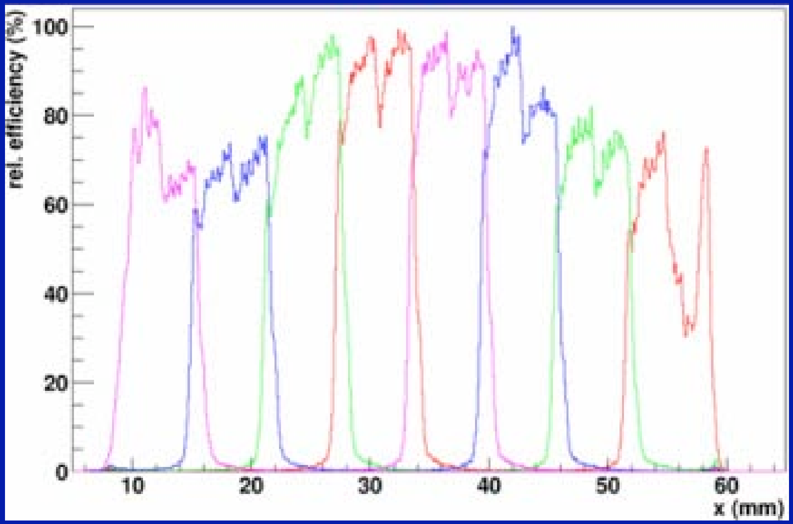
- At **635nm**, which is close to the end of the Bialkali Q.E. range, the relative efficiency scaling to the Photonis PMT is not very reliable.
- At **430nm**, the **measured relative efficiency is 50-60% relative to the Photonis PMT, if we include the late arrivals.** This is approximately expected based on the MCP design.

- Electronics chain used in this test:
  Final SLAC amplifier, LeCroy 4413 discriminators with 100mV threshold, LeCroy 3377 TDCs with 0.5ns/count
- Light source: PiLas laser diodes operating in the single photoelectron mode (635nm & 430nm).

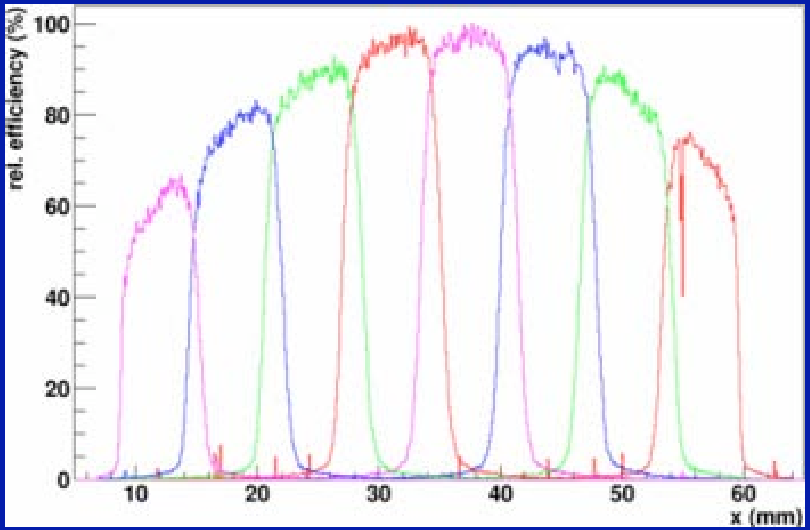
An example of the relative response along a line scan across 8 pads

Scanning setup in bldg 403 at SLAC

Hamamatsu Flat Panel H8500 PMT #2:



Burle 85011-501 MCP-PMT #3:



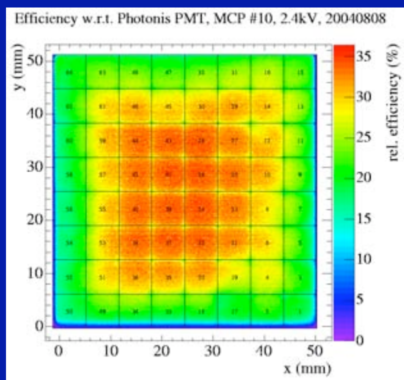
- **Is there a way to make it more uniform ?**
- The Hamamatsu MaPMT uniformity is ~1:2.5 and the Burle MCP-PMT uniformity is ~1:1.5, in this example.
- Electronics chain used in this test:
  Final SLAC amplifier, LeCroy 4413 discriminators with 100mV threshold, LeCroy 3377 TDCs with 0.5ns/count.

Example #1 of a few scans with MCP-PMTs

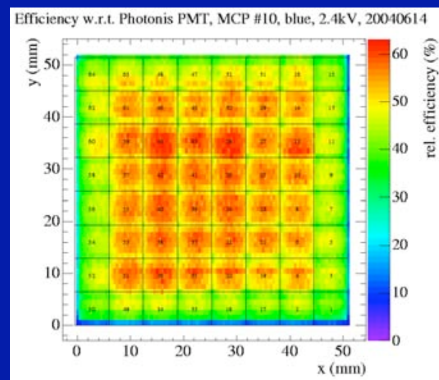
Scanning setup in bldg 403 at SLAC

Burle MCP-PMT #10

635 nm:

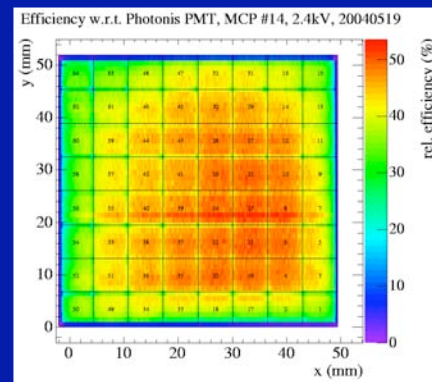


430nm:

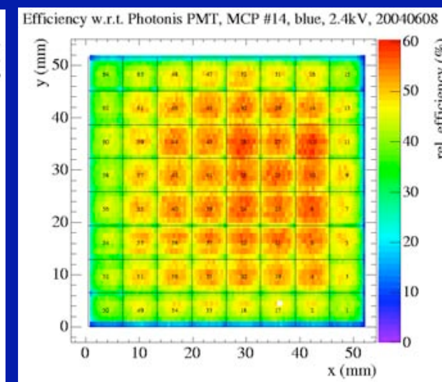


Burle MCP-PMT #14

635 nm:

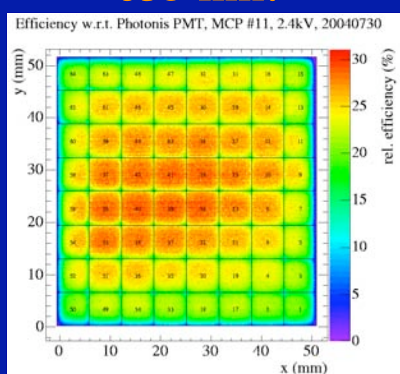


430nm:

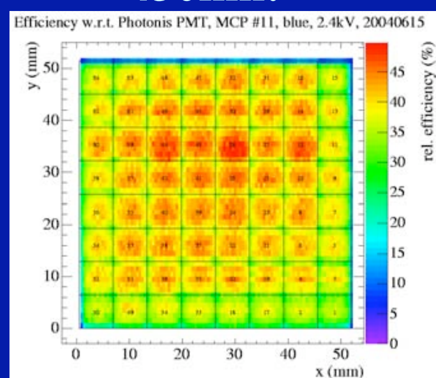


Burle MCP-PMT #11

635 nm:

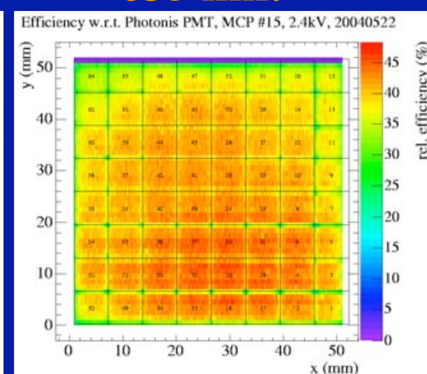


430nm:

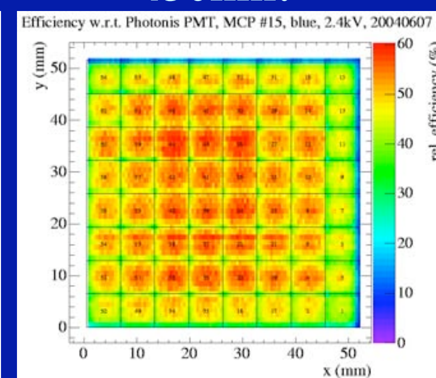


Burle MCP-PMT #15

635 nm:



430nm:



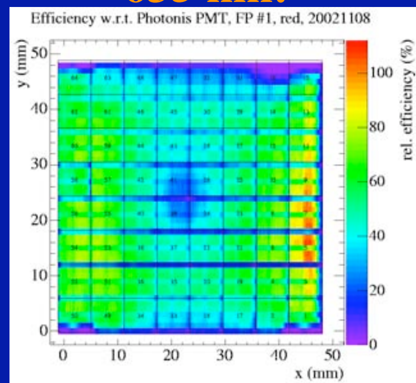
- Typical relative efficiency is 50-60% of the 2 inch dia. Photonis XP 2262B PMT at 430nm. The efficiency drops to 30-50% around the edges at 430nm.

Example #2 of a few scans with MaPMTs

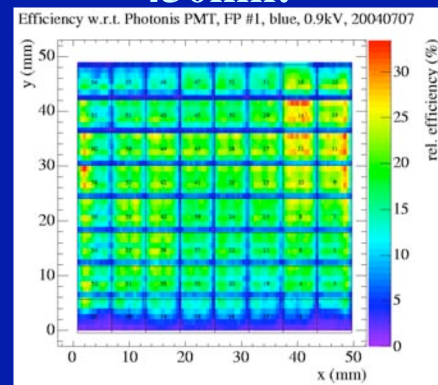
Scanning setup in bldg 403 at SLAC

Hamamatsu MaPMT #1

635 nm:

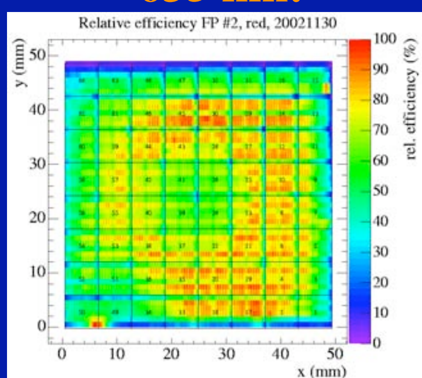


430nm:

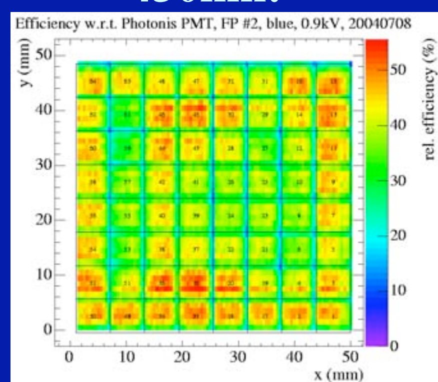


Hamamatsu MaPMT #2

635 nm:

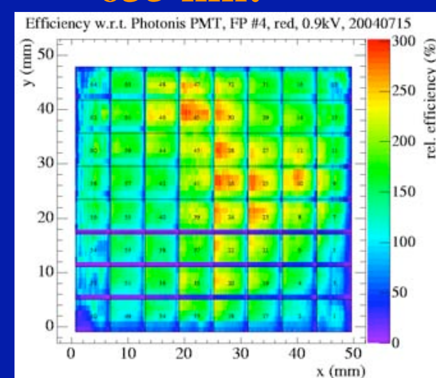


430nm:

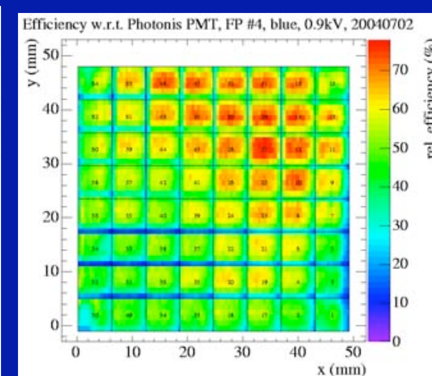


Hamamatsu MaPMT #4

635 nm:



430nm:



- Hamamatsu Flat Panel MaPMT relative efficiency is 50-70% of the Photonis XP 2262B PMT at 430nm. The efficiency drops to 30-50% around the edges at 430nm.

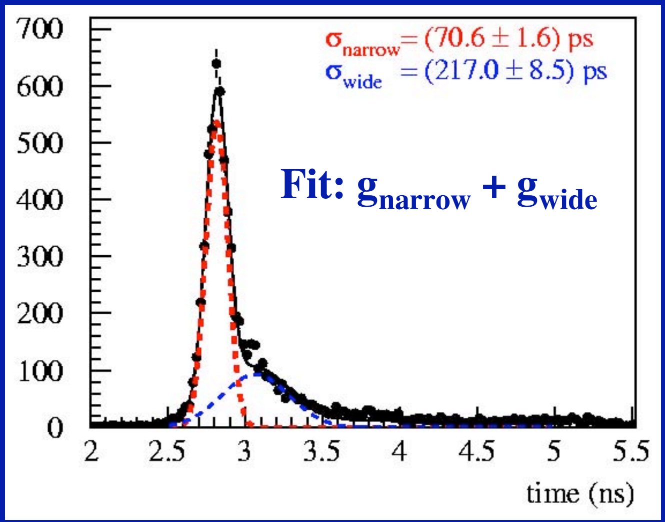
What is a timing resolution limit of <u>standard</u> MCP-PMTs ?

- Here I mean what one can get relatively easily with standard electronics
- MCP with 25 μm hole sizes
- Goal: (a) $\sigma_{TTS} \sim$ 30-150 ps, (b) $\sigma_{track} \sim$ 30-40 ps

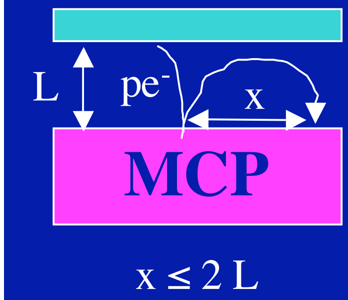
Tails & edge effects in MCP-PMT timing

C. Field, T. Hadig, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff, J. Schwiening, J. Uher, and J. Va'vra, SLAC
RICH 2004, Cancun, Mexico, Nucl.Instr. & Meth., A553(2005)96-106

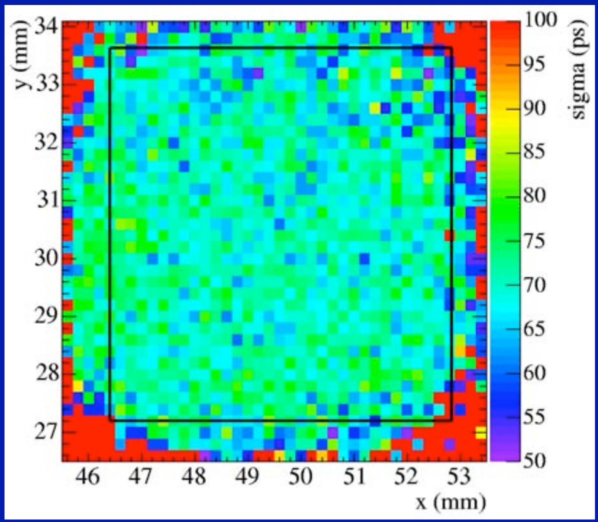
25 μm hole dia. (L = 6mm):



Explanation of tail:



Scan of timing resolution on one pad:



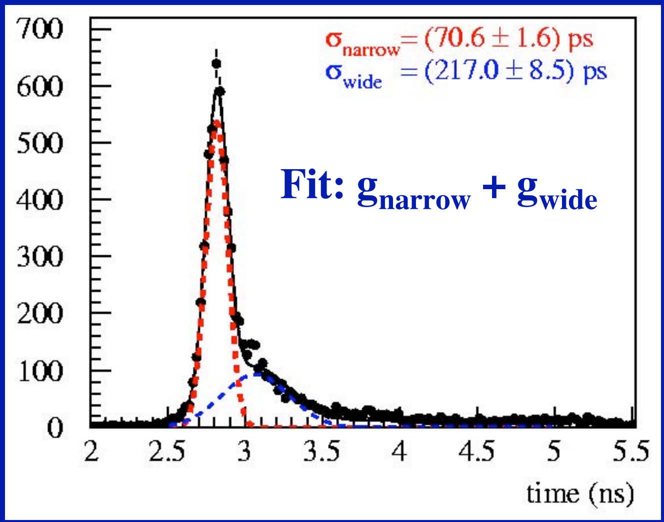
- **Tail has ~ 25% of events for a standard MCP-PMT with L ~ 6 mm**
- **The edge effect is artifact of the charge sharing, which lowers the pulse height, and this causes a time walk of the constant fraction discriminator (CFD)**
- **I expect that this effect will be removed if we correct the pulse height by ADC**

- Experimental conditions:
  Burle/Photonis MCP-PMT, 85011-501, initial design, 25μm holes, B = 0 kG
  SLAC CFD 32 cannels per board
  TDC with 25ps/count TDC
  Measurements done with PiLas laser diode (635nm) in the single photo-electron mode. The laser beam aims at one spot of less than 1 mm in dia.

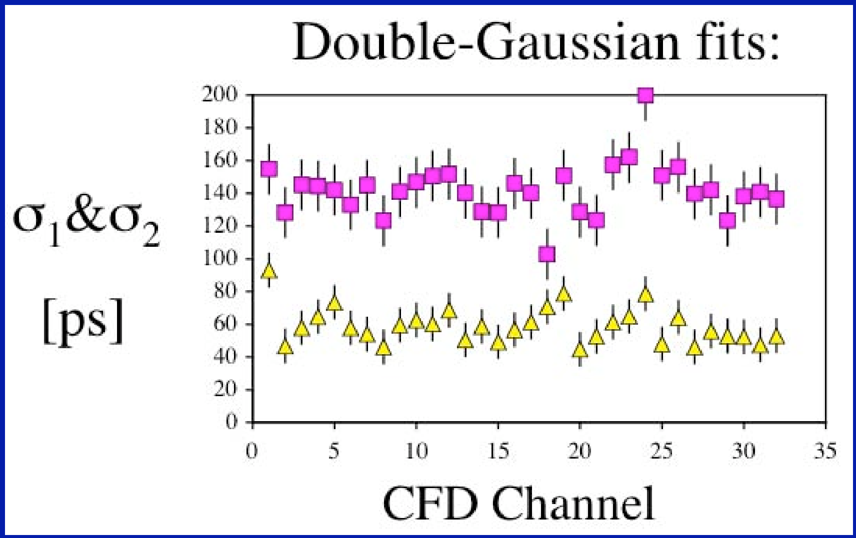
Typical results on the bench

Timing measurement setup in trailer 233 at SLAC

25 µm hole dia. (L = 6mm):



A single MCP-PMT pad, vary CFD ch.:



- **Measure σ_{narrow}~ 50-80 ps and σ_{wide}~ 130-160 ps in the bench environment**
- **Use the same pad over and over, and vary CFD electronics channels**

- Experimental conditions:
  Burle/Photonis MCP-PMT, 85011-501, initial design, 25µm holes, B = 0 kG
  SLAC CFD 32 cannels per board
  TDC with 25ps/count TDC
  Measurements done with PiLas laser diode (635nm) in the single photo-electron mode. The laser beam aims at one spot of less than 1 mm in dia.

