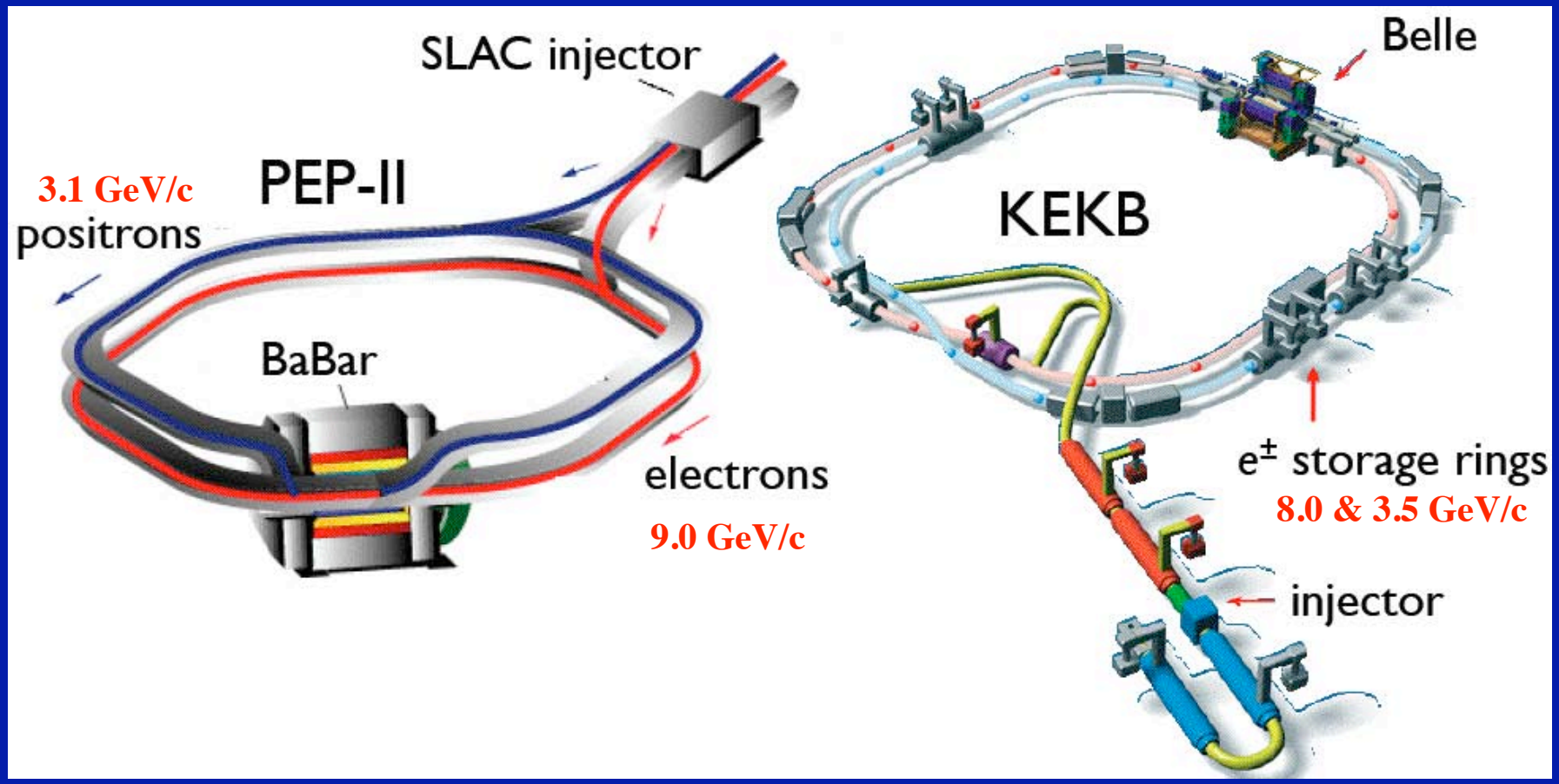
Lecture III: Super-B Particle Identification Systems

J. Va'vra, SLAC

Content of these lectures

- **Lecture I: Basic Design Concepts**
  - Basic PID concepts: Cherenkov detectors, dE/dx, TOF
  - Photocathodes and Photon detection efficiency (PDE)
  - Photon propagation in dispersive media: transmission, chromaticity, internal reflection, etc.
  - DIRC-like detectors, 1-st DIRC-like detector: BaBar DIRC
- **Lecture II: Photon detectors**
  - MaPMTs, MCP-PMTs, GAPDs or SiPMTs, HAPDs, APDs
  - Timing performance, quantum efficiency
  - Aging, rate capability, effects of magnetic field
  - Readout schemes: pixels, strip lines, charge sharing
  - New trends: photocathodes, new MCP-PMT construction methods
- **Lecture III: Detector systems for SuperB and Belle 2**
  - Focusing DIRC (FDIRC) concept,
  - TOP counters
  - Aerogel RICH,
  - TOF detectors
  - Comparison of various methods.