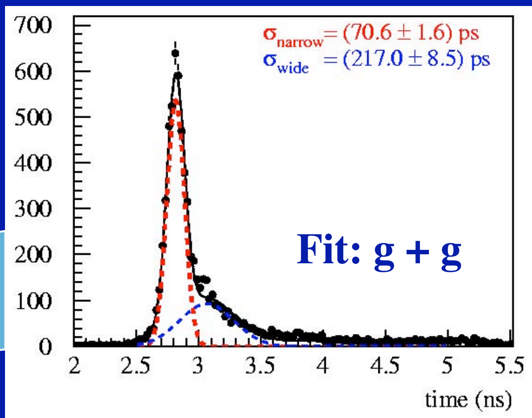
MCP-to-cathode distance - a way to eliminate tail

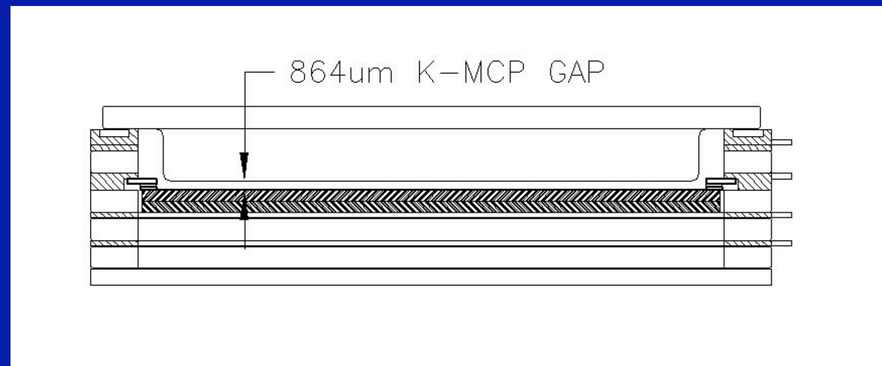
C. Field, T. Hadig, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff, J. Schwiening, J. Uher, and J. Va'vra, **SLAC**

RICH 2004, Cancun, Mexico, Nucl.Instr. & Meth., A553(2005)96-106

MCP-to-Cathode distance = 6 mm

85011-501 Nominal design:

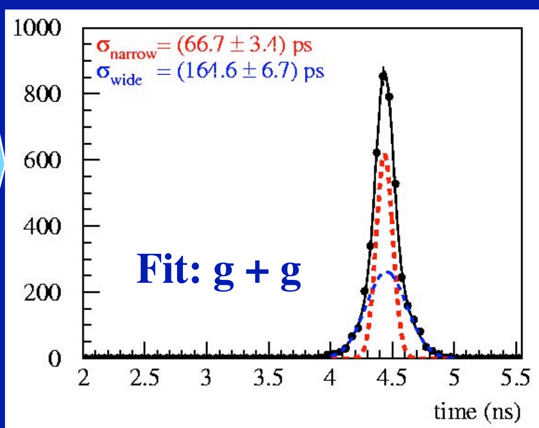




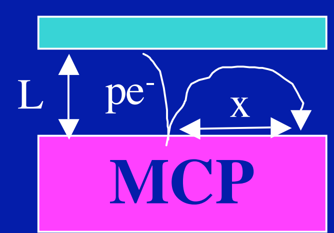
Penalty of this design: the efficiency drops to zero half way through all edge pads.

MCP-to-Cathode distance ~0.85 mm

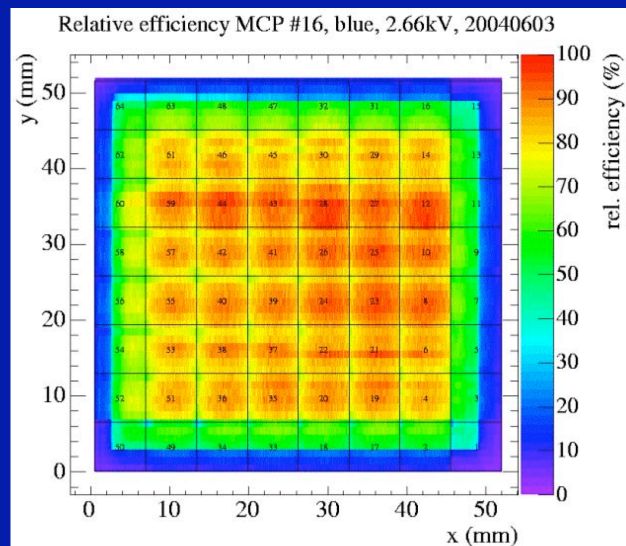
85011 430 Drop Faceplate:



L should be small:



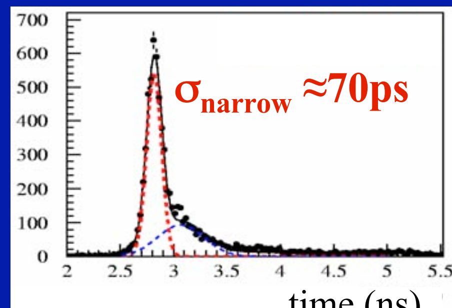
$x \leq 2\,L$

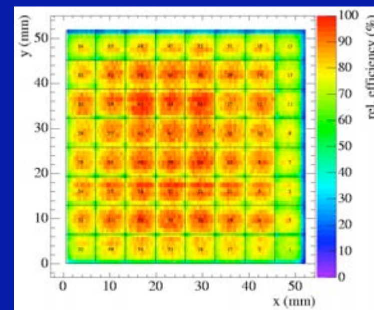


Focusing DIRC prototype photon detectors

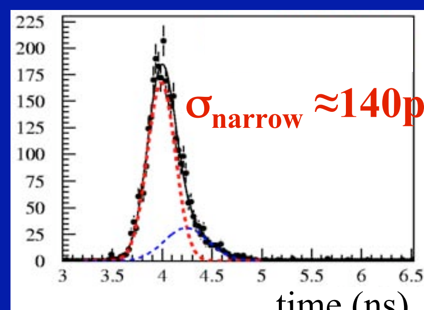
C. Field, T. Hadig, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff, J. Schwiening, J. Uher, and J. Va'vra, SLAC
RICH 2004, Cancun, Mexico, Nucl.Instr. & Meth., A553(2005)96-106

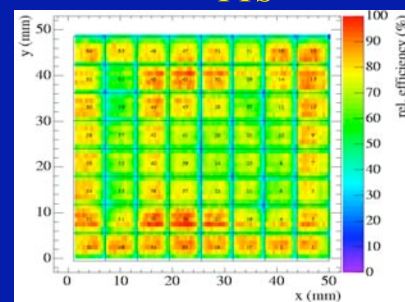
1) Burle 85011-501 MCP-PMT (64 pixels, 6x6mm pad, σ_{TTS} ~50-70ps)



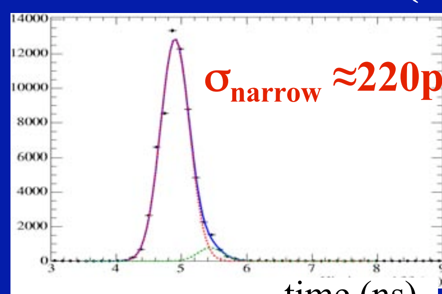


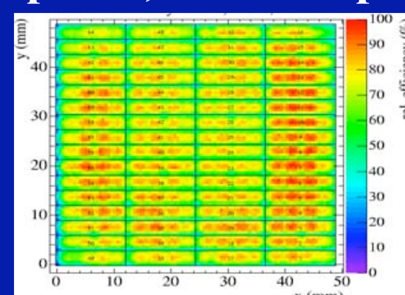
2) Hamamatsu H-8500 MaPMT (64 pixels, 6x6mm pad, σ_{TTS} ~140ps)





3) Hamamatsu H-9500 Flat Panel 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.**

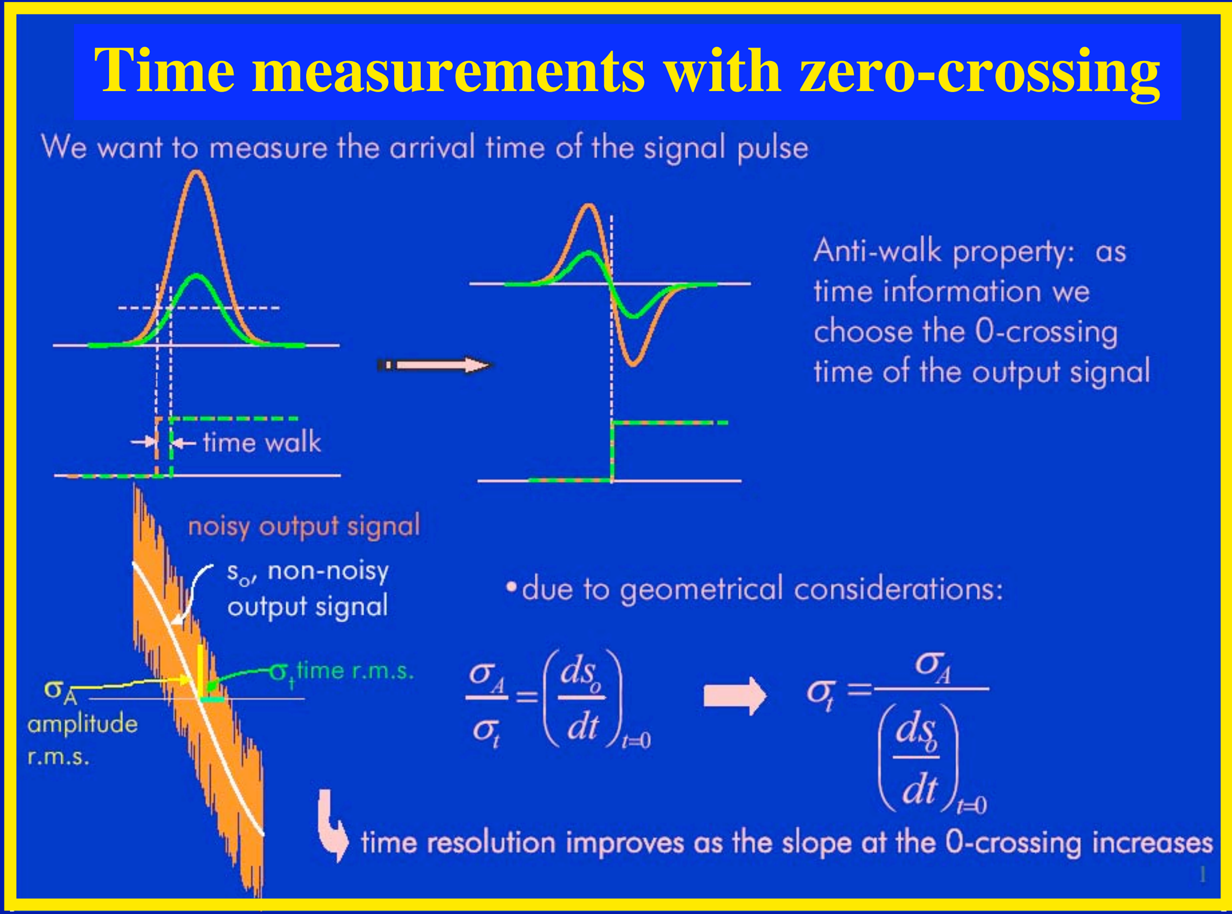
Search for the timing resolution limit

- **Here one needs a very fast electronics !! Things get tougher.**
- **What is the timing strategy ?**
- **MCP with ~10 μm hole sizes**
- **Goal: (a) σ_{TTS} ~ 20-30 ps, (b) σ_{track} < 15 ps**

Low noise & Speed of the amplifier and detector is essential

From V. Radeka talk at RICH2004

Principle of the Constant-Fraction-Discriminator (CFD):



Problem with this nice picture is that the hardware-based correction does not work well as a function of Npe => one has to correct the resulting time-walk.

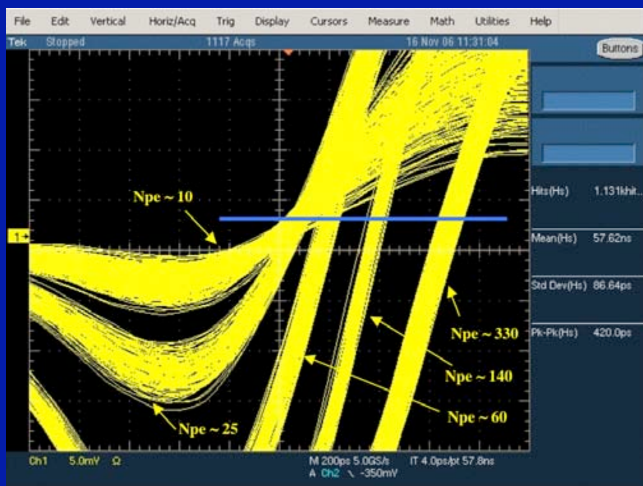
Timing strategy with the MCP-PMT pulses

Timing measurement setup in trailer 233 at SLAC

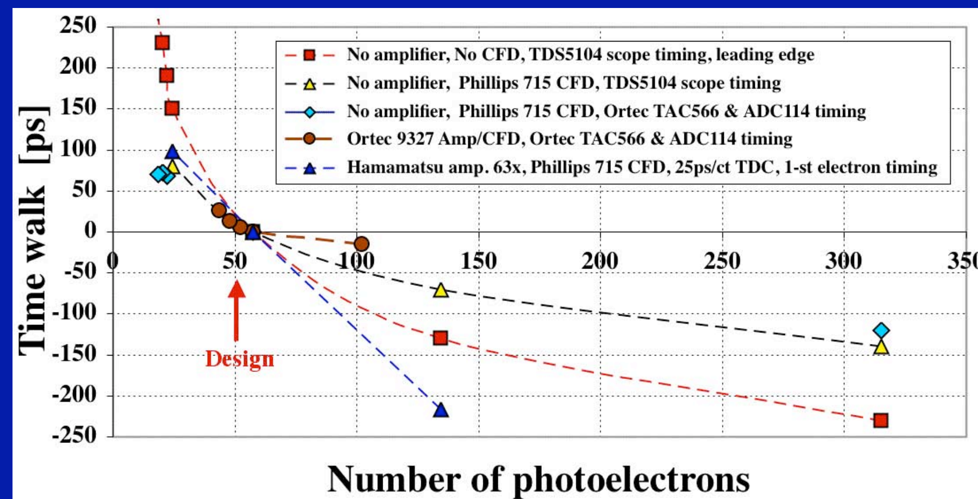
Phillips CFD 715 zero-crossing output:

- MCP-PMT with 10μm holes

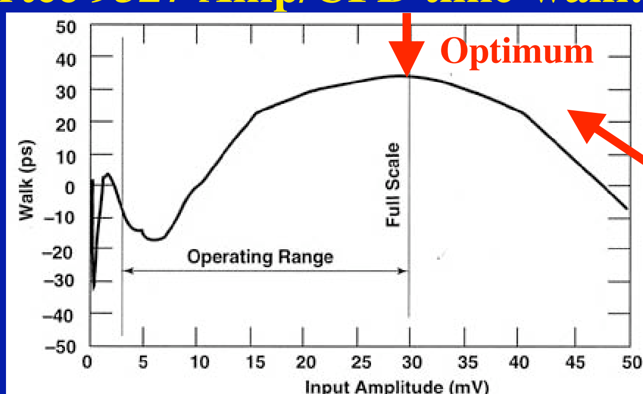
- no amplifier



Time-walk = f(Npe):



Ortec 9327 Amp/CFD time-walk:



- **One must measure amplitude to correct the time-walk, be at an optimum point, and not allow large fluctuations in Npe !!**
- **A significant time-walk even with best Ortec 9327Amp/CFD.**

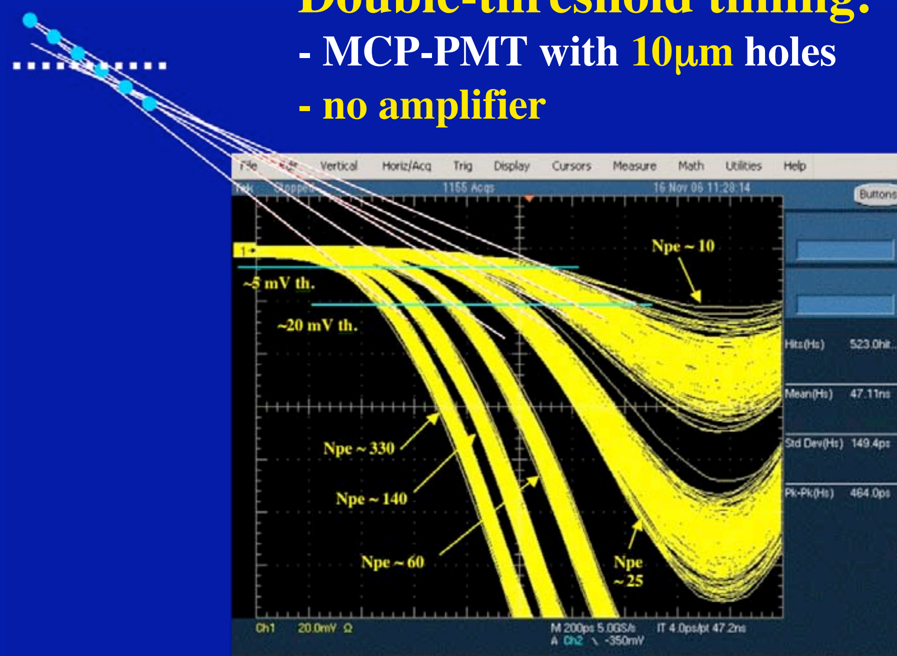
Timing strategy with the MCP-PMT pulses

Timing measurement setup in trailer 233 at SLAC

Double-threshold timing:

- MCP-PMT with 10μm holes

- no amplifier



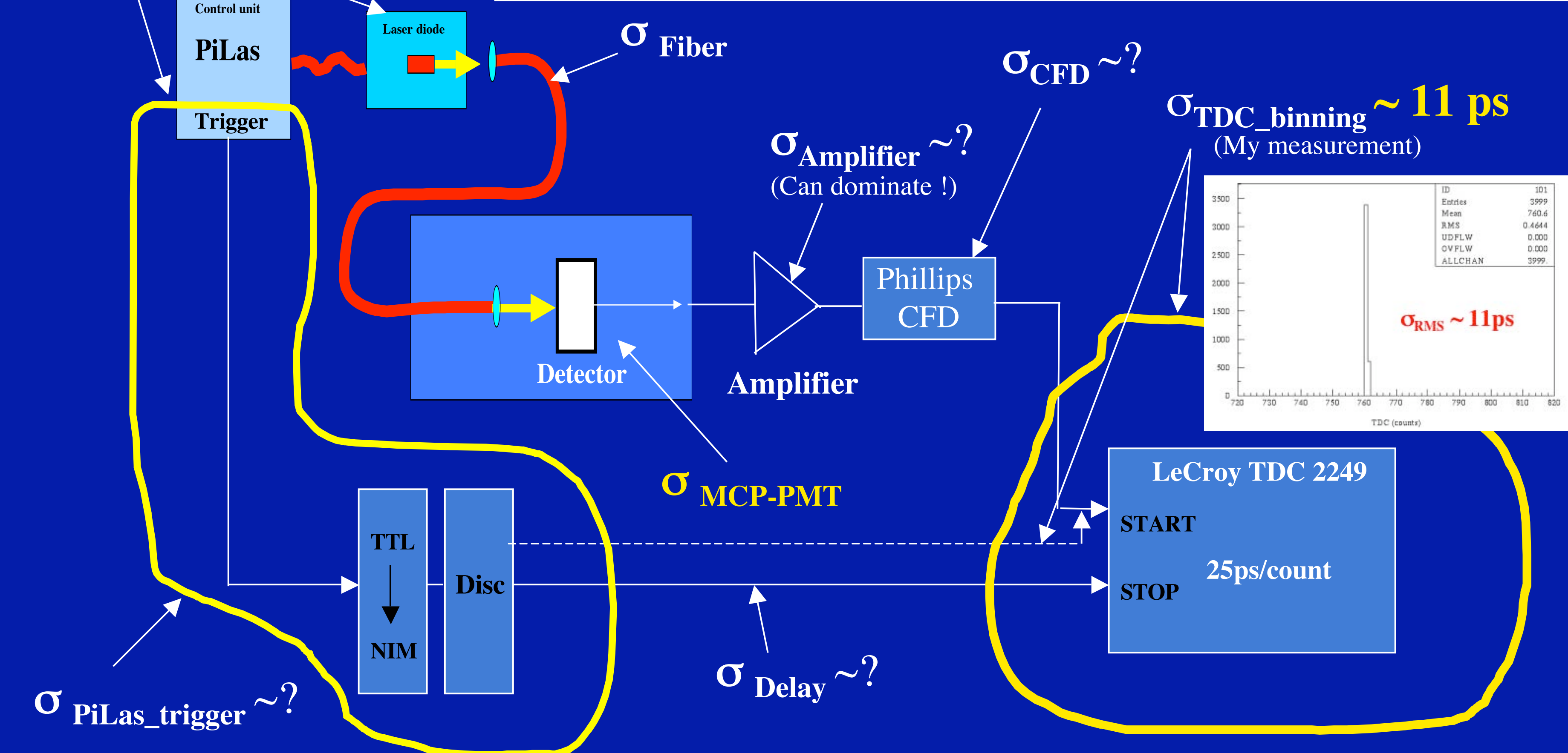
- **Double-threshold timing is not answer:**
  - **there is no unique focus for the intersects**
  - **to digitize two points so close together will cause additional systematic errors if the circuits are on the same board.**

Initial setup with a 25ps/count TDC - Setup A

Timing measurement setup in trailer 233 at SLAC

$\sigma = \sqrt{\{\sigma^2_{MCP\text{-}PMT} + \sigma^2_{Fiber} + \sigma^2_{Amplifier} + \sigma^2_{CFD} + \sigma^2_{Delay} + \sigma^2_{PiLas} + \sigma^2_{TDC\_binning} + \sigma^2_{PiLas\_trigger}\}}$

+ Systematic effects: laser & temperature drifts, etc.