B-factories: PEP II & KEKB

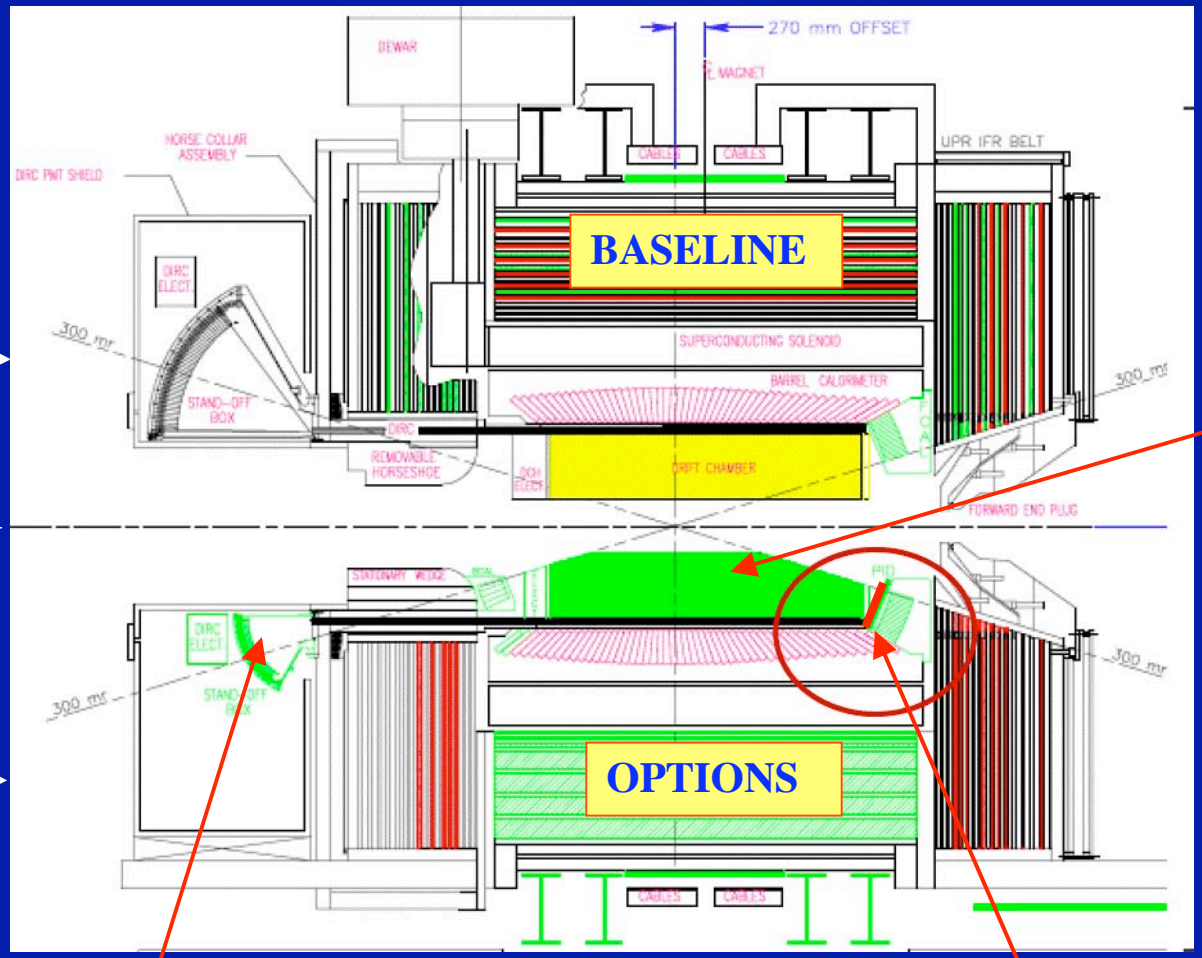


- **Collisions produce relatively low energy particles, typically < 4 GeV/c.**
- **SuperB will have a similar mumentum distribution.**

New PID systems in Super-B

BaBar:

SuperB:

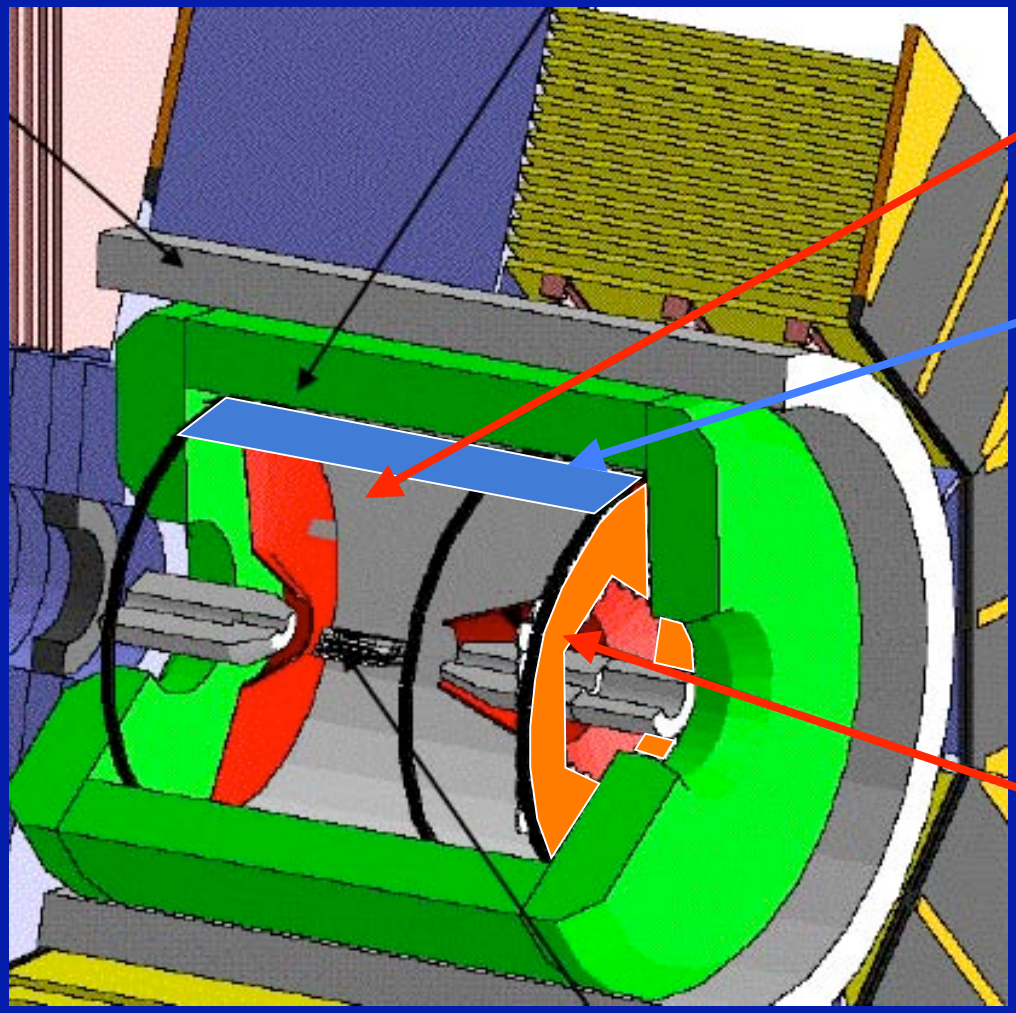


Cluster counting in a new DCH

New Focusing DIRC (FDIRC)

Forward TOF or Forward Aerogel RICH

New PID systems in Super-Belle



Focusing DIRC in SuperB (FDIRC)

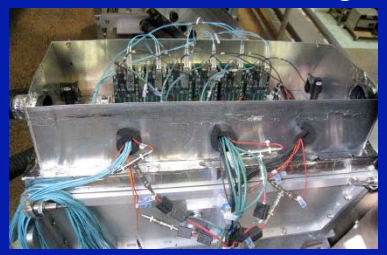
- FDIRC prototype
- Final FDIRC in SuperB

FDIRC prototype

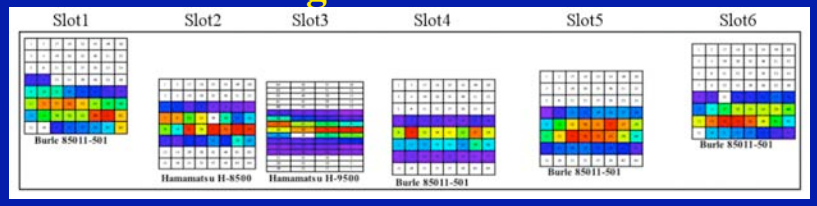
- How to design it ?
- Tests in beam and CRT

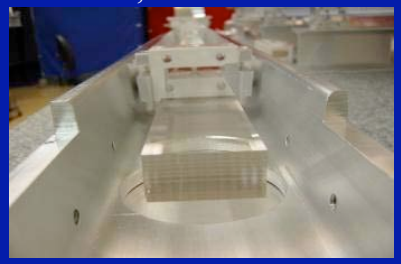
A detector plane using pixilated detectors