Limit of the Single-photon timing resolution - σ_{TTS}

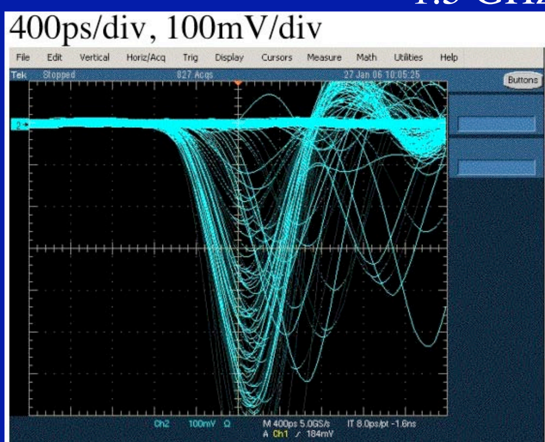
Timing measurement setup in trailer 233 at SLAC

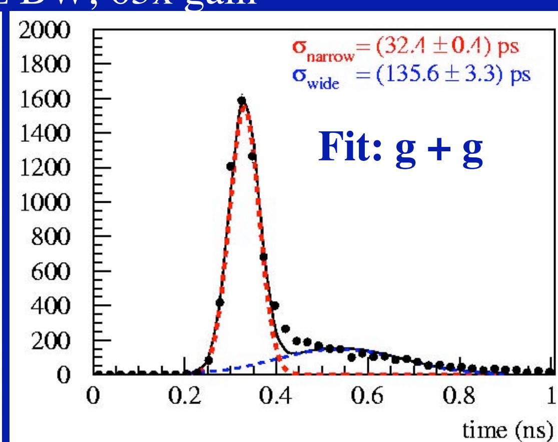
Burle/Photonis MCP-PMT 85012-501 (ground all pads except one)

- **10 μm MCP hole diameter**
- **B = 0 kG**
- **64 pixel devices, pad size: 6 mm x 6 mm.**
- **Phillips CFD**
- **PiLas red laser diode operating in the single photoelectron mode (635 nm).**
- $\sigma_{TTS} < \sqrt{(32^2 - 15^2 - 11^2)}$ **= 26 ps (Npe = 1)**

Hamamatsu C5594-44 amplifier

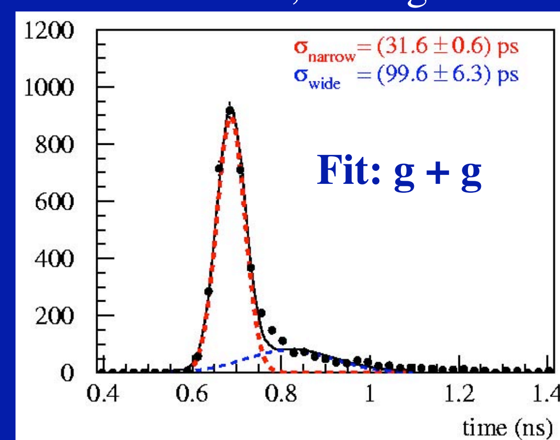
1.5 GHz BW, 63x gain





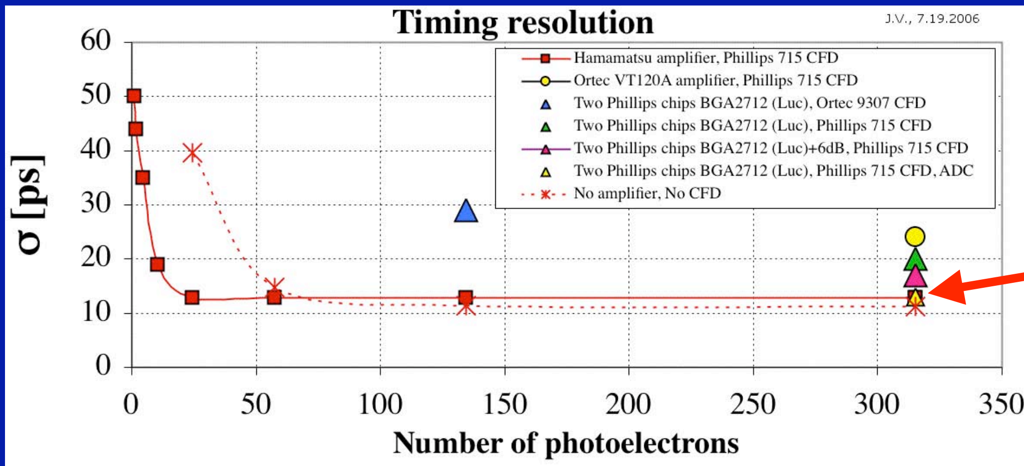
Ortec VT120A amplifier

~0.4 GHz BW, 200x gain + 6dB



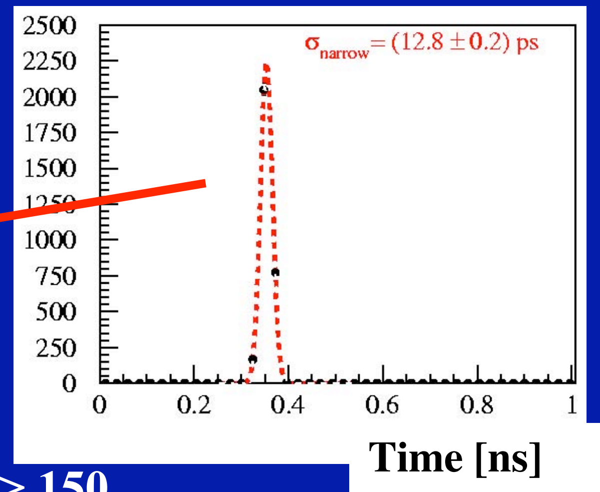
Timing resolution σ = f(Npe) in the initial setup

Resolution with a laser diode = f(Npe):



Resolution:

(Hamamatsu amp. & Npe > 200)



- **MCP-PMT with no amplifier: σ_{RMS} ~10-11 ps for N_{pe} > 150.**
- **MCP-PMT with amplifier: σ_{RMS} > 12.8 ps for N_{pe} > 30 => Amplifier makes it worse**
- **Electronics: $\sigma_{TDC\_binning}$ ~11 ps => TDC binning resolution dominates the result !**
- **Not possible to estimate an upper limit on $\sigma_{MCP\text{-}PMT}$ for these data.**

- **A possible criticism of this approach:**

  a) Amplifier heavily saturates in the single photo-electron mode, which prevents a decent time-walk correction. Therefore one needs a low gain output & ADC

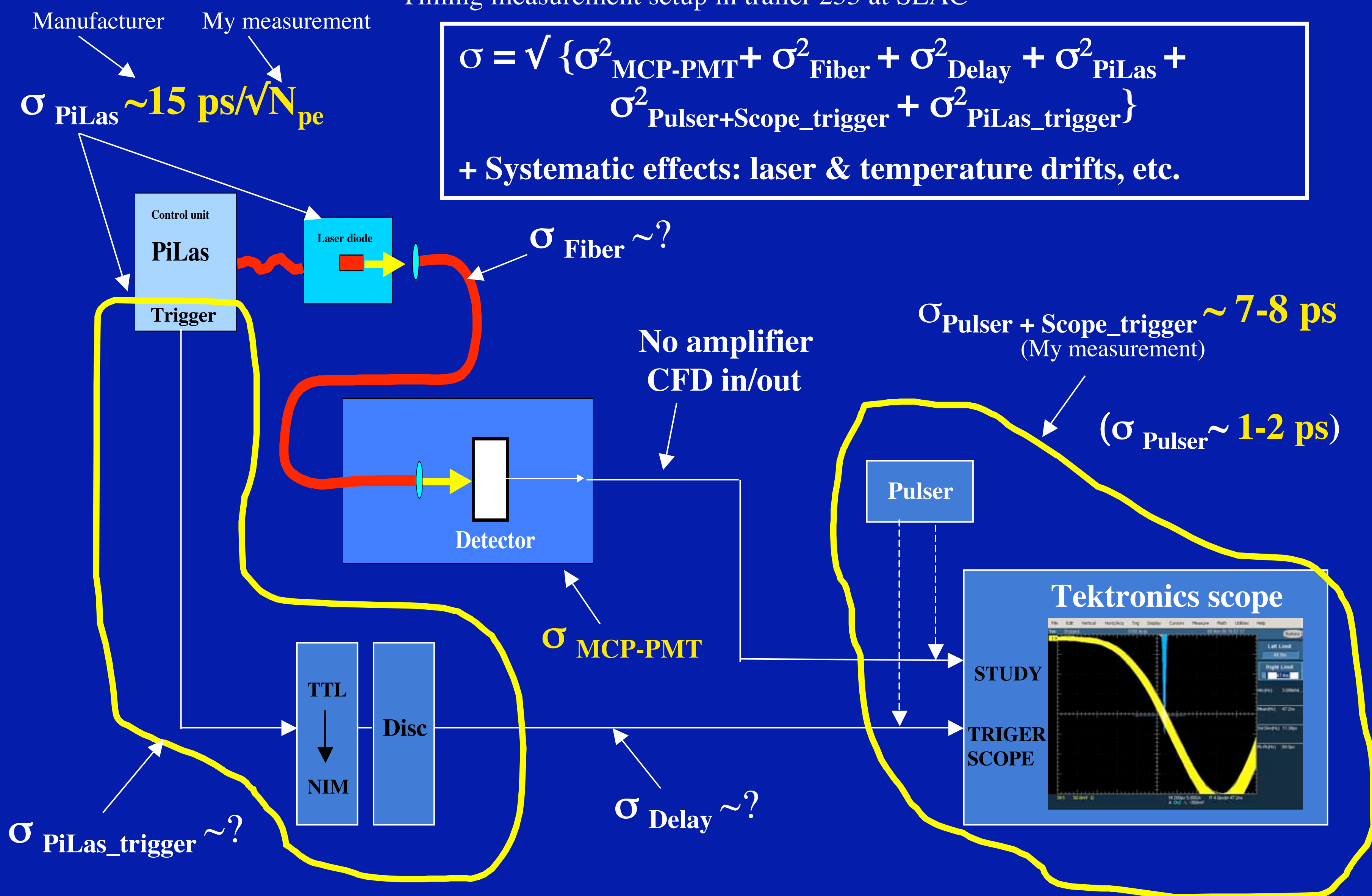
  b) As we will see later, the time-walk correction is the largest for the operation with the single pe^- sensitivity

Timing resolution with a scope - Setup B

Timing measurement setup in trailer 233 at SLAC

$$\sigma = \sqrt{\{\sigma^2_{MCP-PMT} + \sigma^2_{Fiber} + \sigma^2_{Delay} + \sigma^2_{PiLas} + \sigma^2_{Pulser+Scope\_trigger} + \sigma^2_{PiLas\_trigger}\}}$$

+ Systematic effects: laser & temperature drifts, etc.



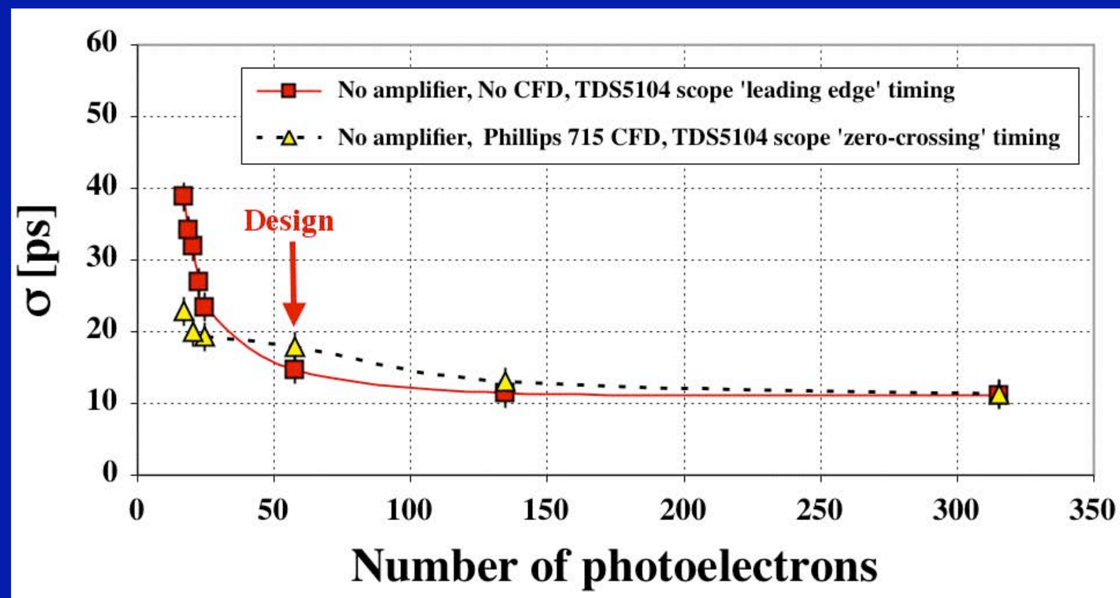
Timing resolution σ = f(Npe) and upper limit on $\sigma_{MCP-PMT}$

- MCP-PMT with 10 μm holes, 64 pads, ground all pads except one being used
- 2.8kV (max allowed)
- No amplifier, CFD in/out
- No magnetic field

Scope calibration with a pulser:

σ_{RMS} ~ 7.6 ps

Resolution with a laser diode = f(Npe):



Upper limit on MCP-PMT contribution to the resolution:

$$\sigma_{MCP-PMT} < \sqrt{\{\sigma^2 - \sigma^2_{Laser\ diode}(N_{pe}) - \sigma^2_{Pulser+Scope\_trigger} + \sigma^2_{Pulser}\}} < 8\text{-}9\ \text{ps}$$

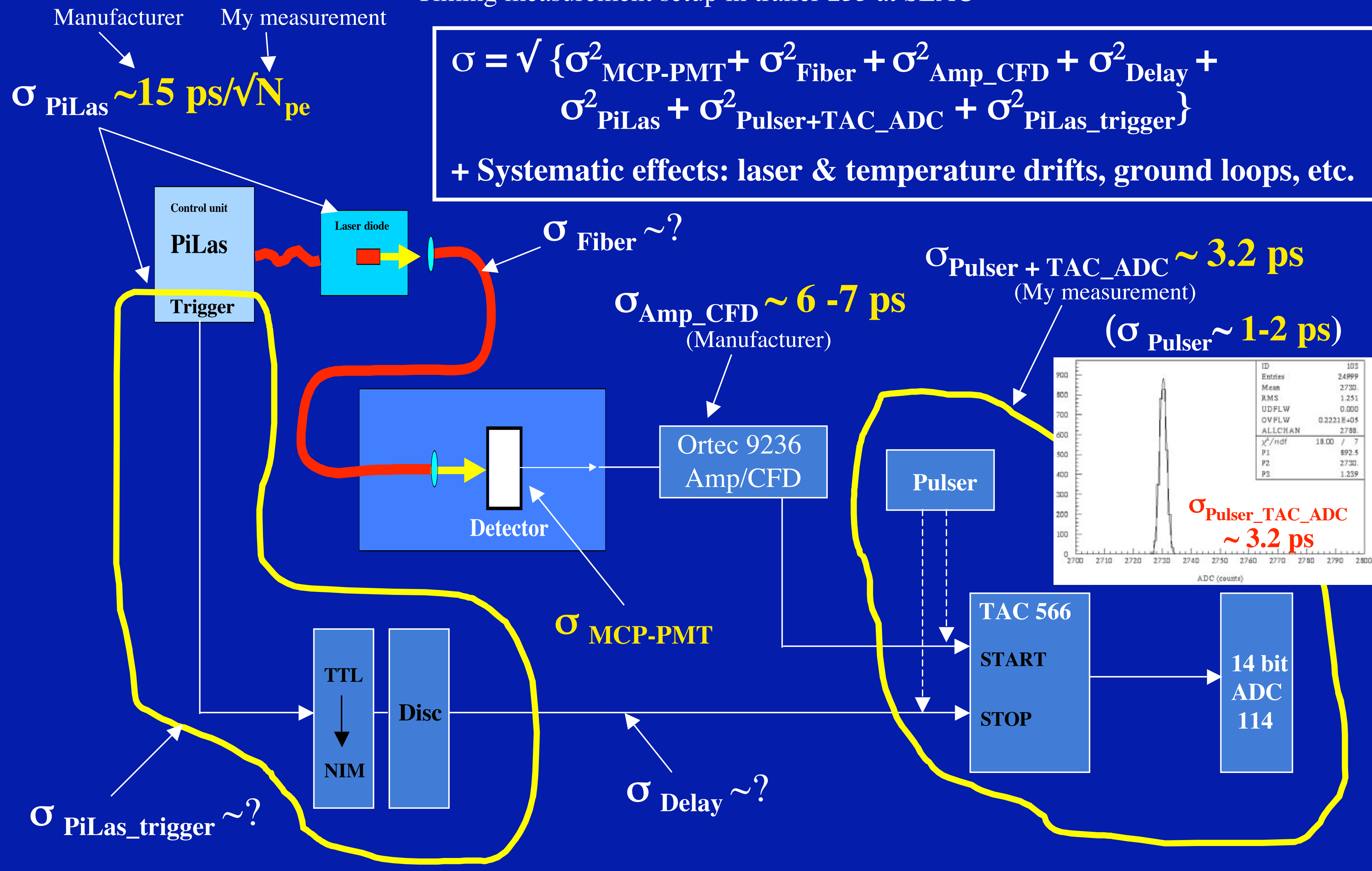
Measure | Manufacturer & Npe measure | Measure | Manufacturer