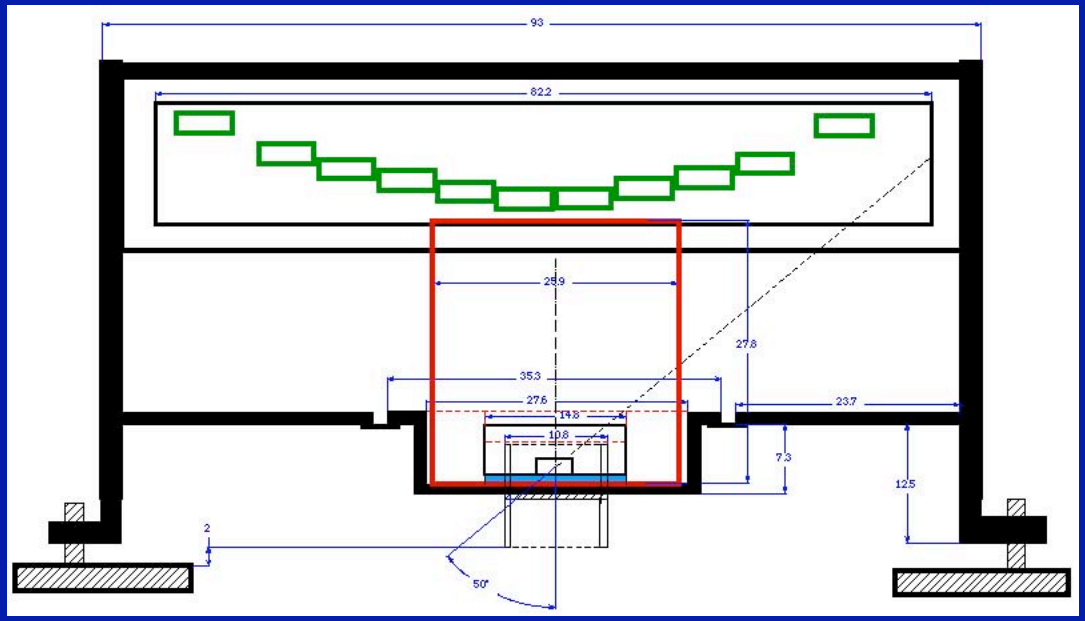
J.F. Benitez, I. Bedajanek, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff. K. Suzuki, J. Schwiening, J. Uher and J. Va'vra, "Development of a Focusing DIRC," IEEE Nucl.Sci, Conference records, October 29, 2006, and SLAC-PUB-12236, 2006

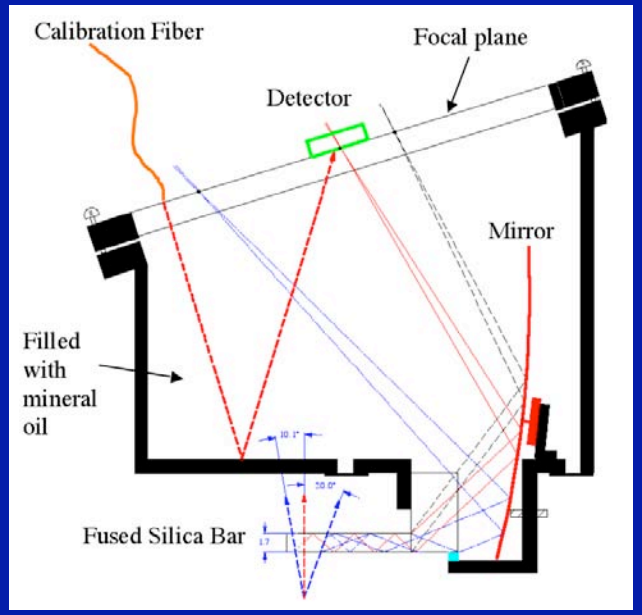


Cherenkov ring on 10GeV e^- test beam:







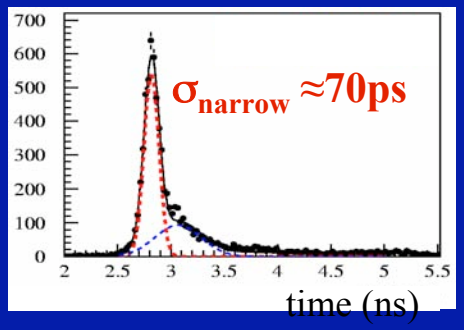


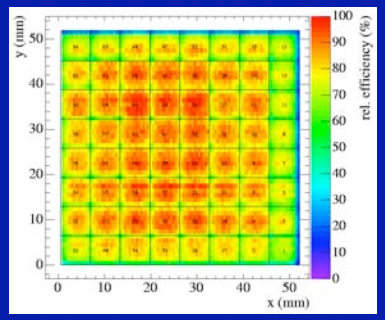
- **Single 3.6 meter-long DIRC bar**
- **Test bed for various detectors and new concepts of electronics.**

Focusing DIRC prototype photon detectors

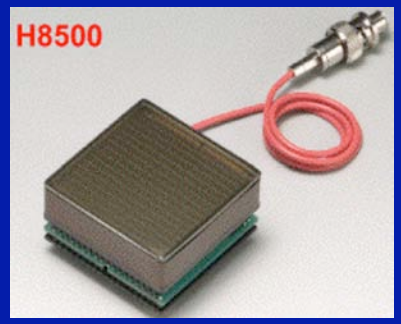
C. Field et al., Nucl.Inst.&Meth., A 553 (2005) 96

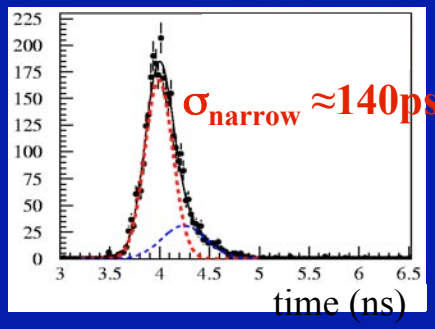
1) Burle 85011-501 MCP-PMT (64 pixels, 6x6mm pad, σ_{TTS} ~50-70ps)

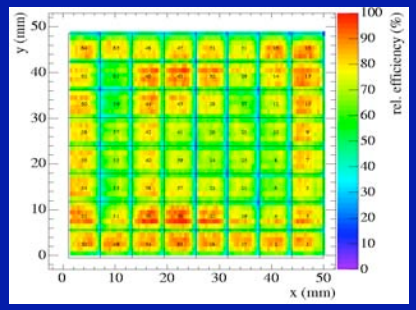




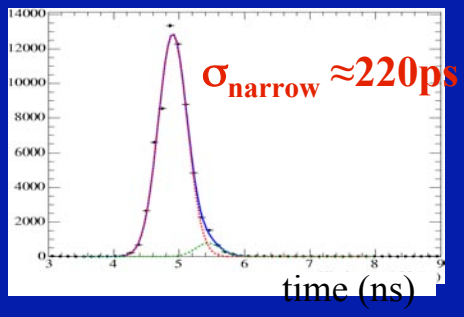
2) Hamamatsu H-8500 MaPMT (64 pixels, 6x6mm pad, σ_{TTS} ~140ps)

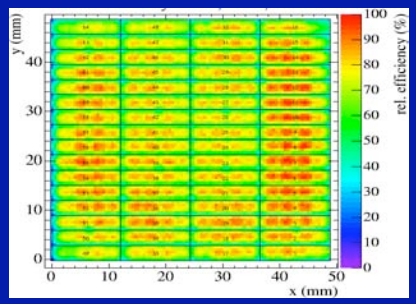






3) Hamamatsu H-9500 Flat Panel MaPMT (256 pixels, 3x12mm pad, σ_{TTS} ~220ps)



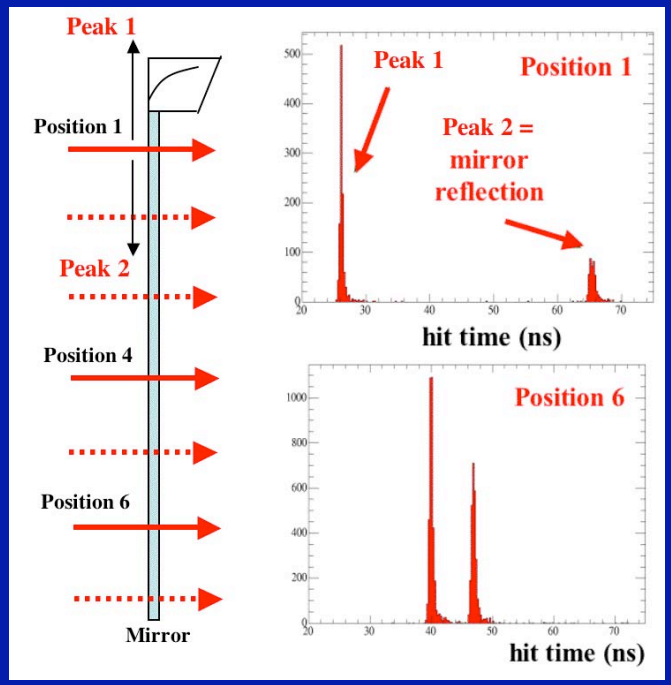


- **Timing resolutions were obtained using a fast laser diode in bench tests with single photons on pad center.**

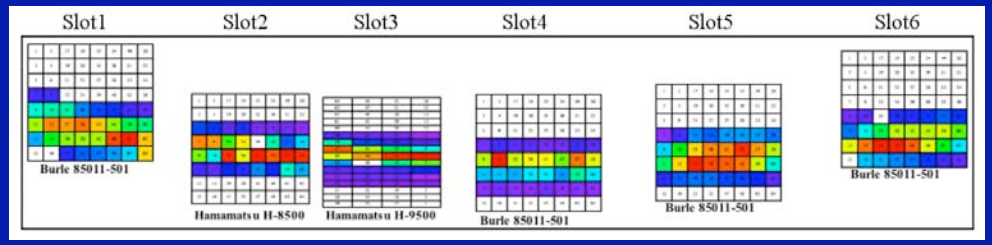
Cherenkov ring in pixel and time domain

J.F. Benitez, I. Bedajanek, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff. K. Suzuki, J. Schwiening, J. Uher and J. Va'vra, "Development of a Focusing DIRC," IEEE Nucl.Sci, Conference records, October 29, 2006, and SLAC-PUB-12236, 2006

Cherenkov ring in the time domain:



Cherenkov ring in the pixel domain:

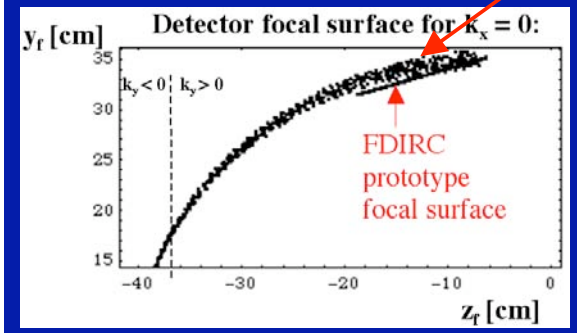


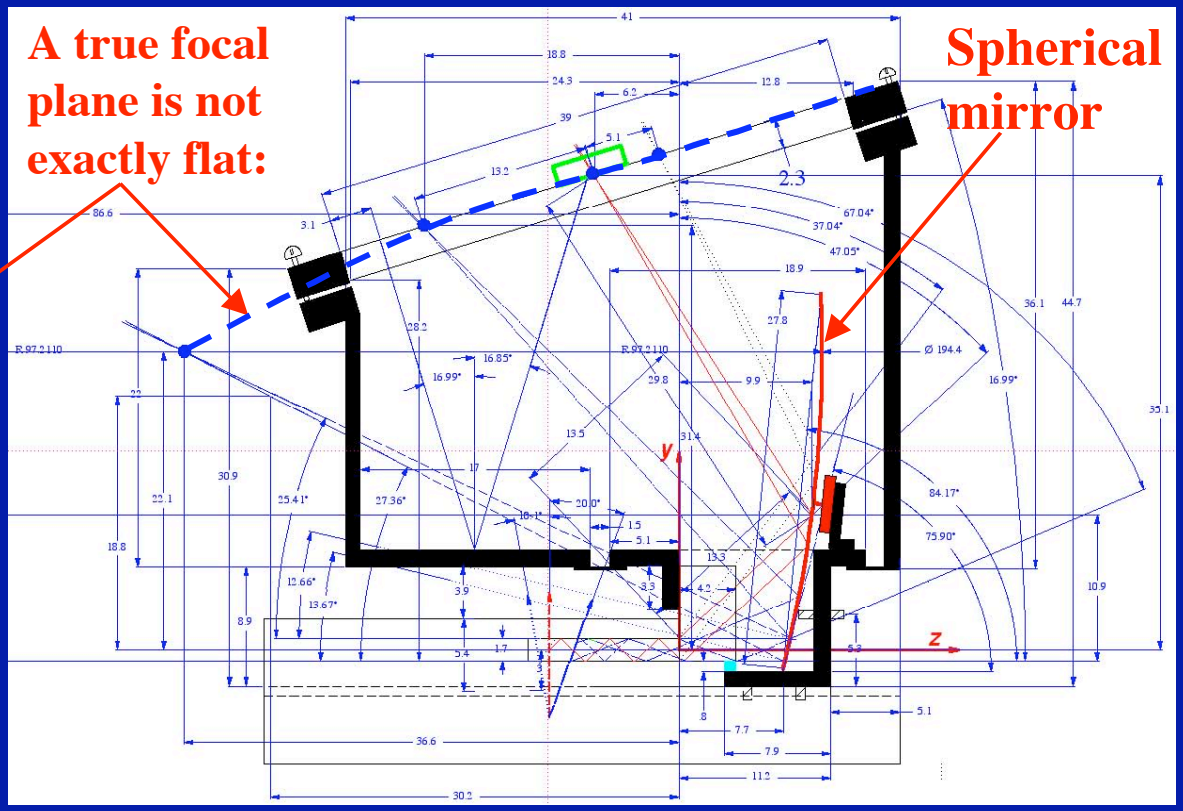
- **Both domains can be used to determine θ_c.**
- **FDIRC use time to resolve the forward-backward ambiguity, do chromatic corrections, reject the background, etc.**

FDIRC prototype optics design

J.Va'vra, "Simulation of the FDIRC Optics with Mathematica", SLAC-PUB-13464, Nov., 2008

A simulation of a focal surface shape with Mathematica program
(throw pairs of two parallel photons several dip angles And find their intersect in 2D):





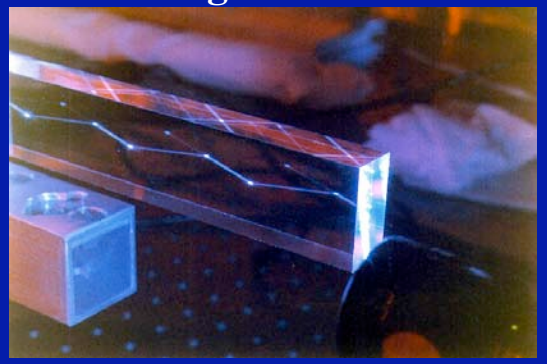
- **Use a drafting program Graphite, do ray-tracing by hand in 2D.**
- **Verify it with a ray tracing program in 3D.**
- **Verify the design with Geant 4 Monte Carlo simulation in 3D.**

Ray tracing in DIRC rectangular bar

J.Va'vra, "Simulation of the FDIRC Optics with Mathematica", SLAC-PUB-13464, Nov., 2008

An example a ray tracing code for photon propagation in a bar using the Mathematica program:

Laser image in the bar:



Mathematica code:

```
Label[bar];
 (Nev=1; Label[start];
x0 = 0; y0 = (0+Random[]*barh-barh/2); z0 = -barl/2;
zbarstart = - barl; zbarend = 0;
Theta = 90/(180/Pi); Phi = 90/(180/Pi);
Thetac = 47.3/(180/Pi); Phic = (180+Random[]*2*45-45)/(180/Pi);
kx = Cos[Phi]*(Cos[Theta]*Sin[Thetac]*Cos[Phic] + Sin[Theta]*Cos[Thetac]) - Sin[Phi]*Sin[Thetac]*Sin[Phic];
ky = Sin[Phi]*(Cos[Theta]*Sin[Thetac]*Cos[Phic] + Sin[Theta]*Cos[Thetac]) + Cos[Phi]*Sin[Thetac]*Sin[Phic];
kz = Cos[Theta]*Cos[Thetac] - Sin[Theta]*Sin[Thetac]*Cos[Phic];
l = Abs[(zbarend - z0)/kz];
xend=x0+(zbarend-z0)*kx/kz;
yend=y0+(zbarend-z0)*ky/kz;
nx=Round[xend/barw];
ny=Round[yend/barh];
If[l>0, path=(zbarend-z0)*Sqrt[(kx/kz)^2+(ky/kz)^2+1], path=(2*barl-zbarend)*Sqrt[(kx/kz)^2+(ky/kz)^2+1]];
t= Sqrt[1-1/nrefr^2];

Do[x=xend-barw*i; If[Abs[x]< barw&&Abs[kx]<t&&Abs[ky]<t&&i==nx, xbarexit[Nev]=x], {i, 0, 200, 2}];
Do[x=xend-barw*i; If[Abs[x]< barw&&Abs[kx]<t&&Abs[ky]<t&&i==nx, xbarexit[Nev]=x], {i, -2, -200, -2}];
Do[x=barw*i-xend; If[Abs[x]< barw&&Abs[kx]<t&&Abs[ky]<t&&i==nx, xbarexit[Nev]=x], {i, 1, 199, 2}];
Do[x=barw*i-xend; If[Abs[x]< barw&&Abs[kx]<t&&Abs[ky]<t&&i==nx, xbarexit[Nev]=x], {i, -1, -199, -2}];
Do[y=yend-barh*i; If[Abs[y]< barh&&Abs[kx]<t&&Abs[ky]<t&&i==ny, ybarexit[Nev]=y], {i, 0, 200, 2}];
Do[y=yend-barh*i; If[Abs[y]< barh&&Abs[kx]<t&&Abs[ky]<t&&i==ny, ybarexit[Nev]=y], {i, -2, -200, -2}];
Do[y=barh*i-yend; If[Abs[y]< barh&&Abs[kx]<t&&Abs[ky]<t&&i==ny, ybarexit[Nev]=y], {i, 1, 199, 2}];
Do[y=barh*i-yend; If[Abs[y]< barh&&Abs[kx]<t&&Abs[ky]<t&&i==ny, ybarexit[Nev]=y], {i, -1, -199, -2}];
If[OddQ[nx], kx = -kx, kx = kx];
If[OddQ[ny], ky = -ky, ky = ky];
dircosx[Nev] = kx;
dircosy[Nev] = ky;
dircosz[Nev] = kz;
nbouncex[Nev] = Abs[nx];
nbouncey[Nev] = Abs[ny];
Nev=Nev+1; If[Nev<2000, Goto[start]])
```

Particle direction: θ and ϕ

Cherenkov photon emission point: x_0, y_0, z_0 with polar and angles θ_c and ϕ_c

Direction cosines in the bar system:

$$\vec{k} = \begin{pmatrix} k_x \\ k_y \\ k_z \end{pmatrix} = \begin{pmatrix} \cos\phi(\cos\theta\sin\theta_c\cos\phi_c + \sin\theta\cos\theta_c) - \sin\phi\sin\theta_c\sin\phi_c \\ \sin\phi(\cos\theta\sin\theta_c\cos\phi_c + \sin\theta\cos\theta_c) + \cos\phi\sin\theta_c\sin\phi_c \\ \cos\theta\cos\theta_c - \sin\theta\sin\theta_c\cos\phi_c \end{pmatrix}$$

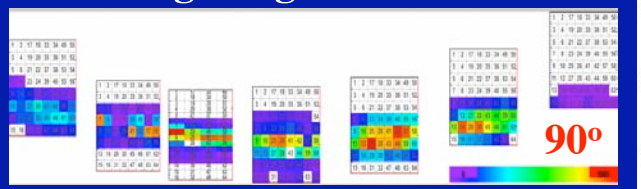
- **Mathematica code describes a photon bouncing in the rectangular bar.**

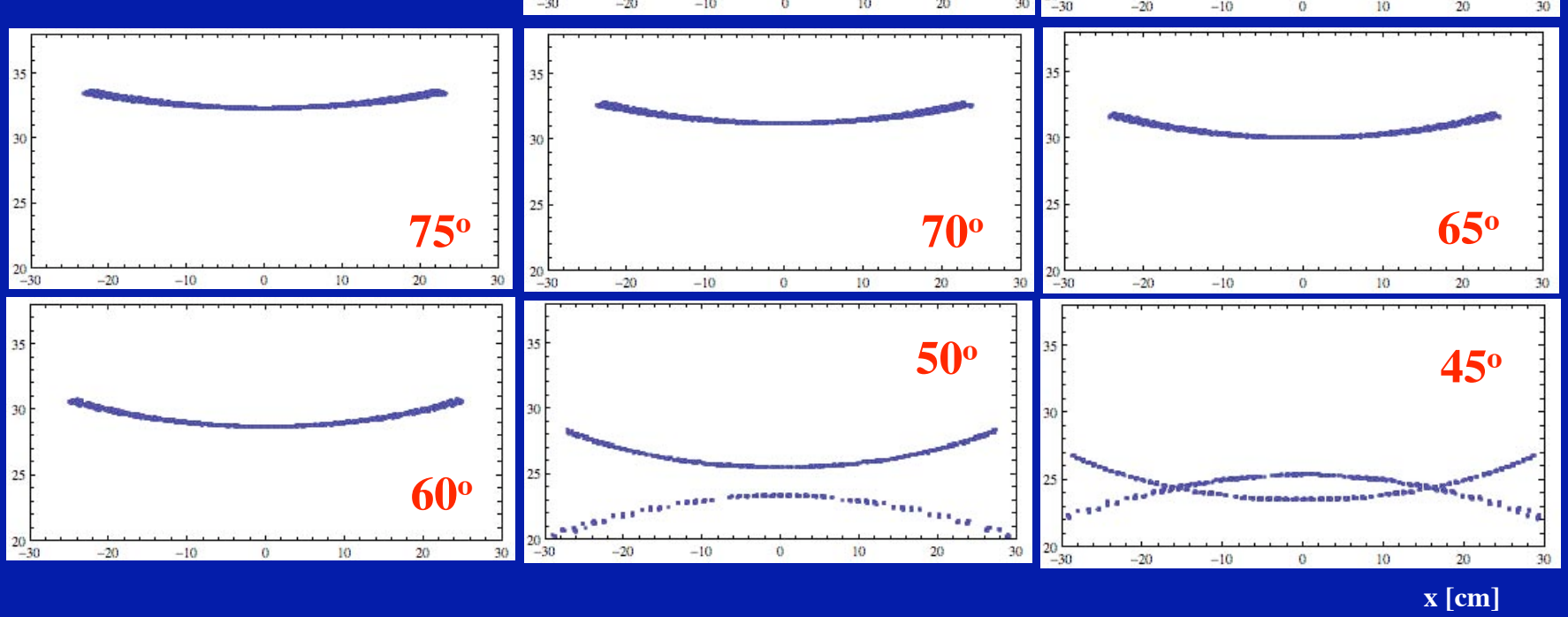
Cherenkov ring image for FDIRC prototype = $f(\theta_{dip})$