Timing resolution with TAC & ADC - Setup C

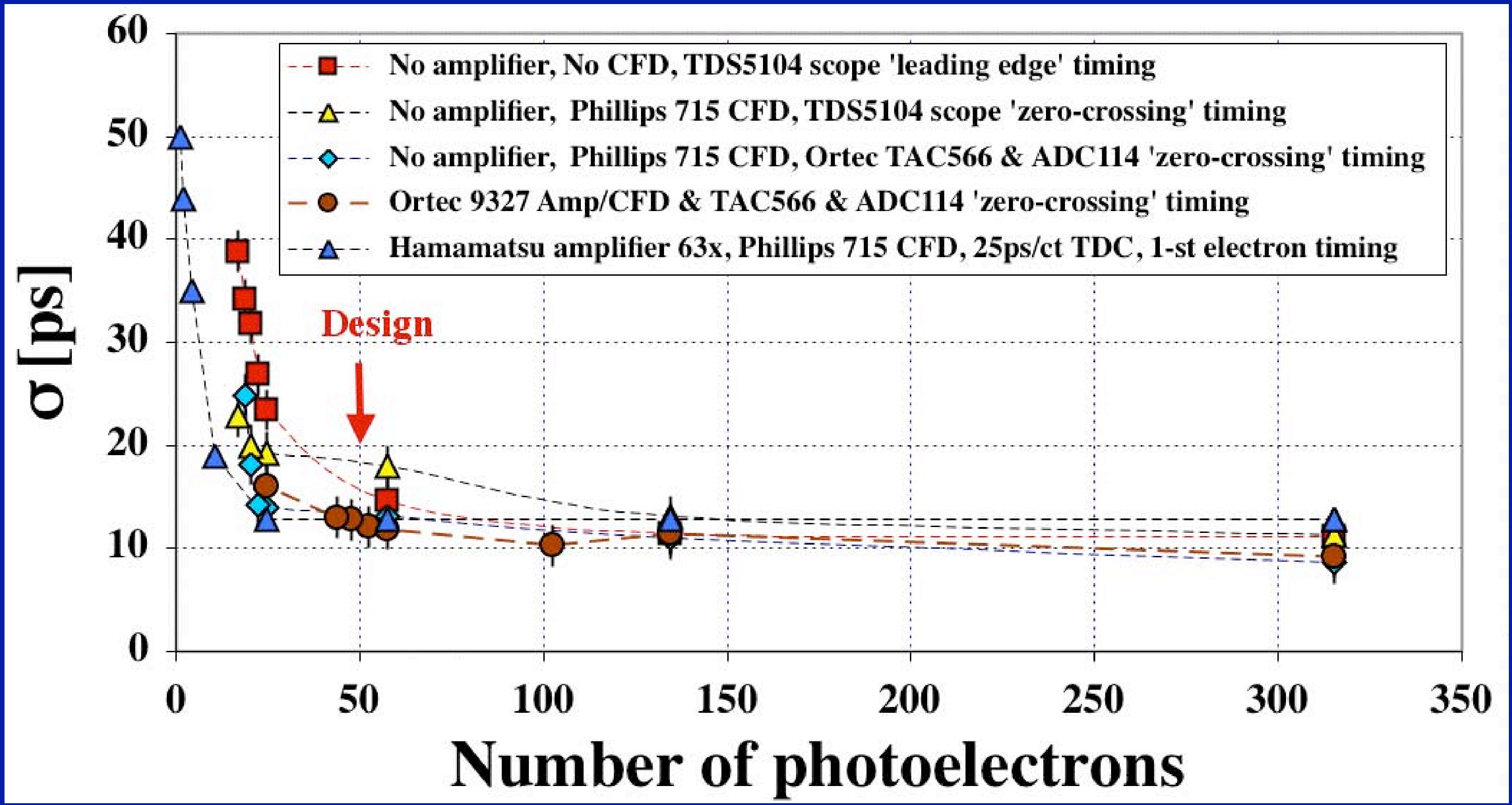
Timing measurement setup in trailer 233 at SLAC

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

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

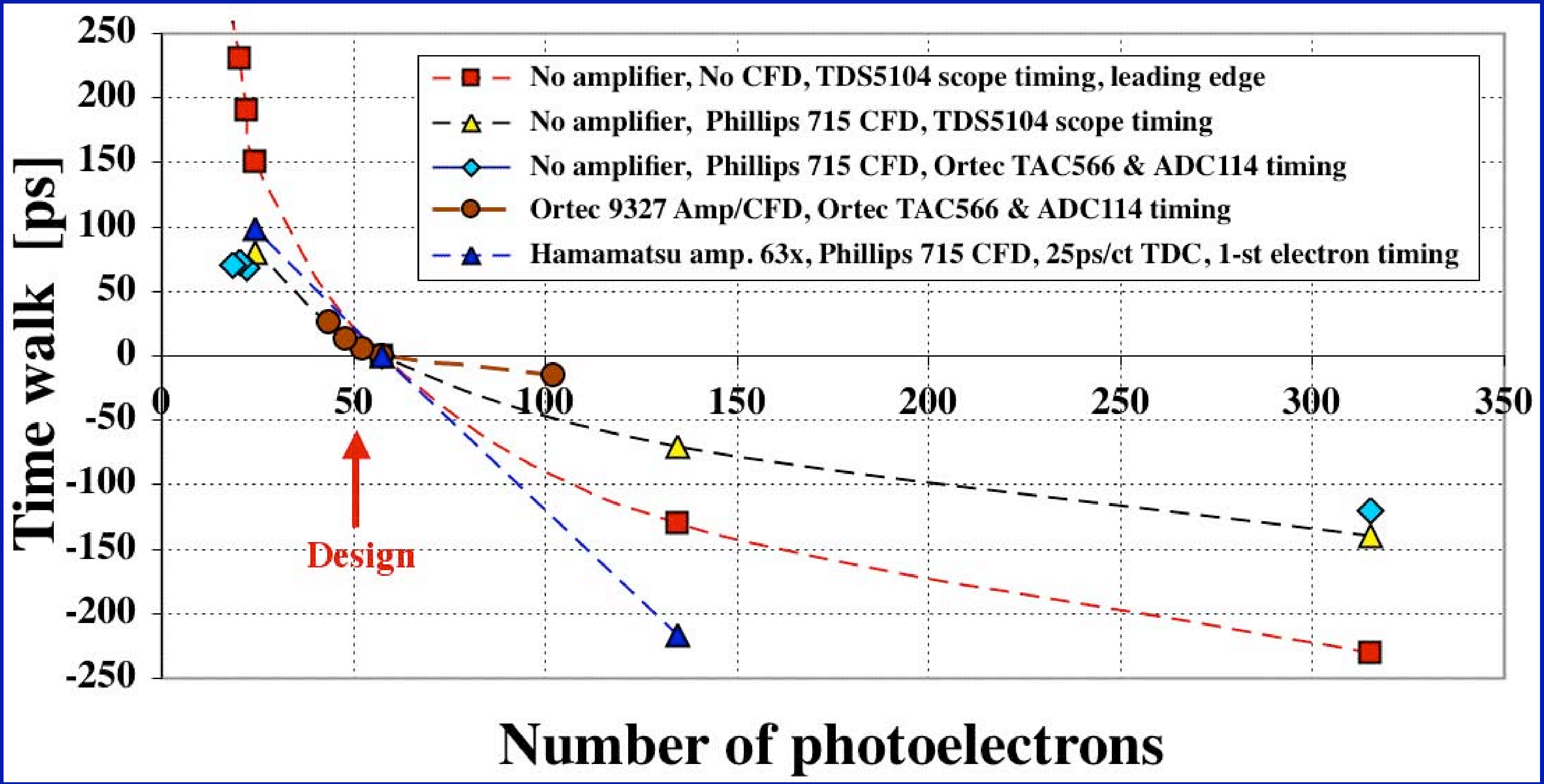


Timing resolution σ = f(Npe)



- Npe = 50-60 for 1cm-thick Quartz radiator + window & with Burle Bialkali QE.
- A goal to reach σ < 15 ps seems possible.
- The Ortec 9327-like performance is good.

Time-walk = f(Npe)

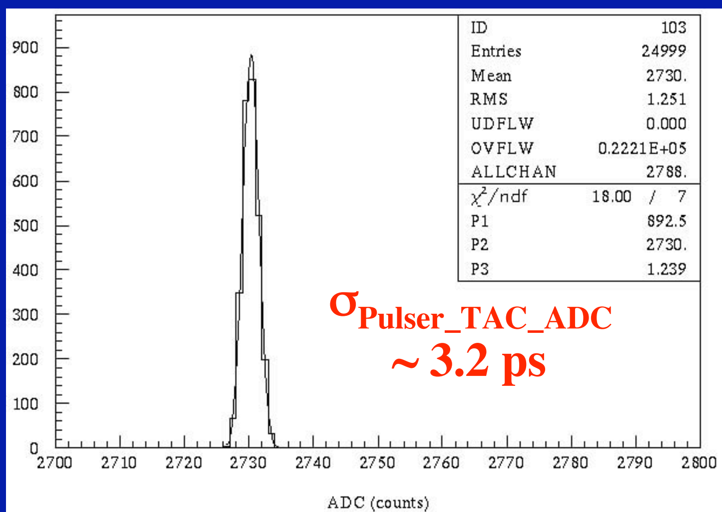


- **Time-walk <u>needs</u> to be corrected for any variation of Npe, <u>for all methods</u> !**
- **Ortec 9327 time-walk is smallest, but still significant.**

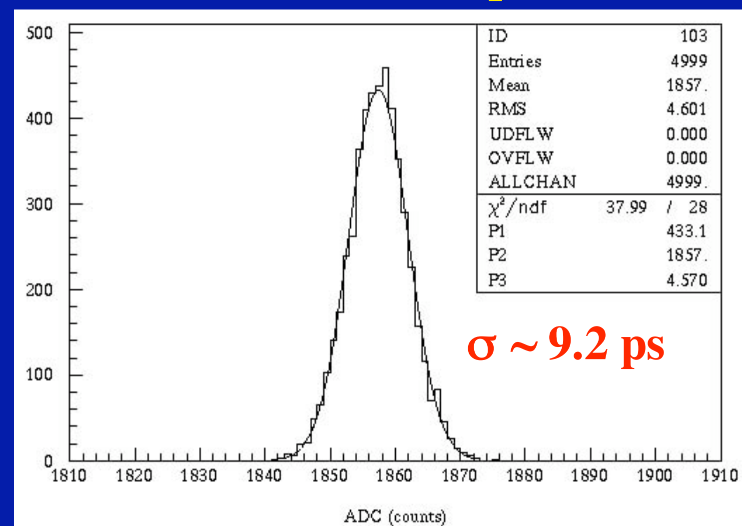
Determine upper limit on $\sigma_{MCP\text{-}PMT}$

- MCP-PMT with 10 μm holes, 64 pads, ground all pads except one being used
- 2.33 kV with Ortec 9327 Amp/CFD (max. allowed voltage is 2.8kV => plenty of margin available for a future magnetic field operation).

Calibrate $\sigma_{Pulser + TAC\_ADC}$:



Determine σ for Npe ~ 300:



(Note: σ ~ 8.6 ps with Phillips CFD 715)

Upper limit on MCP-PMT contribution to the resolution:

$$\sigma_{MCP\text{-}PMT} < \sqrt{\{ \sigma^2 - \sigma^2_{PiLas}(N_{pe}) - \sigma^2_{Amp\_CFD} - [\sigma^2_{Pulser+TAC\_ADC} - \sigma^2_{Pulser}]\}} < 5.8\ ps$$

- σ: 9.6 ps
- $\sigma_{PiLas}(N_{pe})$: < 1 ps (PiLas & measure)
- σ_{Amp_CFD}: 6-7 ps (Ortec)
- $\sigma_{Pulser+TAC\_ADC}$: 3.2 ps
- σ_{Pulser}: ~ 1-2 ps (manufacturer)

Next steps

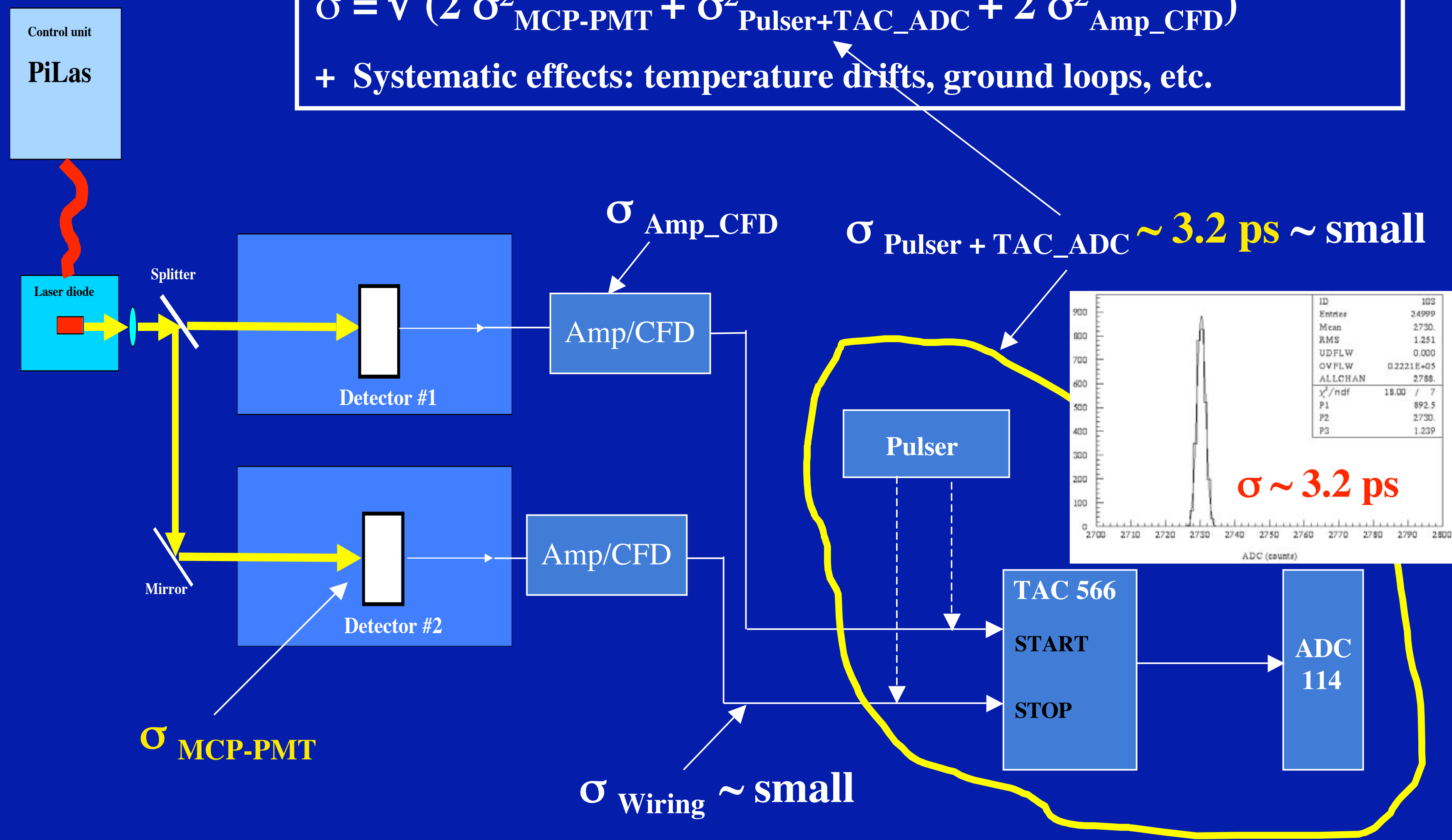
1. Laser diode setup for two identical MCP-PMTs
2. Beam test with 4 MCP-PMT pads instrumented
3. Modification of the MCP-PMT design
4. New electronics
5. Magnetic field effects
6. Aging

Setup with two MCP-PMTs - Setup D

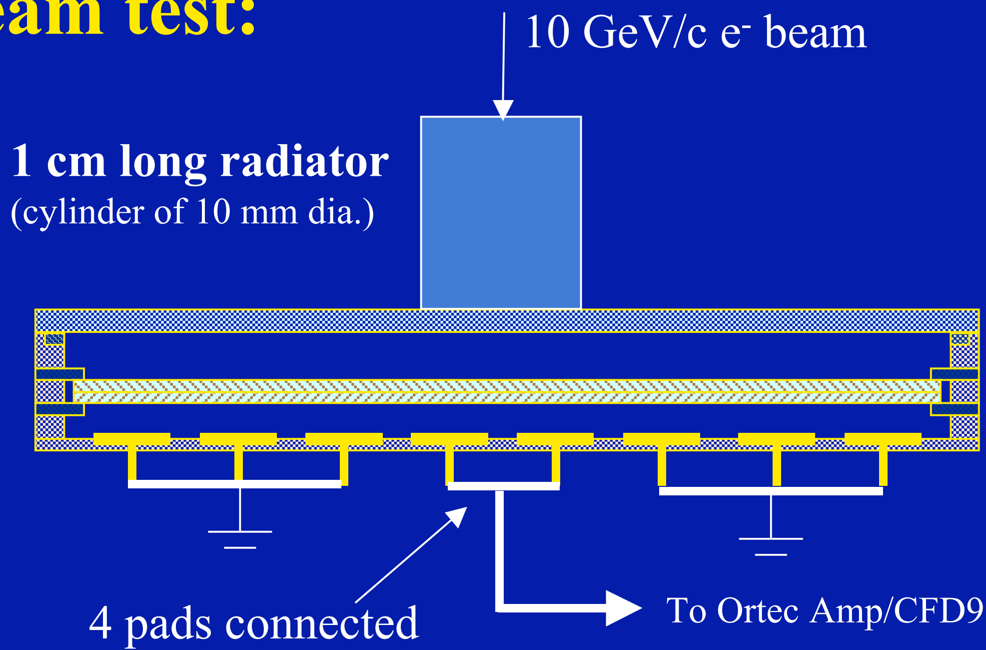
Timing measurement setup in trailer 233 at SLAC

$$\sigma = \sqrt{(2\,\sigma^2_{MCP\text{-}PMT} + \sigma^2_{Pulser+TAC\_ADC} + 2\,\sigma^2_{Amp\_CFD})}$$

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



2. Beam test:



Real tube:

Expected performance - Npe is marginal if one includes recoils !!!! :

$N_o \sim 60$ cm^{-1} & Npe ~ 42 for Burle Bialkali QE

$N_o \sim 30$ cm^{-1} & Npe ~ 20 for Photonis Multi-alkali S-25 QE

3. Further next steps:

- **Equal time signal paths and improve the ground return.**
- **Decide on electronics strategy: Probably leading & trailing edges**

Bad effects

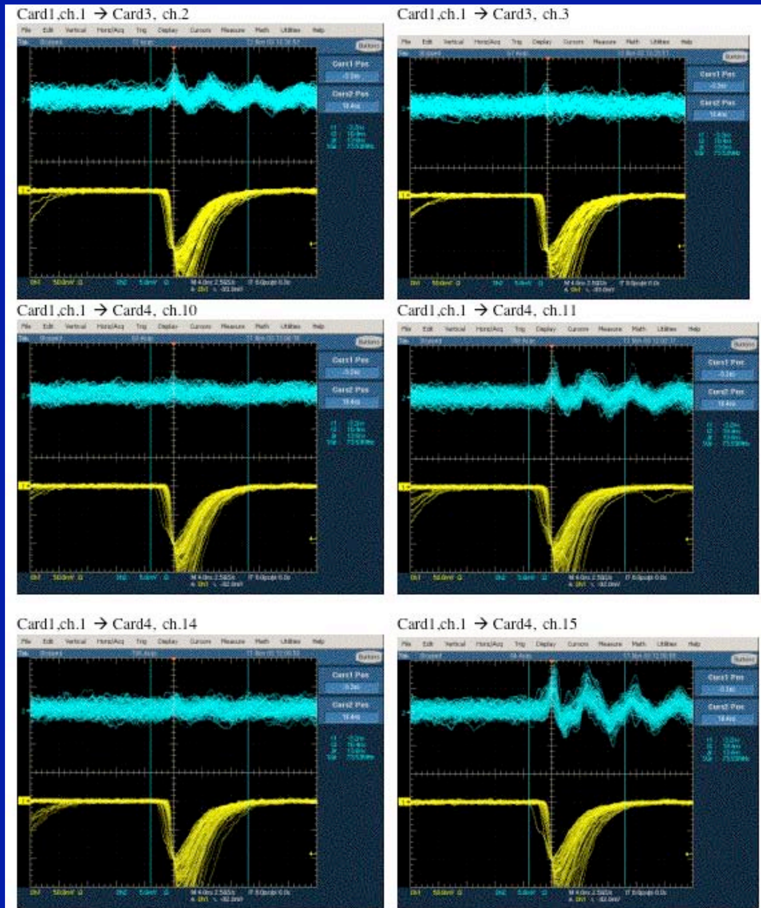
- Cross-talk, coherent resonance effect, charge sharing, aging, etc.

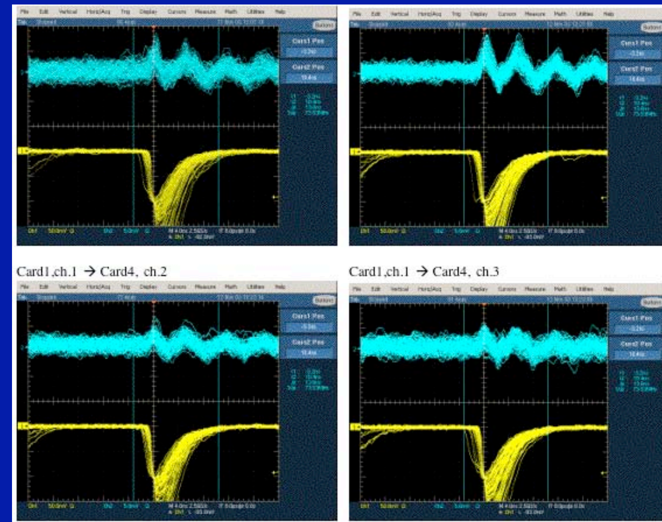
Cross-talk

- We see a cross-talk to far away pads

Cross-talk in MCP-PMT

Timing measurement setup in trailer 233 at SLAC





- It is clear that there is a cross-talk to far away pads, probably related to the pad interconnection layout.
- It is clear that the peripheral pads are mostly affected.

From Burle on 11.13.2003:

Thanks Jerry.

This helps significantly. The noise you see is not internal to the device and should be something we can control with a PCB modification, and maybe a slight change in the packaging. We will let you know when we have something identified as a fix.

Thanks again, your data has been very helpful!
Regards,
Paul

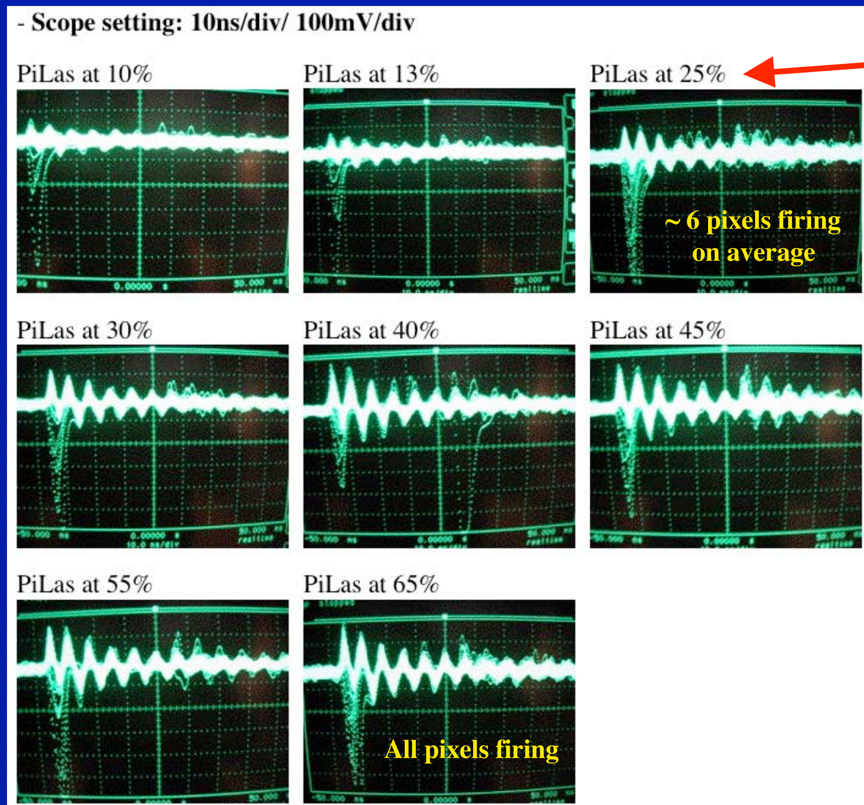
- **There is a cross-talk even to far away pads at a level of 0.1-4%**
- **All cross-talk waves have the same periodicity. This may create coherent excitation effects.**

Coherent resonance effects

- Observed on MCP-PMTs in the Focusign DIRC prototype.
- This effect must be fixed as it would degrade the timing resolution

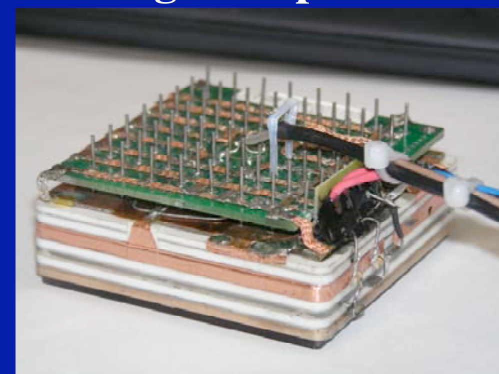
Coherent resonance effects in MCP-PMT

Prototype, Slot 4: Focusing DIRC prototype setup in the ESA test beam at SLAC



At this power we get a 10% probability that a given pixel fires

Wiring is responsible:

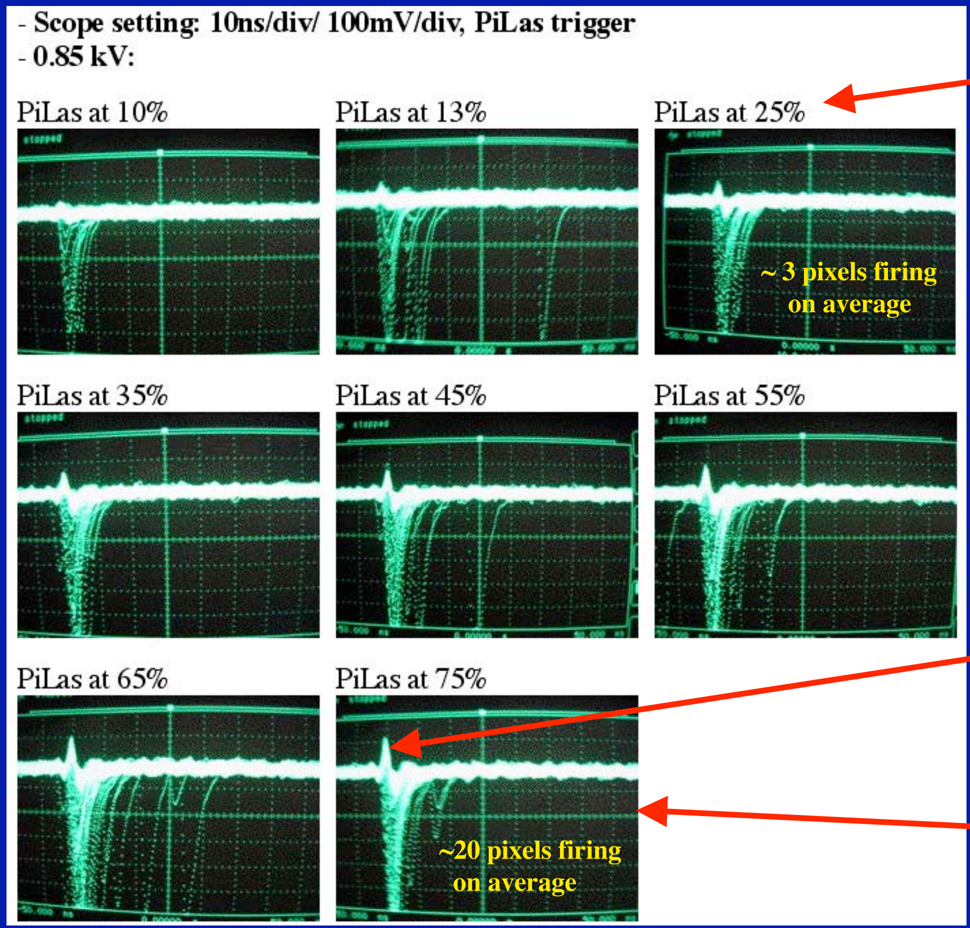


- **The effect is generated by a PiLas producing enough light that multiple pixels fire within < 1 ns. At a 25% PiLas power setting, we get a 10% probability that a given pixel fires, i.e., 6-7 pixels firing per tube.**

- During a test beam run we typically get up to 3-4 Cherenkov photons per MCP-PMT, and they do not arrive at the same time, so we may not suffer from this problem.

Coherent resonance effects in MaPMT

Prototype, Slot 3: Focusing DIRC prototype setup in the ESA test beam at SLAC



At this power we get a 5% probability that a given pixel fires

Evidence for the cross-talk

At this power we get a 30% probability that a given pixel fires

- **The coherent oscillation effect does not exist with the Hamamatsu MaPMTs (the same amplifier, the same LV PS, the same grounding scheme). One starts seeing a cross-talk though as number of pixel firing increases.**

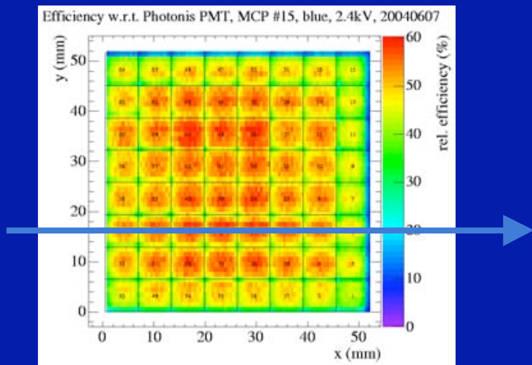
Charge sharing

- Relevant for the pixel boundary definition.
- Relevant for ultimate timing resolution
- One can use it to advantage by ADC-based interpolation

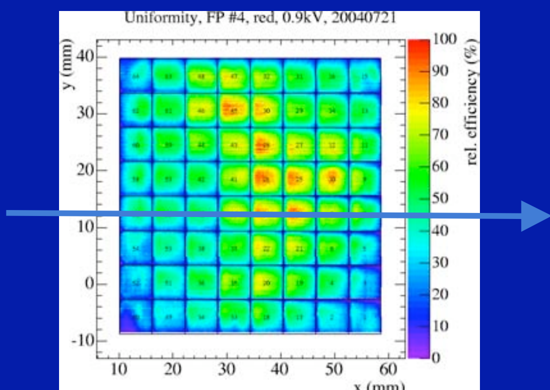
Charge Sharing Range - compare MCP-PMT & MaPMT

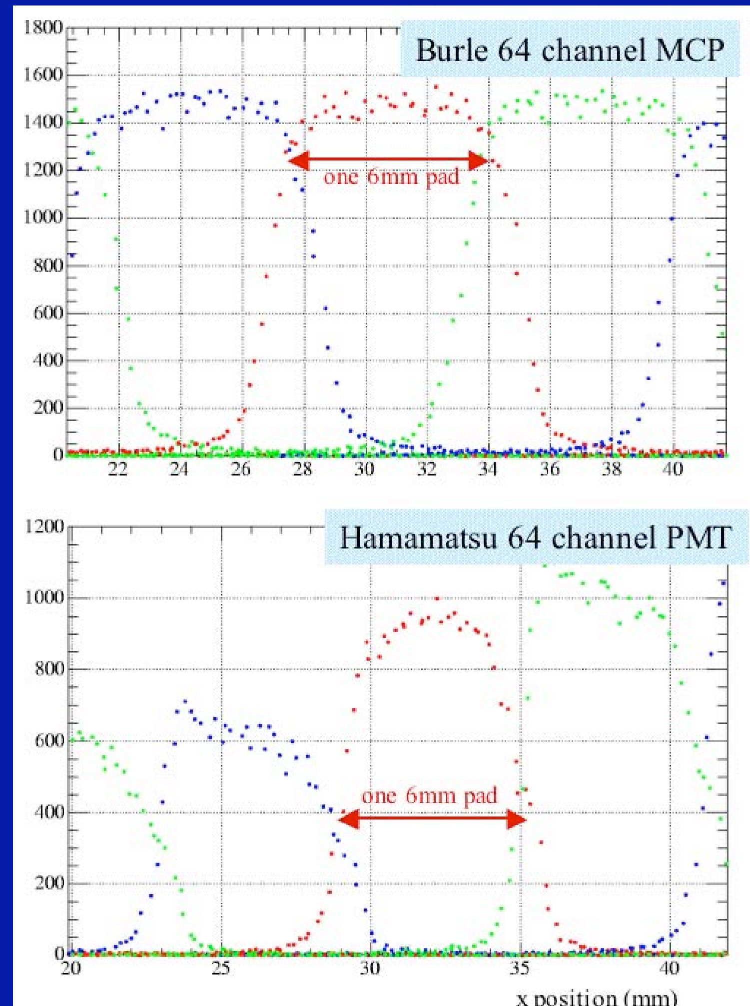
Scanning setup in bldg 403 at SLAC

Burle/Photonis MCP-PMT



Hamamatsu H-8500 MaPMT



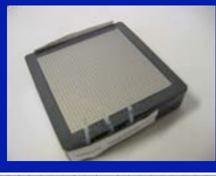


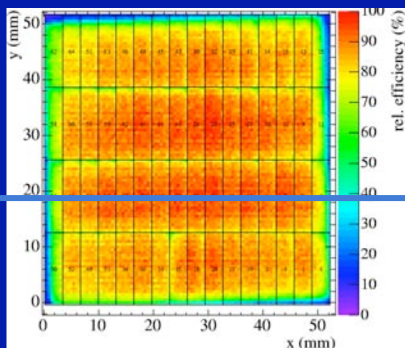
- **Hamamatsu MaPMT has smaller charge sharing range (50-70%) than Burle MCP-PMT**
- **One could turn this to advantage if one instruments each pad with an ADC**

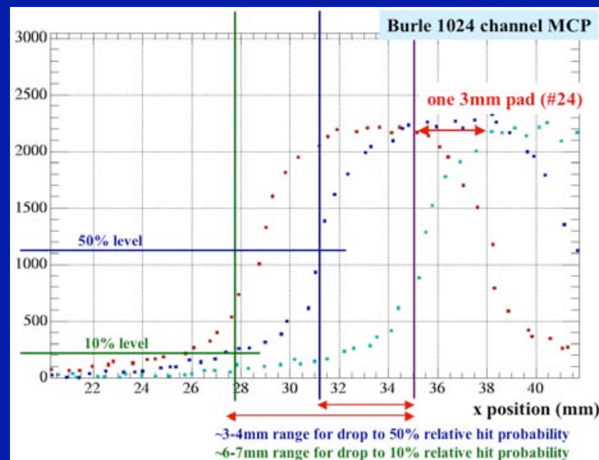
Charge Sharing Range in 1024 pad MCP-PMT

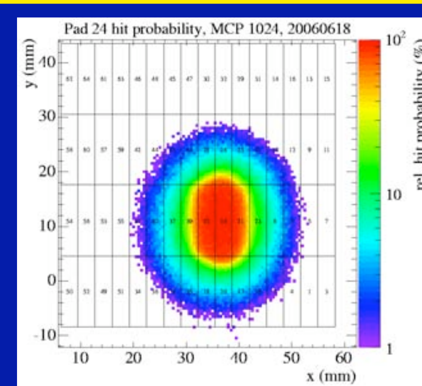
Scanning setup in bldg 403 at SLAC

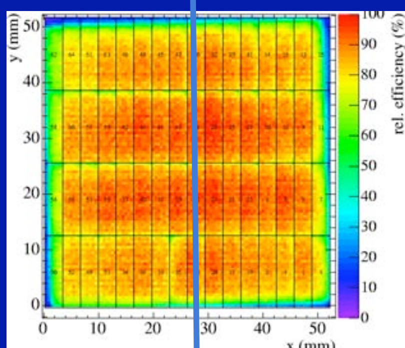
Attempt to make 3x12 mm pixels out of a 1024-pixel tube failed !!

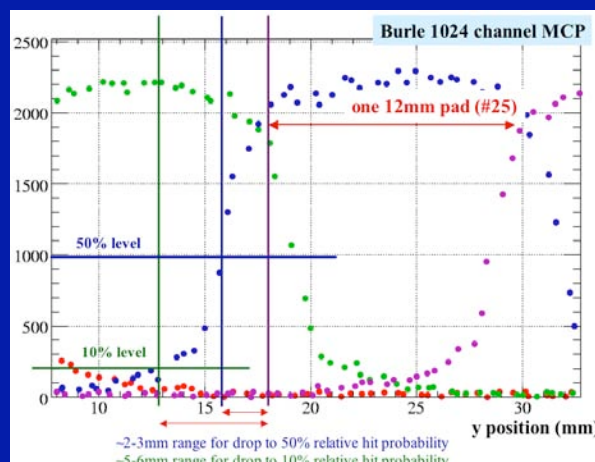




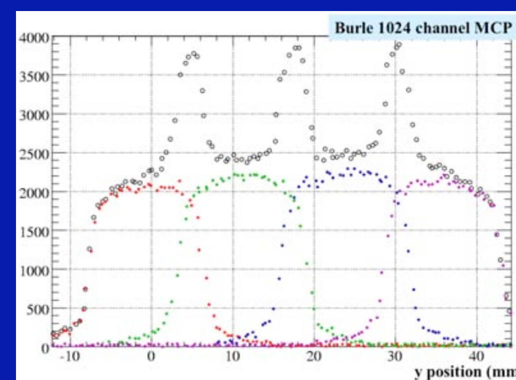








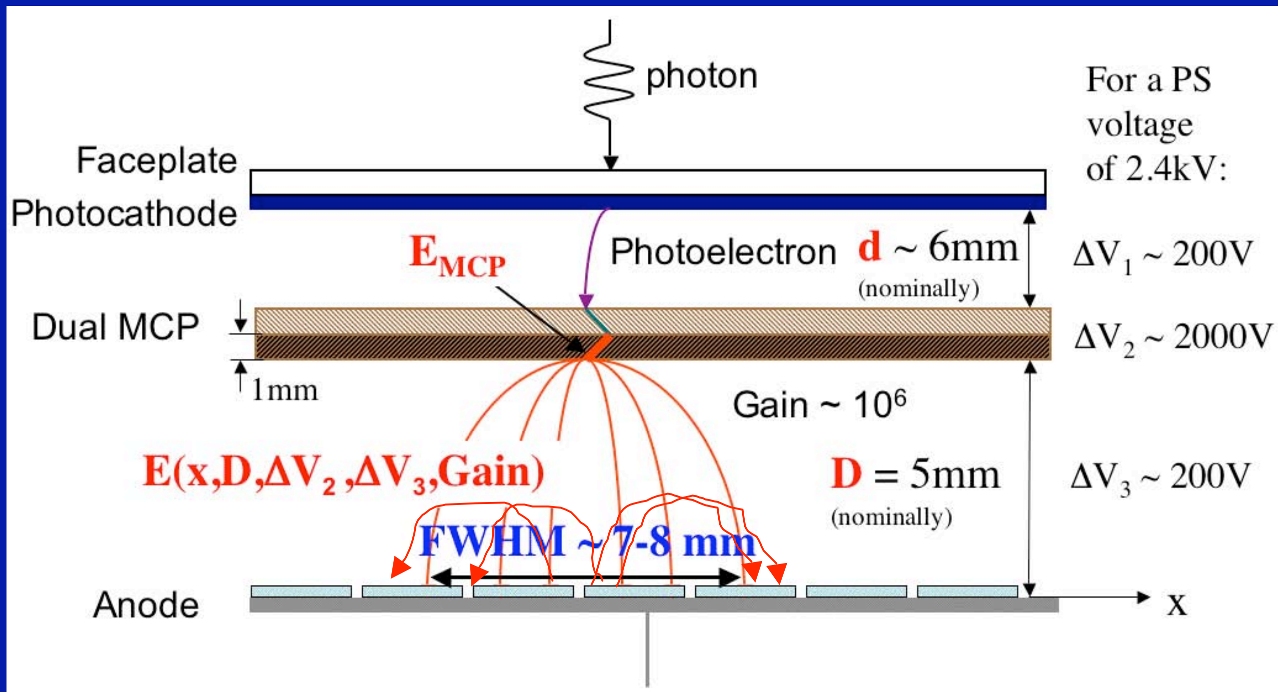
Add a sum:



- **A very large tail of the charge sharing. A FWHM of the charge spread ~ 7-8 mm !!!**
- **In y-direction the effect seems to be slightly smaller (capacitance effect ?)**

A large anode charge spread affects the timing resolution

A standard MCP-PMT:



- The charge spread in the avalanche, based on our measurements: **FWHM ~ 7-8 mm !!!!!!!**
- (a) D and E_{MCP}/E too large ! (b) 20% of electrons recoils from anode ! => charge spread
- A large charge spread could affect the timing performance:
  - A pad of 3 mm in size is de facto 10-11 mm wide => $\sigma_{pixel} \sim 10.5/\sqrt{12}$ mm <=> $\sigma_t \sim 10$ ps !
  - The "equal-time" connections to a common point outside of the MCP-PMT will help, however, at some level of timing, tiny differences in electron trajectories may dominate.