J.Va'vra, "Simulation of the FDIRC Optics with Mathematica", SLAC-PUB-13464, Nov., 2008

Calculated images in the flat detector plane located in the mirror's focus:

Real ring image in the beam:

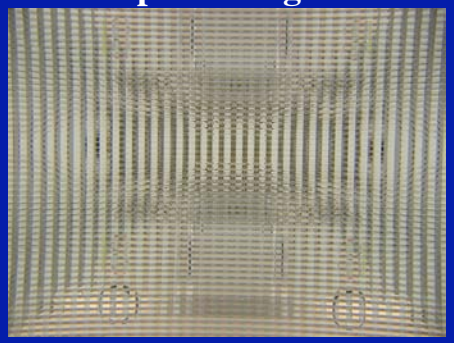




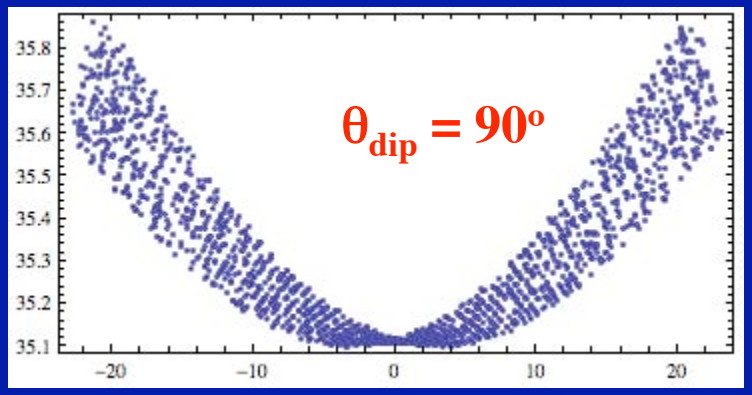
Zoom into the details of the Cherenkov ring image

J.Va'vra, "Simulation of the FDIRC Optics with Mathematica", SLAC-PUB-13464, Nov., 2008

Kaleidoscope looking into a bar:

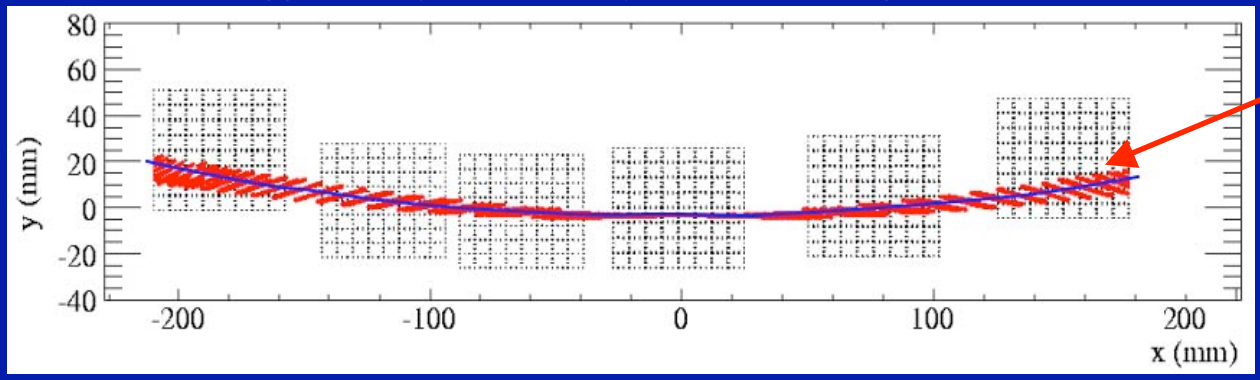


y [cm] Mathematica code image from a track with θ_{dip} = 90°:



x [cm]

Another view at wiggles - they affect mostly Cherenkov wings;:



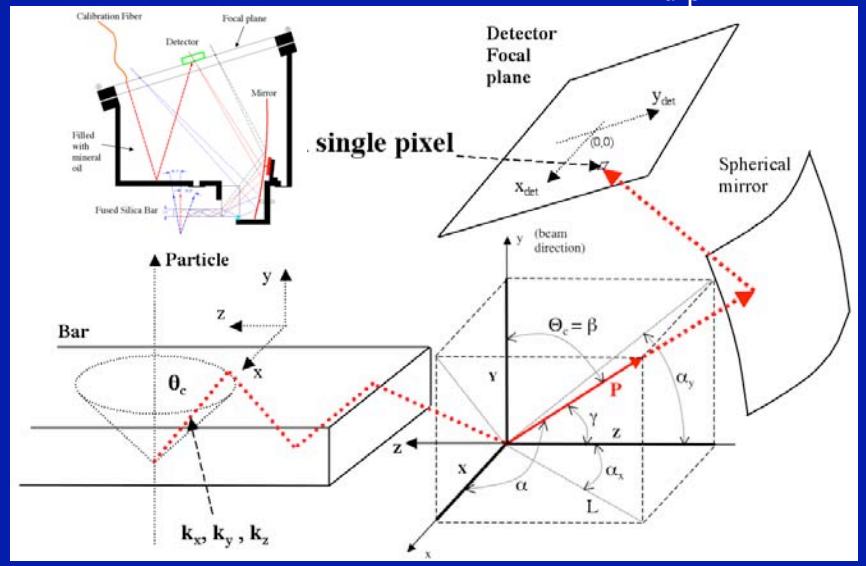
Wiggles: major contribution to θ_c resolution

- **<u>Kaleidoscopic wiggles</u> in image come from the bar rectangular bar structure.**
- **One would see this structure only if a detector would have a very high resolution.**
- **Could one correct them analytically ?**

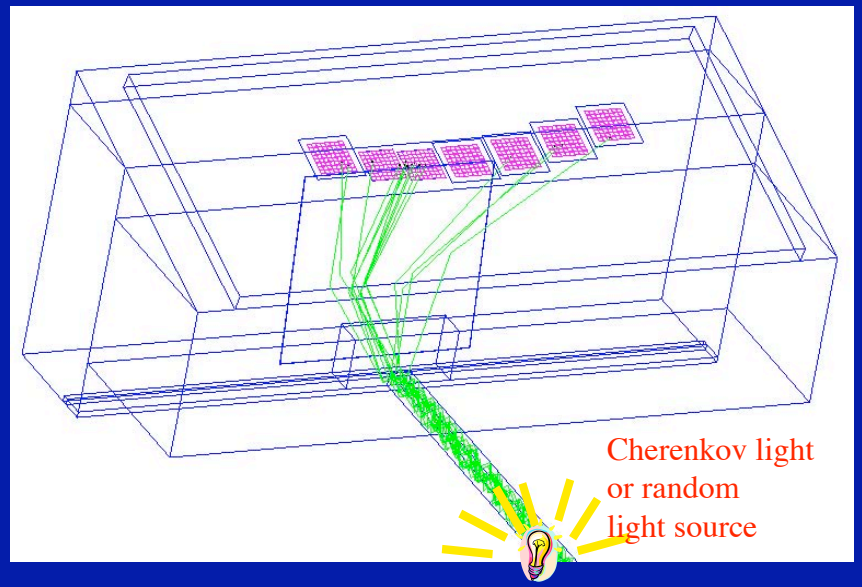
Focusing DIRC prototype pixel reconstruction