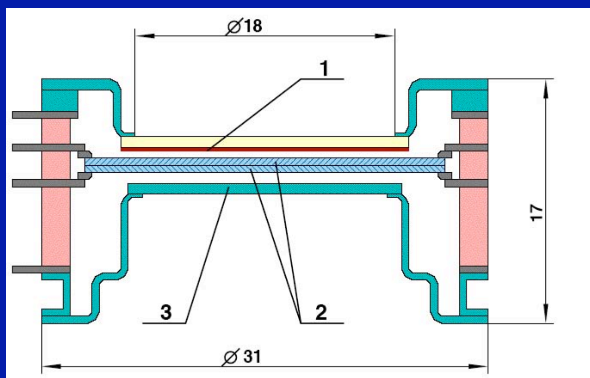
MCP-PMT in the magnetic field

- **A typical need is to reach a good performance at ~15 kG**

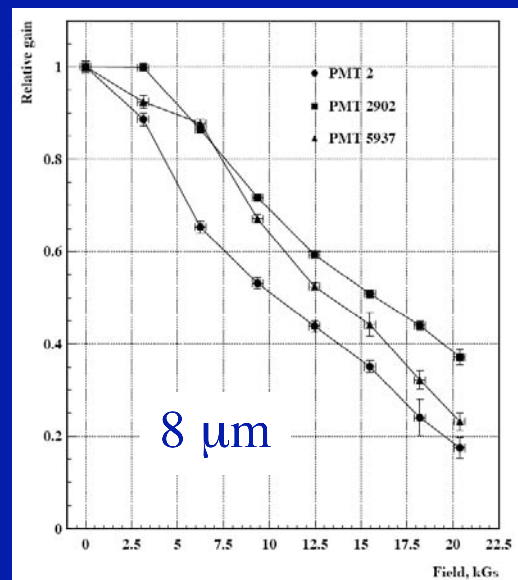
MCP gain reduction in a magnetic field

Russian MCP-PMT:

Barnyakov et al., **Novosibirsk, Russia**, The 10th Pisa meeting, La Biodola, Italy, 2006

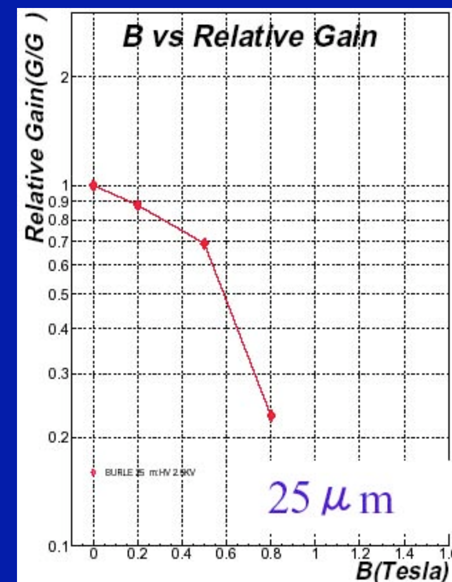


1 — photocathode, 2 — two MCP ,
3 — anode
Gap photocathode – MCP is 0.2 mm.
Diameter of MCP channels is 8 μm.



Burle MCP-PMT:

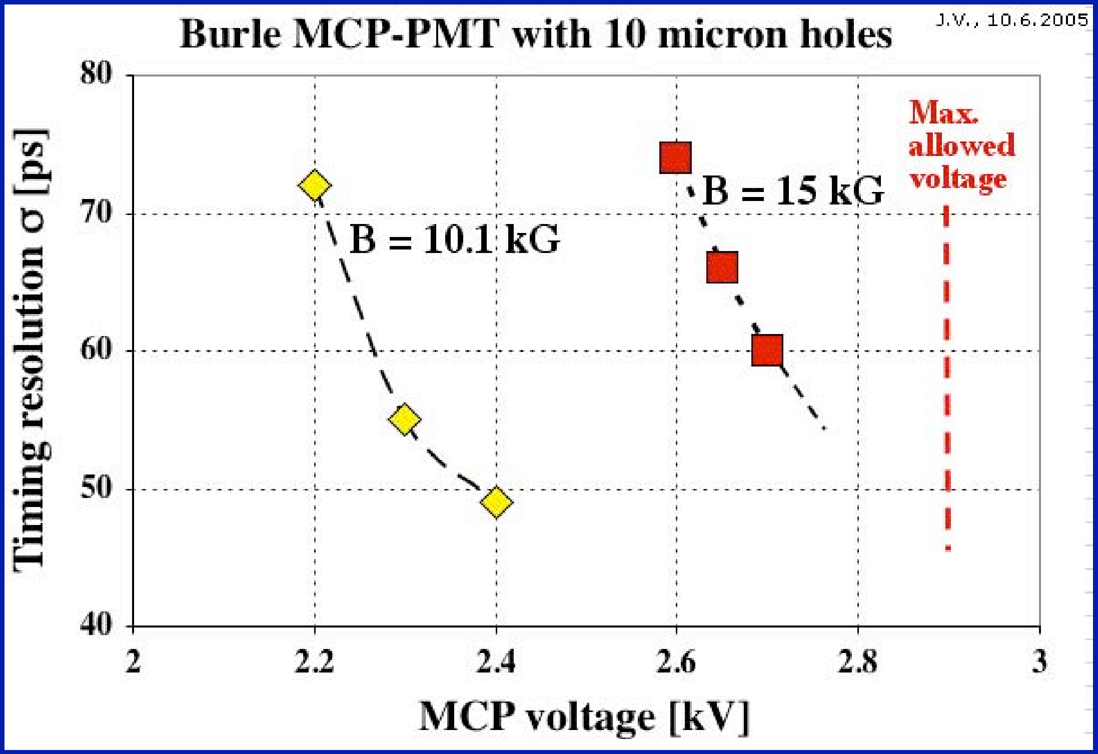
M.Akatsu et al., Nagoya, Japan



- **Gain in MCP: G ~ e$^{(A*MCP\ thickness/MCP\ dia)}$ - drops in a magnetic field.**
- **The 25µm dia. holes are too large. One needs to reduce their size to ~6-10µm dia., to operate at 15kG.**

Single photon timing resolution at B = 15 kG with Burle/Photonis MCP-PMT with 10 μm holes

J. Va'vra et al., The 10th Pisa meeting on Advanced detectors, a Biodola, Italy, 2006



- **Reduction of pulse height in a large magnetic field leads to the degradation of the timing resolution for fixed voltage. One has to increase voltage to compensate for loss of pulse height.**
- 10μm hole 4-pad Burle/Photonis MCP-PMT with Ortec VT-120A amplifier.

Aging

- Goal is to reach safety up to a level of 3×10^{14} photons/cm^2.

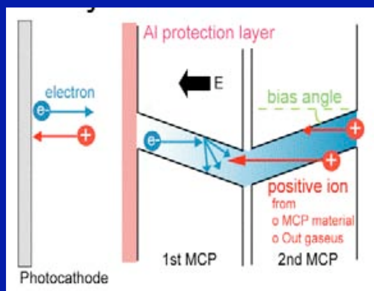
Aging rate of MCP-PMT

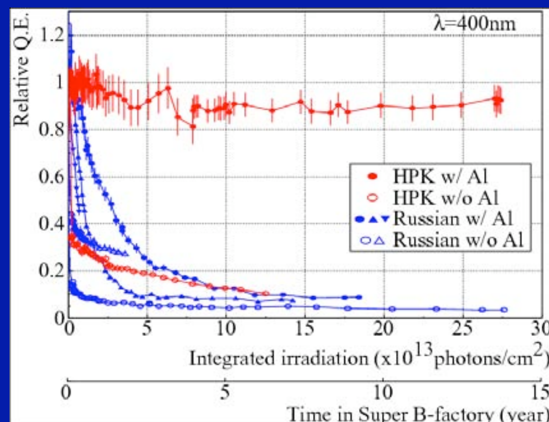
I.Adachi, et al., **Nagoya University,** SuperB workshop at SLAC

A. Barnyakov et al., **Novosibirsk, Russia**

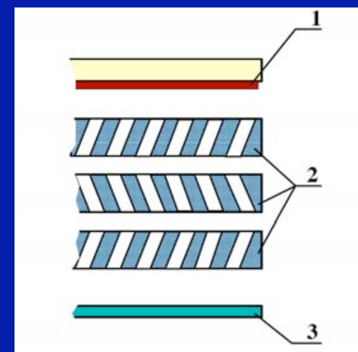
The 10th Pisa meeting, La Biodola, Italy, 2006

Protective Al_2O_3 film:

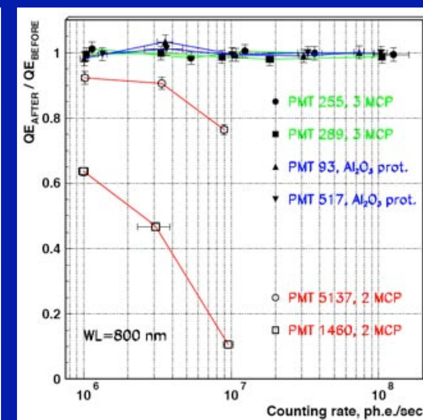




Three MCP solution:



1 — Photocathode, 2 — Three MCP, 3 — Anode



- The protective **Al_2O_3 layer** blocks the positive ions backflow to cathode.
- Nagoya group predicts **~13 years of lifetime** at Super B-factory.
- However, there is a price: a **40% reduction** of the photoelectron transmission.
- Japanese group concluded that the Russian protective film does not work as well.
- Russian results indicate that the blockage of positive ions with **3 MCPs** seems to be as effective as with a protective Al_2O_3 layer, up to a rate of ~10^8 pe^-/sec. They do not show an equivalent integrated charge dose as the Nagoya people show.

Focusing DIRC prototype

- **A possible upgrade of BaBar DIRC for future Super B factory.**

BaBar DIRC RICH = Detection of Internally Reflected Cherenkov light

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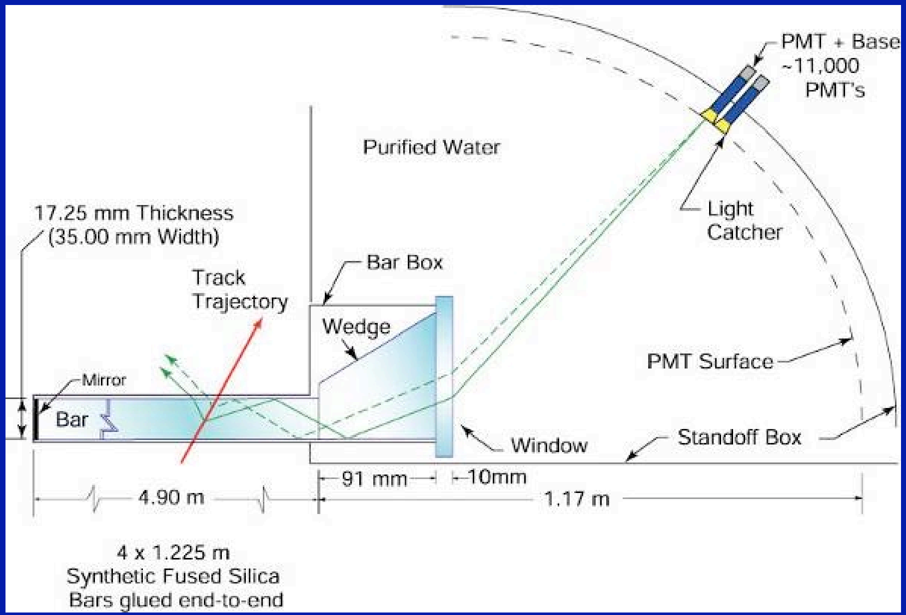
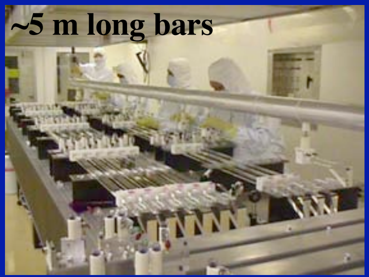
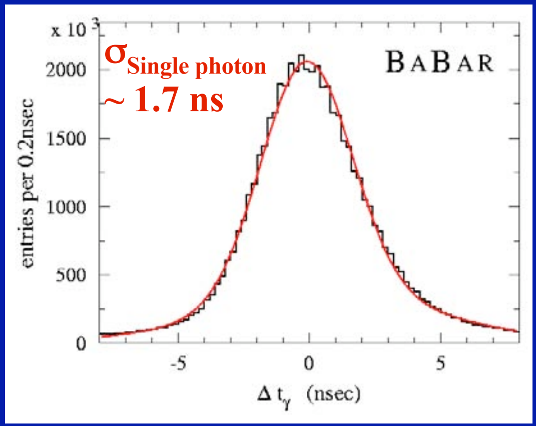
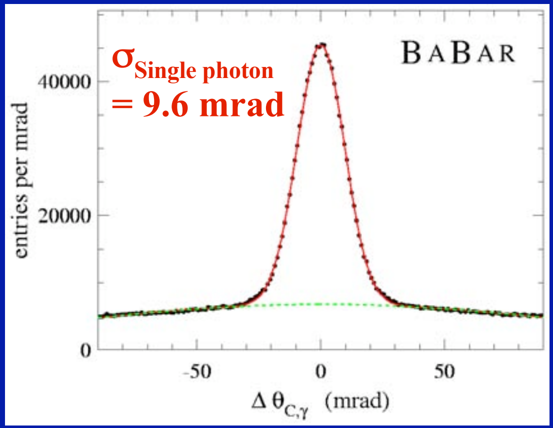
- **Very successful** in hadronic particle identification, with ~ 3σ π-K separation at 4 GeV/c.
- **3D imaging of photons: θ_c ,ϕ_c & time**

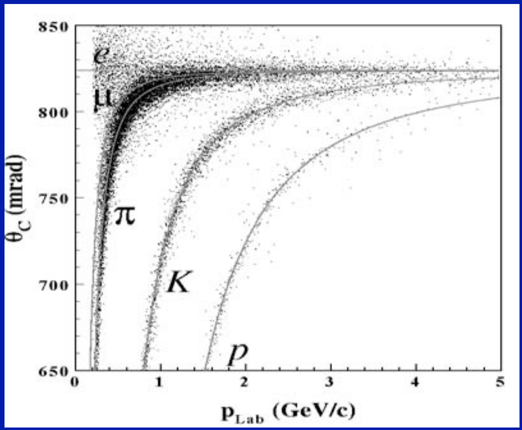
Principle of BaBar DIRC RICH:









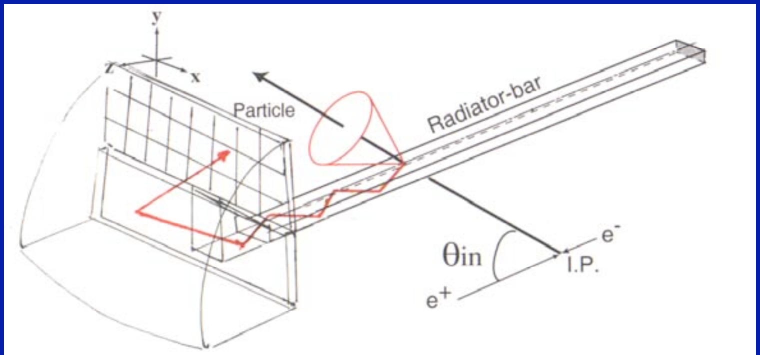


Motivation to develop a new DIRC at Super-B

Goal:

- Super-B will have 100x higher luminosity

- Backgrounds are not yet understood, but they would scale with the luminosity if they are driven by the radiative Bhabhas



⇒ **DIRC needs to be smaller and faster:**

- Focusing and smaller pixels can **reduce the expansion volume by a factor of 7-10 !**
- Faster PMTs reduce a sensitivity to background.

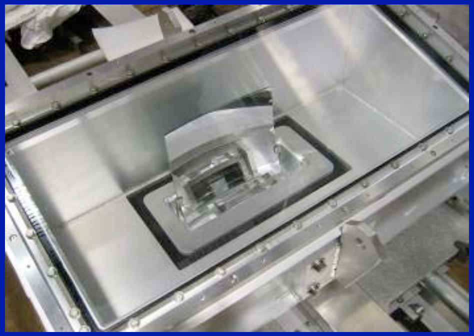
Additional benefit of the faster photon detectors:

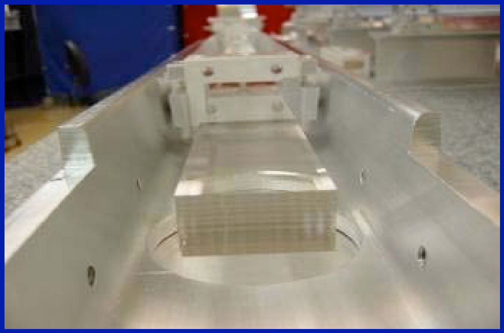
- Timing resolution improvement: **σ ~1.7ns (BaBar DIRC) -> σ ≤150ps (~10x better)** which allows a measurement of a **photon color** to correct the chromatic error of θ_c.

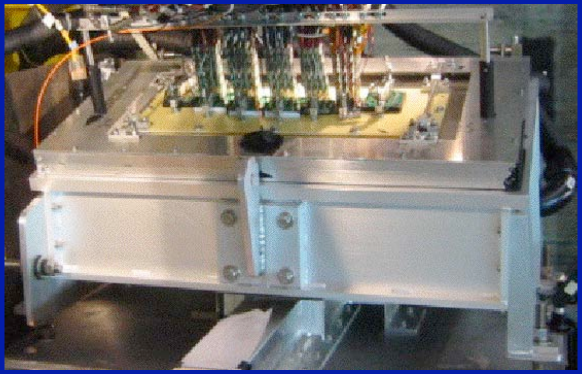
Focusing mirror effect:

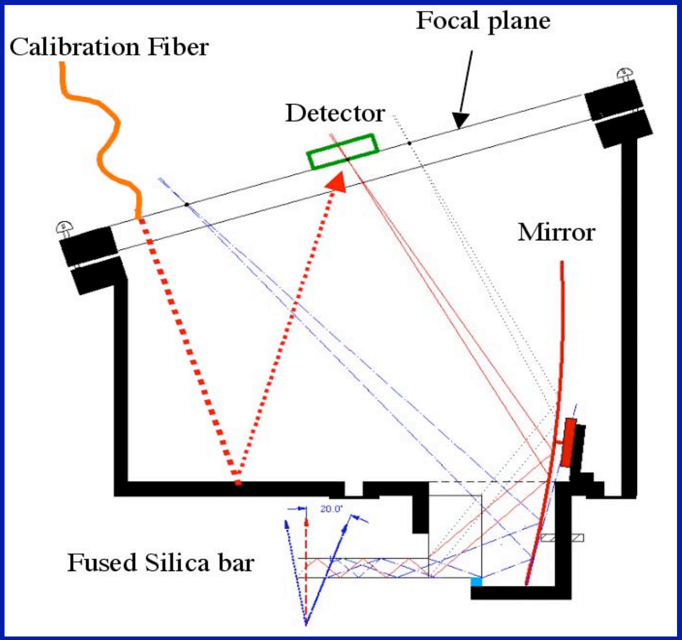
- Focusing eliminates effect of the bar thickness (contributes σ ~ 4 mrads in BaBar DIRC)
- However, the spherical mirror introduces an aberration, so its benefit is smaller.

Focusing DIRC prototype optics









- **Radiator:**
  - a 3.7 m long BaBar DIRC fused silica bar.
- **Optical expansion region:**
  - filled with a mineral oil to match the fused silica refraction index.
  - include optical fiber for the electronics calibration.
- **Focusing optics:**
  - a spherical mirror with 49cm focal length focuses photons onto a detector plane.

Focusing DIRC prototype photon detectors

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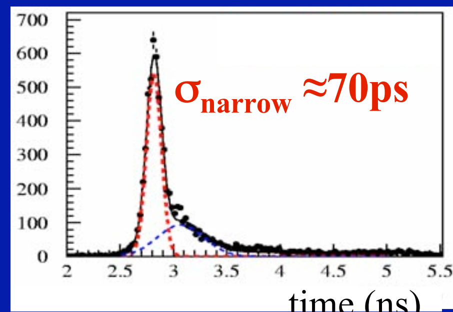
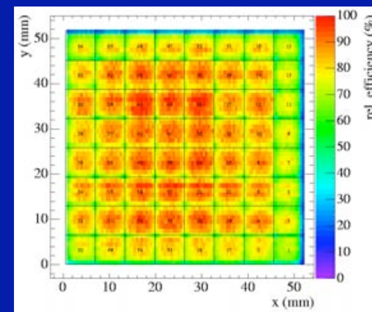
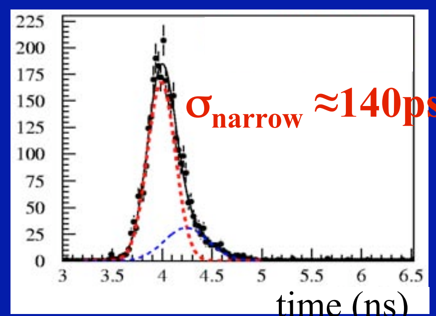
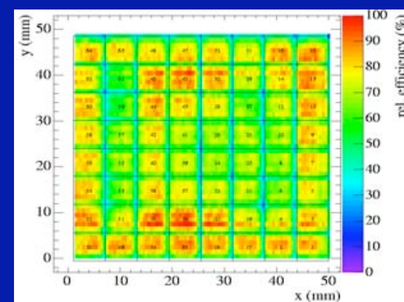
1) Burle 85011-501 MCP-PMT (64 pixels, 6x6mm pad, σ_{TTS} ~50-70ps)



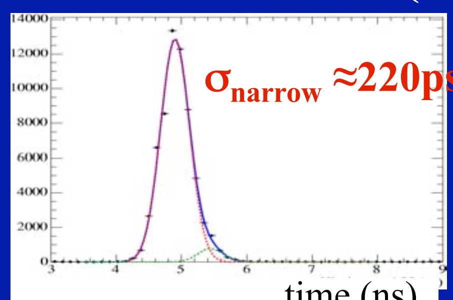


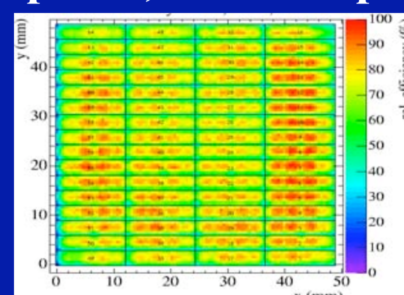
2) Hamamatsu H-8500 MaPMT (64 pixels, 6x6mm pad, σ_{TTS} ~140ps)





3) Hamamatsu H-9500 Flat Panel 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.**

Focusing DIRC electronics

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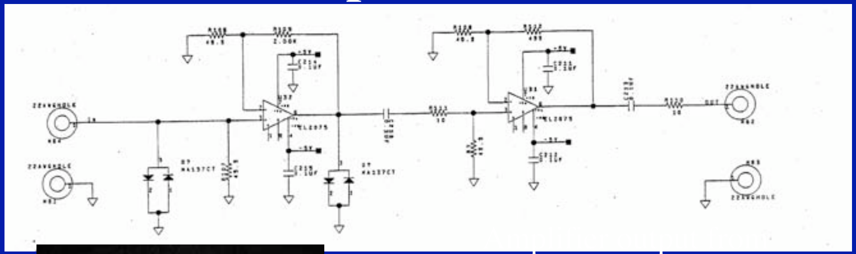
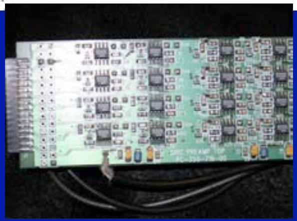
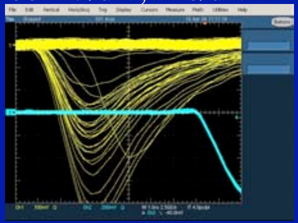
SLAC Amplifier:

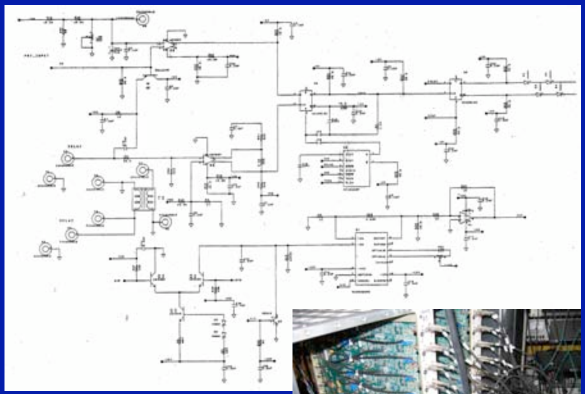




MCP-PMT (trigger on PiLas),
100mV/div, 1ns/div



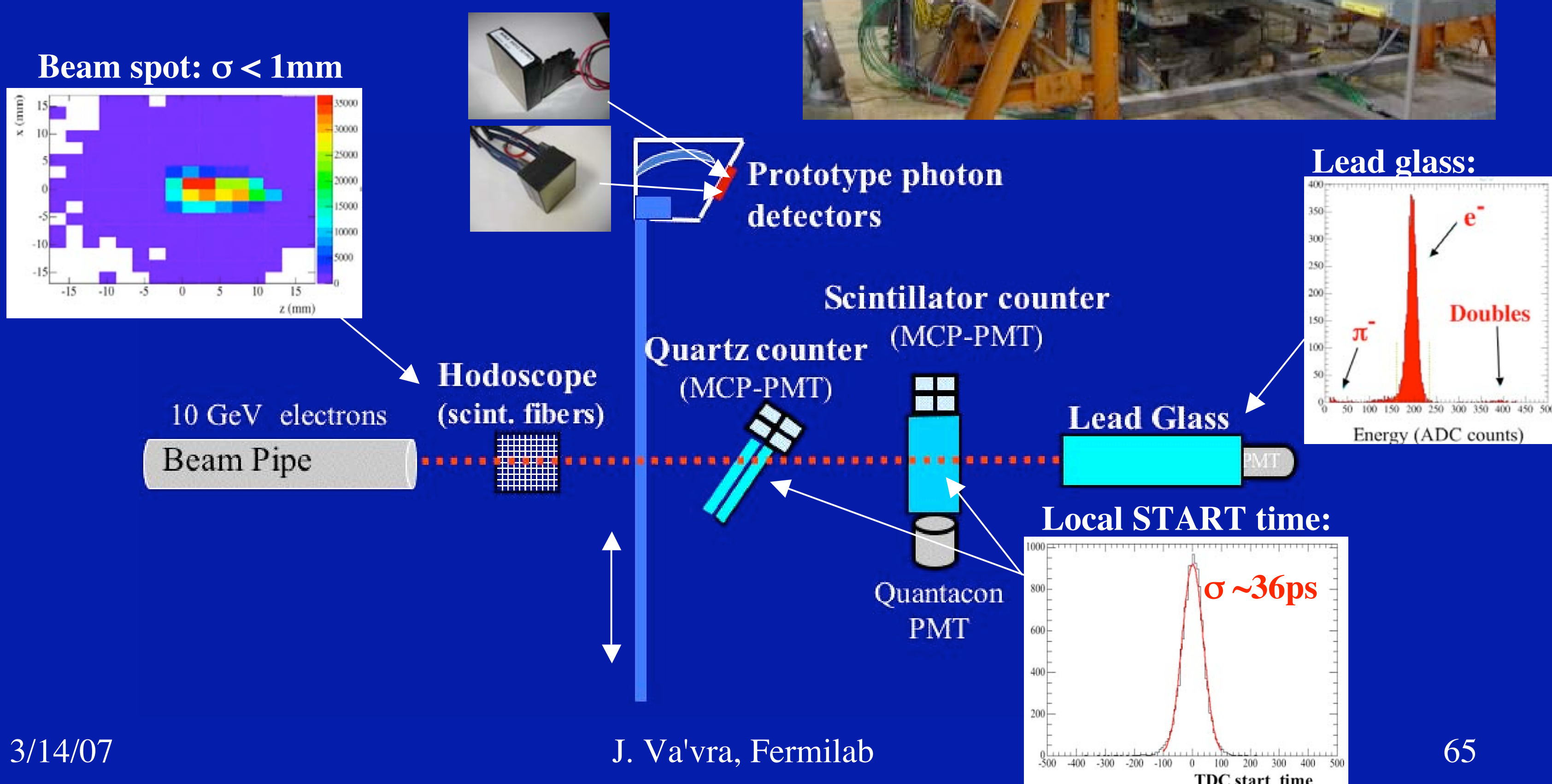
SLAC CFD:



- **Amplifier**, based on two Elantek 2075EL chips, has a voltage gain of ~130x, and a rise time of ~1.5ns.
- **Constant-fraction-discriminator** (32 channels/board).
- **Phillips TDC** with 25ps/count.

Beam Test Setup

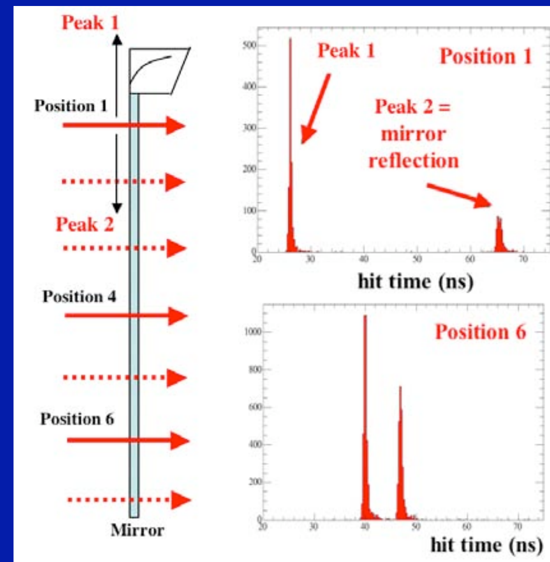
- SLAC 10 GeV/c electron beam
- Beam enters bar at 90º angle.
- Prototype is movable to 7 beam positions along bar.
- Time start from the LINAC RF signal, but correctable with a local START counter



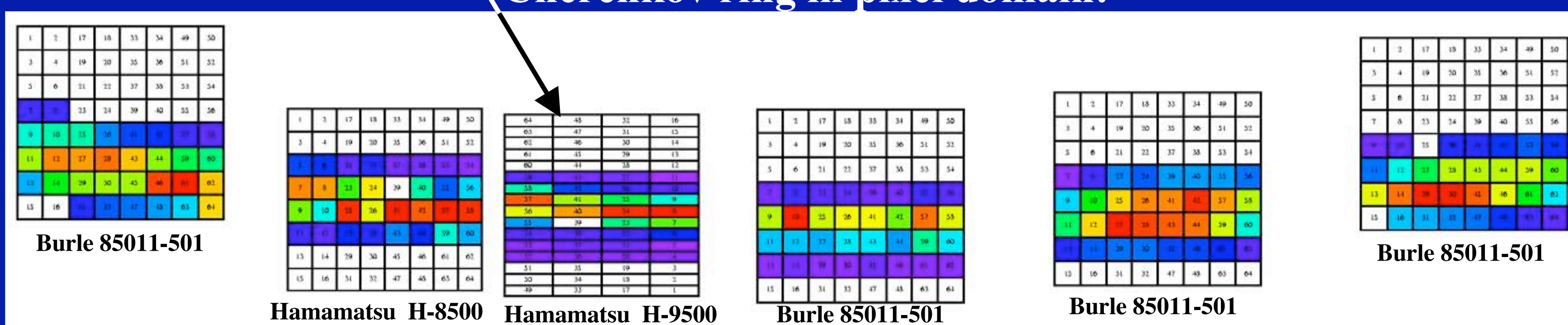
Cherenkov Photons in Time and Pixel domains

- 10 GeV/c electron beam data.
- ~ 200 pixels instrumented.
- Ring image is most narrow in the 12x3mm pixel detector.

Cherenkov photons in time domain:

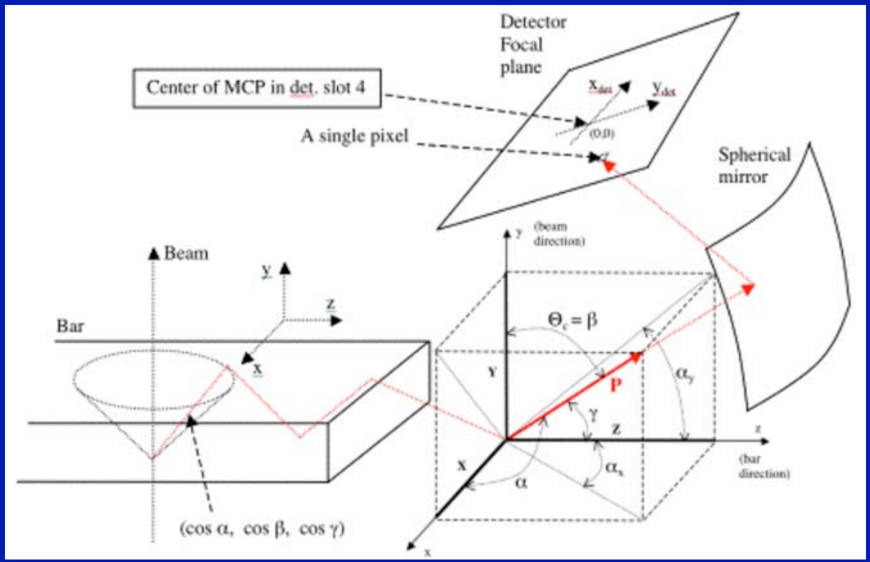


Cherenkov ring in pixel domain:

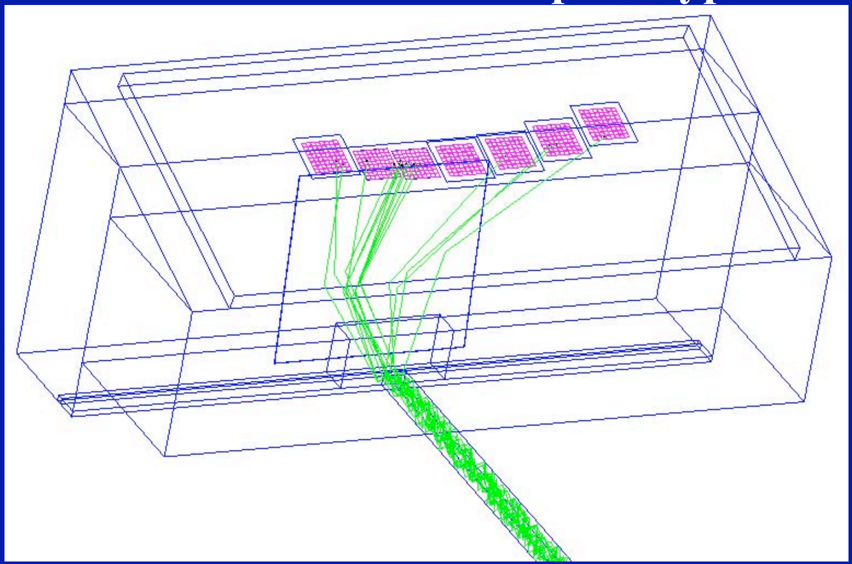


Focusing DIRC prototype reconstruction

Prototype coordinate systems:



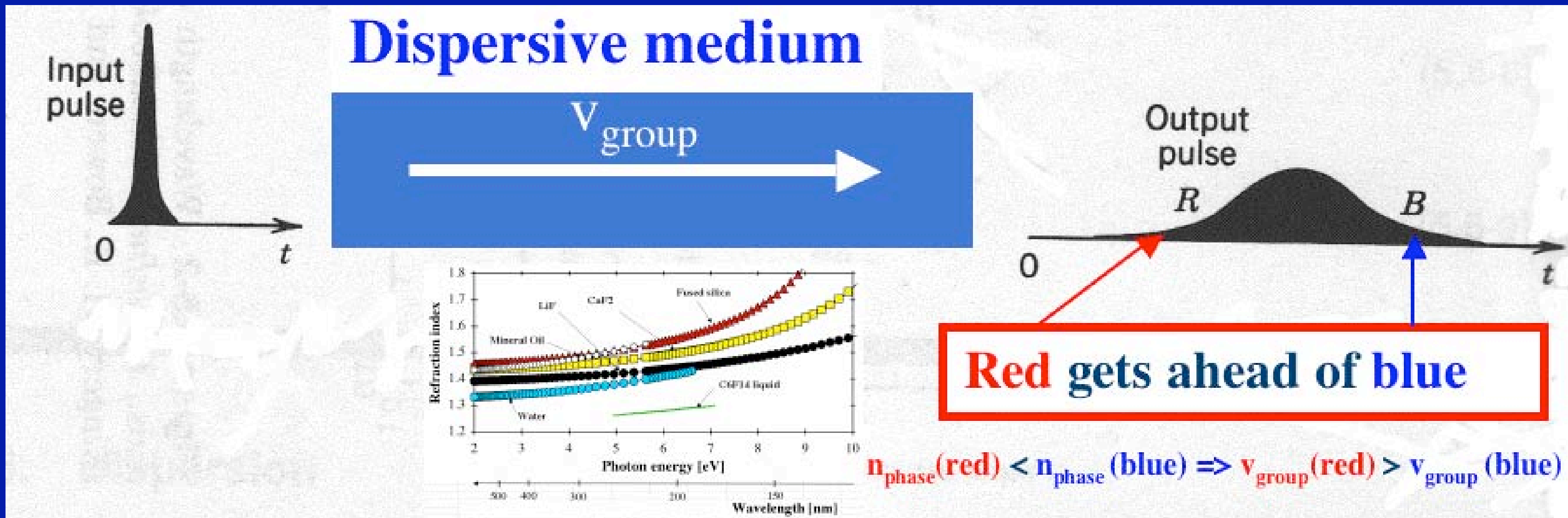
Geant 4 simulation of the prototype:



- **Each detector pixel determines these photon parameters for average λ :**
  θ_c, cos α, cos β, cos γ, Photon path length, time-of-propagation, number of photon bounces.

- **We use GEANT4 simulation to obtain the photon track parameters for each pixel.**
  (it is checked by a ray-tracing software)

Color tagging by measurement of photon propagation time



$$v_{group} = c_0 / n_{group} = c_0 / [n_{phase} - \lambda * dn_{phase}/d\lambda]$$

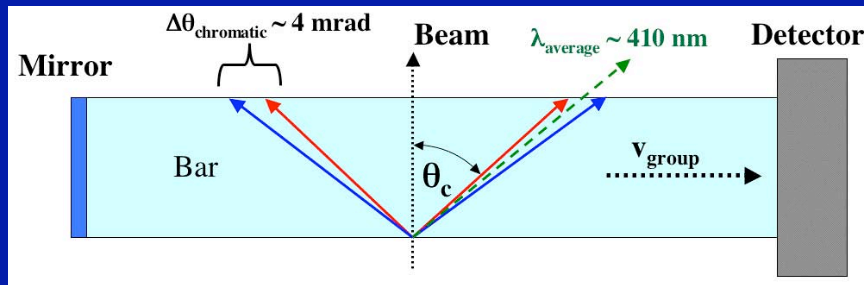
$$t = TOP = L / v_{group} = L\,[n_{phase} - \lambda * dn_{phase}/d\lambda] / c_0$$ = Time-Of-Propagation

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

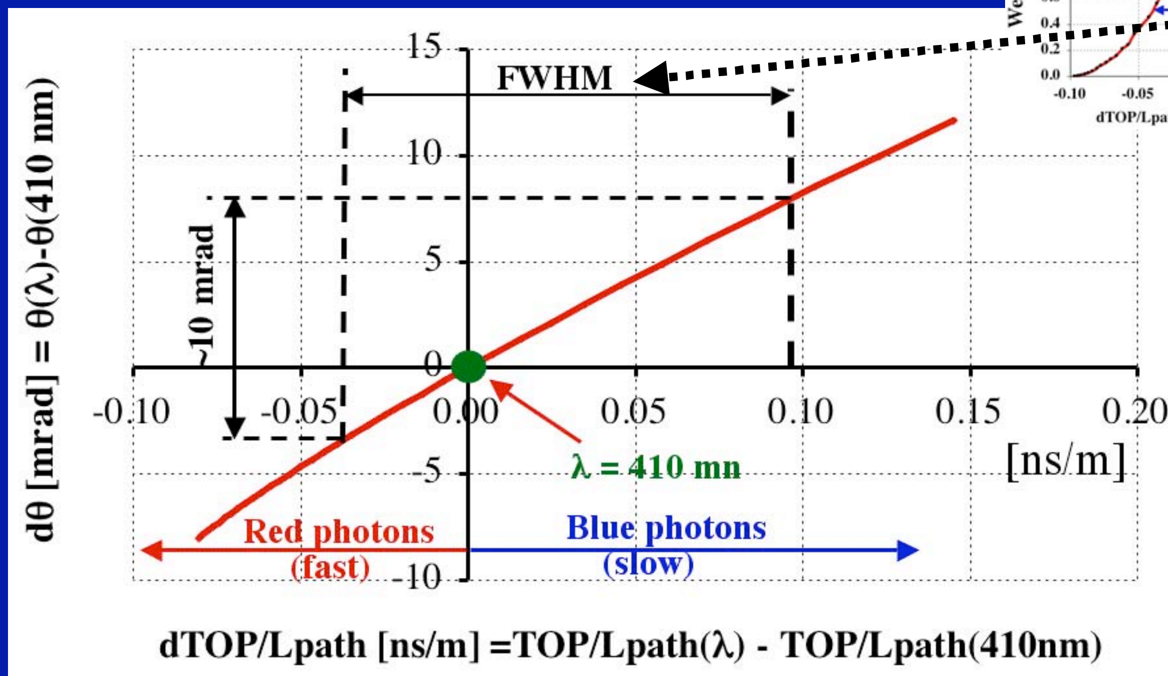
dt is pulse dispersion in time, length **L**, wavelength bandwidth **dλ**, refraction index **n(λ)**

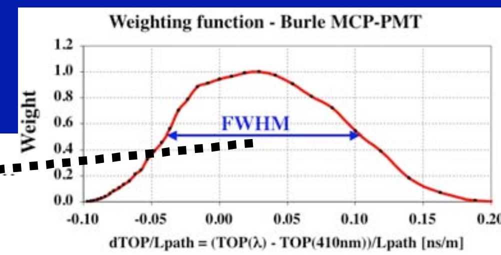
- We have determined in Fused Silica: **dt/L = dTOP/L ~ 40ps/meter**.
- **Our goal is to measure the color of the Cherenkov photon by timing !**

Cherenkov light: tagging color of photon by time



Principle of chromatic correction by timing:





TOP = time of propagation of photon in the bar

TOP/Lpath $= 1/v_{group}(\lambda)$

Cherenkov angle production controlled by n_{phase} ($\cos\theta_c = 1/(n_{phase}\beta)$): θ_c (red) < θ_c (blue)

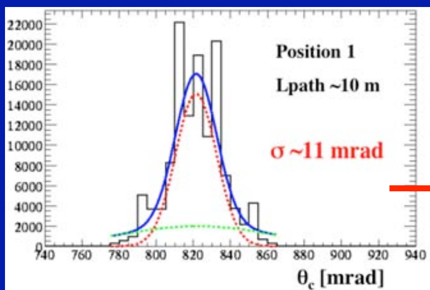
Propagation of photons is controlled by n_{group} ($v_{group} = c_0/n_{group} = c_0/[n_{phase} - \lambda * dn_{phase}/d\lambda]$): v_{group} (red) > v_{group} (blue)

θ_C resolution and Chromatic correction

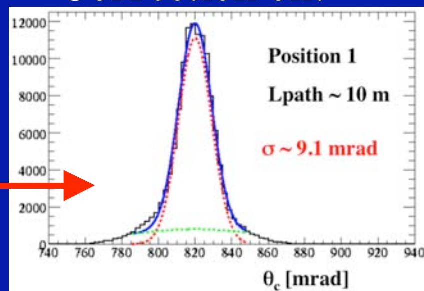
All pixels:

3mm pixels only:

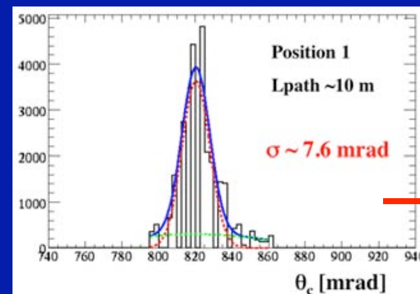
Correction off:



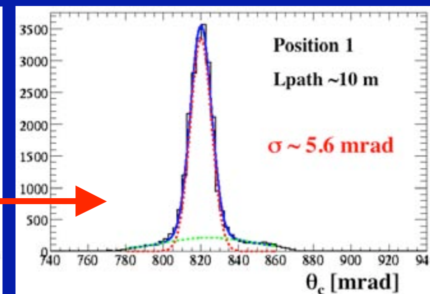
Correction on:

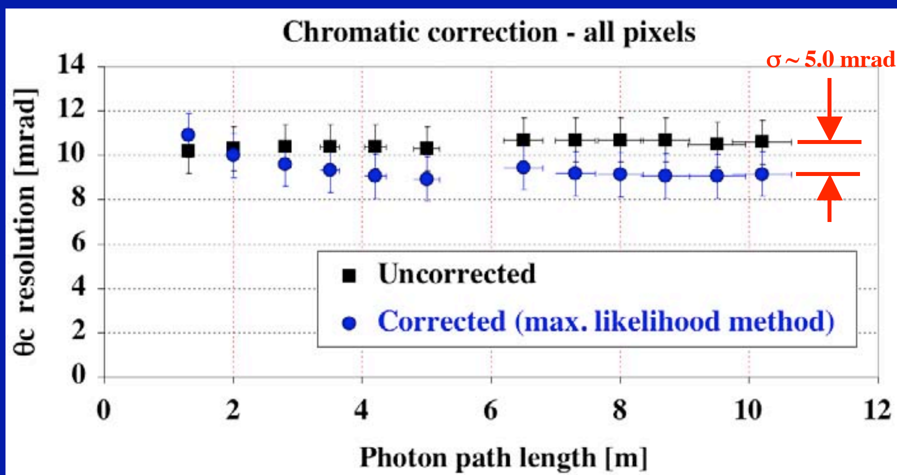


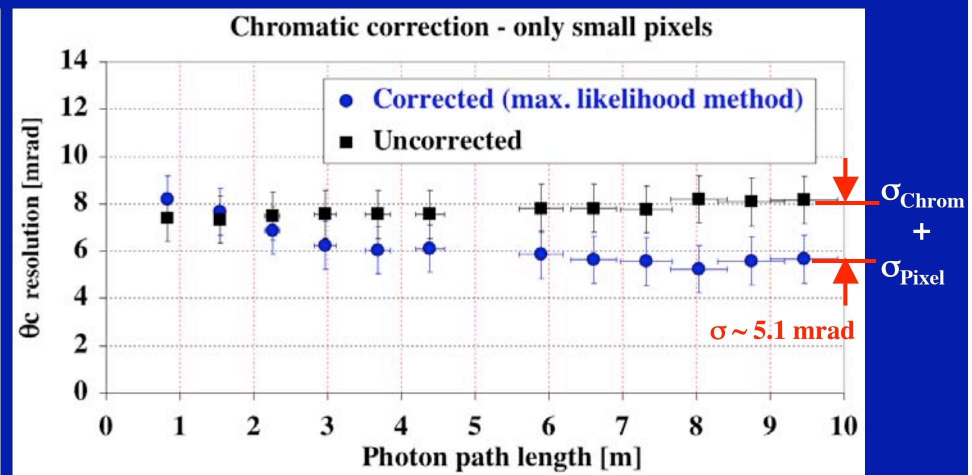
Correction off:



Correction on:



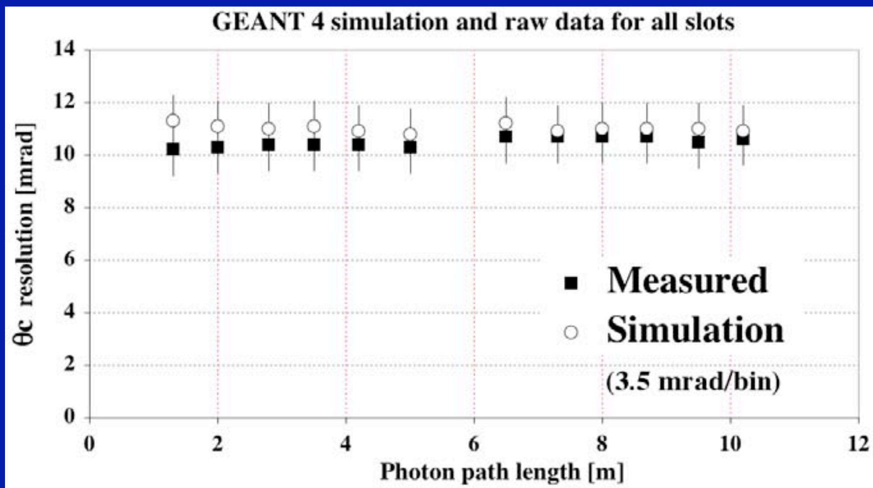




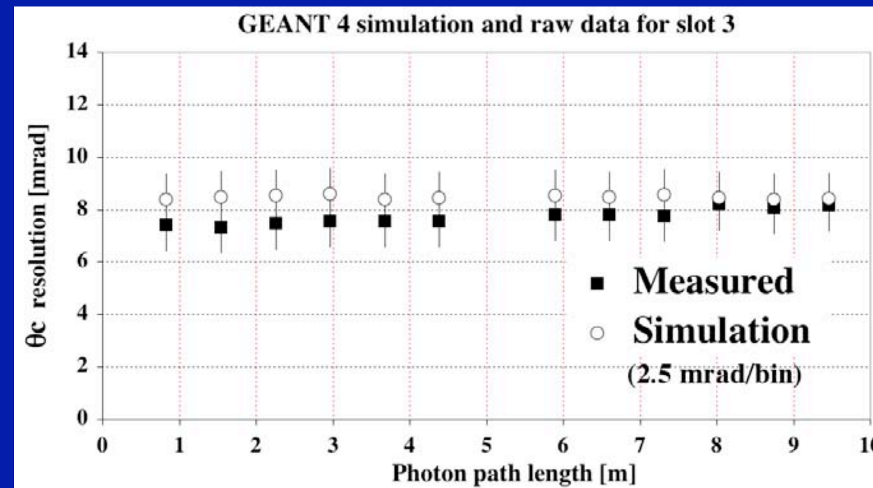
- The chromatic correction starts working for Lpath > 2-3 meters due to a limited timing resolution of the present photon detectors. The maximum likelihood technique does better for short Lpath than other methods
- Holes in the uncorrected distributions are caused by the coarse pixilization, which also tends to worsen the resolution. In the corrected distributions this effect is removed because of the time correction.
- Smaller pixel size (3mm) helps to improve the Cherenkov angle resolution; it is our preferred choice.

θ_C resolution and Geant 4 MC simulation

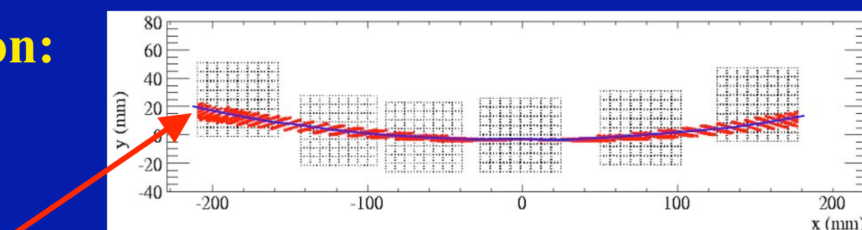
θ_c resolution - all pixels:



θ_c resolution - 3mm pixels only:



- **Main contributions to the θ_c resolution:**
  - **chromatic smearing**: ~ 3-4 mrad
  - **pixel size**: ~5.5 mrad
  - **optical aberrations of this particular design**:

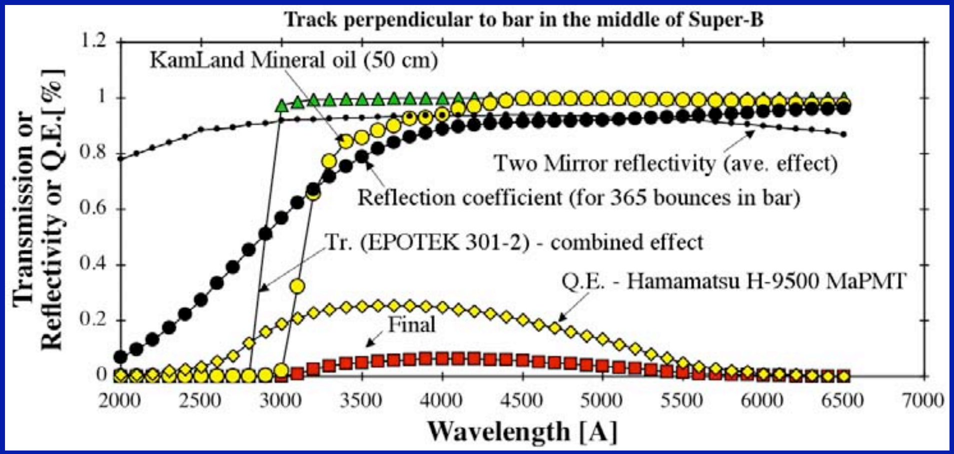


grows from 0 mrad at ring center to 9 mrad in outer wings of Cherenkov ring

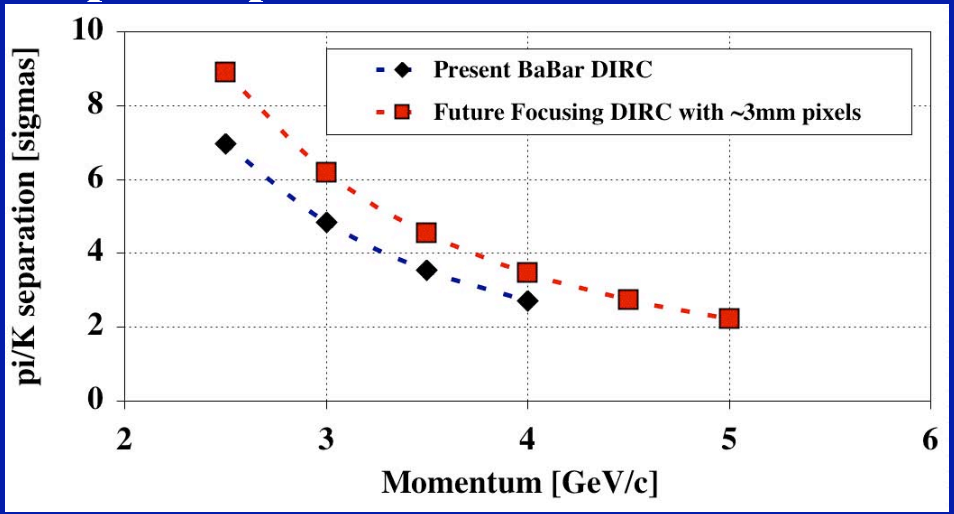
(this effect is caused by the spherical focusing mirror in the present design)

Expected final performance at incidence angle of 90°

Focusing DIRC prototype bandwidth:



Expected performance of a final device:



- Prototype's **Npe_measured** and **Npe_expected** are consistent within **~20%.**
- **Hamamatsu H-9500 MaPMTs**:
  We expect **No ~ 31 cm^{-1}**, which in turn gives **Npe ~ 28** for 1.7 cm fused silica, and somewhat better performance in **pi/K** separation than the present BaBar DIRC.
- **Burle-Photonis MCP-PMT:**
  We expect **No ~ 22 cm^{-1}** and **Npe ~ 20** for B = 0kG.
- **BaBar DIRC design**:
  No ~ 30 cm^{-1}, and **Npe ~ 27**.

Conclusions

- **We have demonstrated that we can correct the chromatic error of θ_C.** **This is the first RICH detector which has been able to do this.**
- **Expected N_o and Npe is comparable to BaBar DIRC for MaPMT H-9500.**
- **Expected improvement of the PID performance with 3x3mm pixels: ~20-30% compared to BaBar DIRC for pi/K separation, if we use H-9500 MaPMT.**
- The main defense against the background at Super-B is to make (a) the expansion volume much smaller, which is possible only with highly pixilated photon detectors, and (b) use of faster detectors.

- **Our present best results with the laser diode:**
  - **$\sigma \sim 12$ ps for Npe = 50-60 (expected from 1cm thick Cherenkov radiator).**
  - **$\sigma_{TTS} < 26$ ps for Npe ~ 1.**
  - **Upper limit on the MCP-PMT contribution: $\sigma_{MCP\text{-}PMT} < 6.5$ ps.**
  - **TAC/ADC contribution to timing: $\sigma_{TAC\_ADC} < 3.2$ ps.**
  - **Total electronics contribution at present: $\sigma_{Total\_electronics} \sim 7.2$ ps.**

    (One has to be aware that the time-walk, due to variation of Npe, has to be corrected).

- **Next test beam run:** Add (a) ADC-based pixel interpolation, (b) 2-nd hodoscope after a bar, (c) ASIC-based readout on one MCP-PMT allowing a measurement of time and pulse height, (d) test of the TOF detector.

Backup slides