J. Vavra, "FDIRC prototype design" log book, page 129; G4 simulation by I. Bedajanek

Prototype coordinate systems - $\theta_{dip} = 90^o$:



kx,ky,kz determined from Geant 4 simulation:



- **<u>Each detector pixel</u> has a unique assignment of k_x,k_y,k_z for average λ :**

$k_x = \cos\alpha$, $k_y = \cos\beta$, $k_z = \cos\gamma$ - photon direction cosines

$\cos\theta_c = k_y$, θ_c - Cherenkov angle => $m = p\sqrt{(n^2\cos^2\theta_c - 1)}$, if p is known from tracking

L_{path} (direct) = $z_{particle\ position} * \sqrt{[(k_x / k_z)^2 + (k_y / k_z)^2 + 1]}$ - Photon path length in bar #1

L_{path} (indirect) = $(2*L_{bar} - z_{particle\ position}) * \sqrt{[(k_x / k_z)^2 + (k_y / k_z)^2 + 1]}$ - Photon path length in bar #2

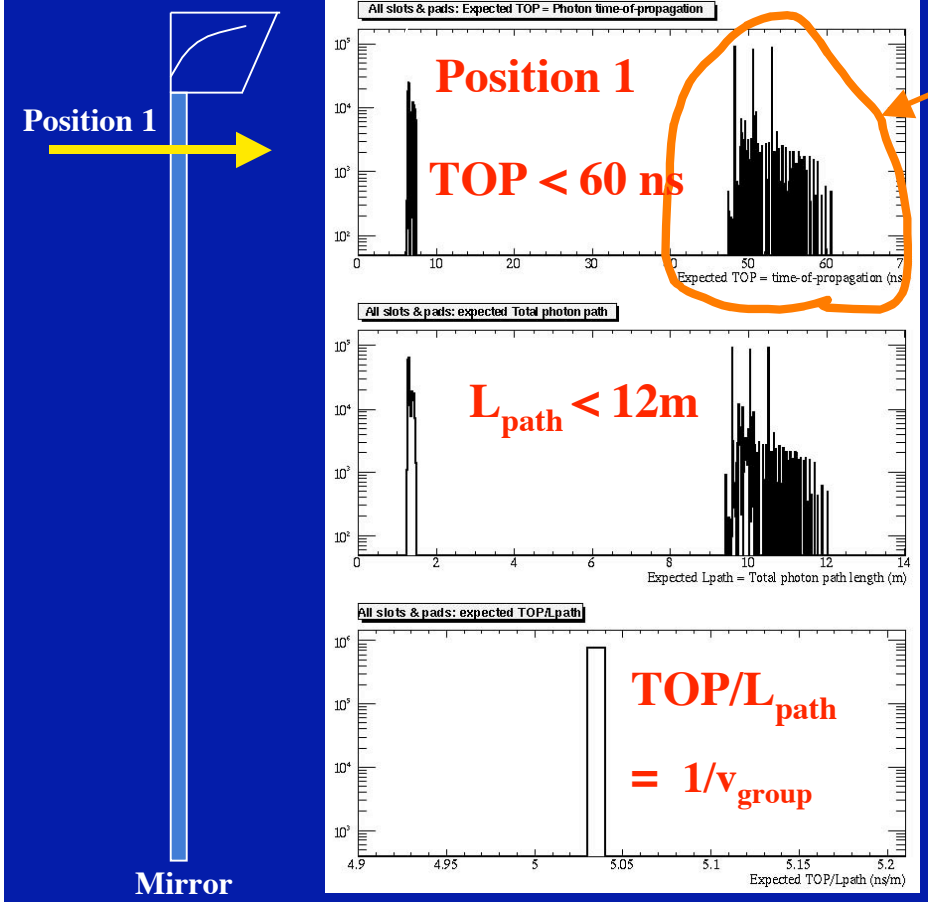
TOP = $L_{path} / v_g = L_{path}\, n_g / c = L_{bar}\, n_g/(k_z\, c)$ - time-of-propagation in bar

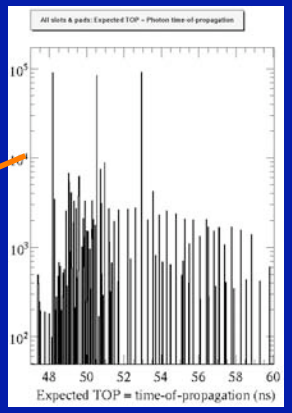
$N_{bounces} = n_x + n_y = L_{path} /[bar_{width}\, abs(k_z / k_x)] + L_{path} /[bar_{height}\, abs(k_z / k_y)]$ - number of photon bounces

$\Delta TOP = (TOP_{measured} - TOP_{expected})$

J.V., "Beam test FDIRC" log book #5, page 19-33, 2008, Run 4, position 1, 10GeV e^-

Expected distributions:

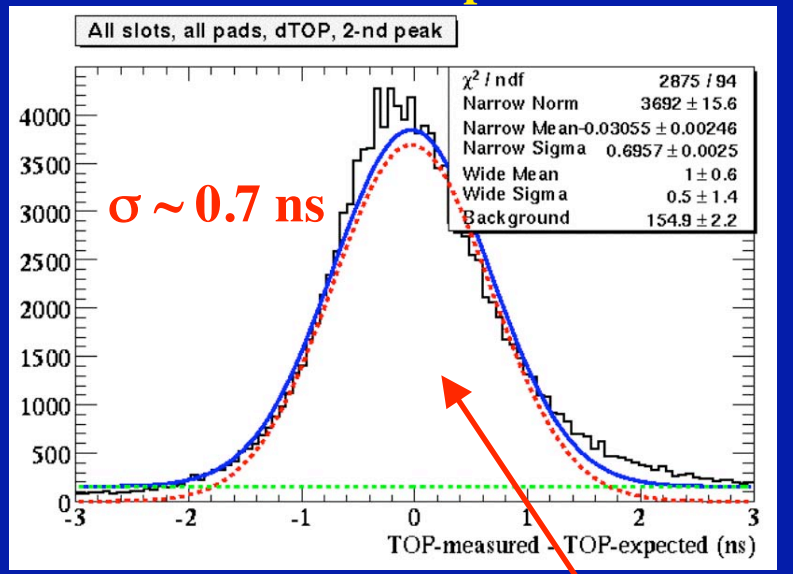




$TOP_{expected}$

Although the TOP distribution is very broad, ΔTOP is narrow

Measured - Expected:



$\Delta TOP = (TOP_{measured} - TOP_{expected})$ is dominated by the chromatic broadening

Overall detection efficiency = f(λ) and its dependency on various variables

-We need this to determine:

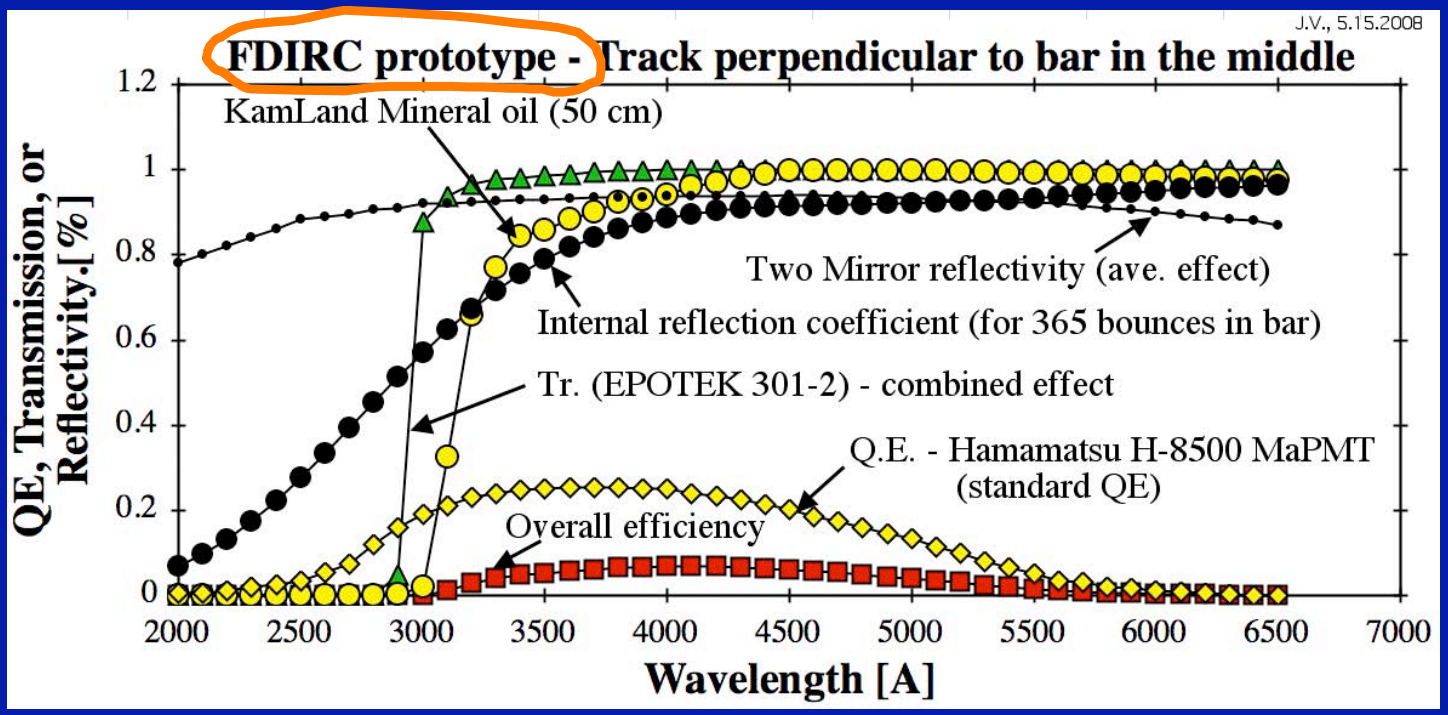
a) Chromatic effects

b) Number of photoelectrons Npe

c) Effect of each material used in the detector

FDIRC prototype: efficiency = f(λ)

J.V., "No-FDIRC.xls" spreadsheet, 2008

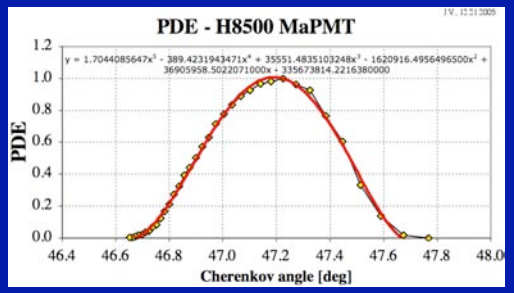


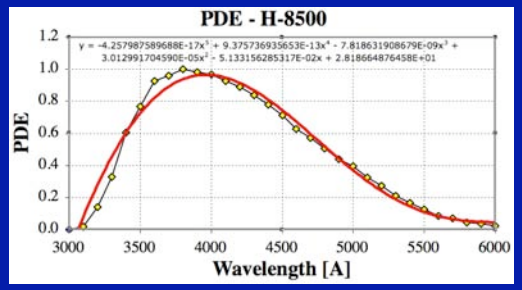
- **This defines a bandwidth (BW) of the detector:**
  (Larger the BW, larger Npe, but also a larger the chromatic broadening)
- **$N_o \sim 33\ cm^{-1}$, L = 1.7 cm, $\theta_{dip} = 90^o$, middle of bar**
- **Npe ~ $370\ L \int \varepsilon(E) \sin^2 \theta_c\ dE \sim 30$ photoelectrons**

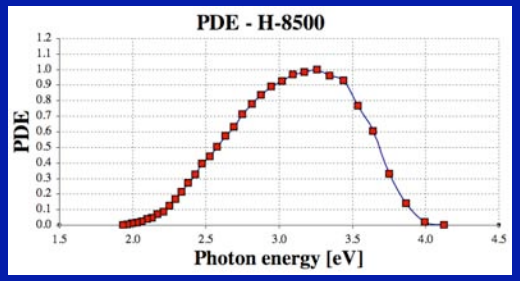
FDIRC prototype: PDE = f(various variables)

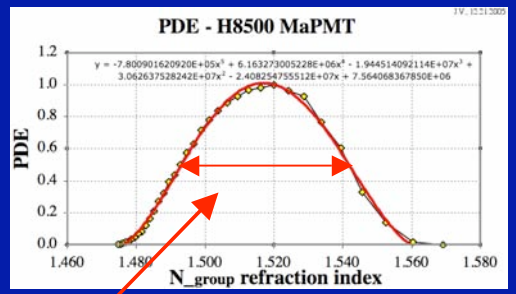
J.V. , "Focusing DIRC design.xls" spreadsheet

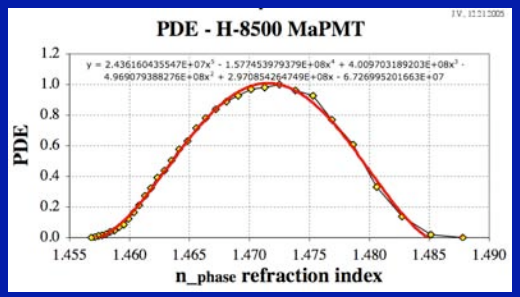
H-8500 MaPMT with super Bialkali, θ_{dip} = 90°, Lpath = 7 m, DIRC quartz bar

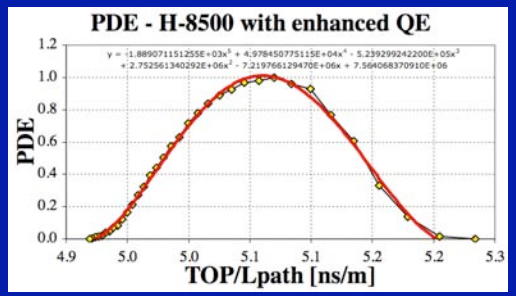




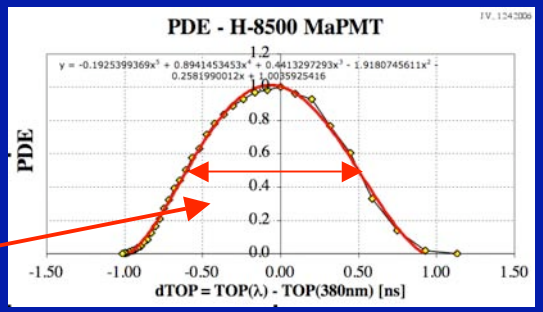


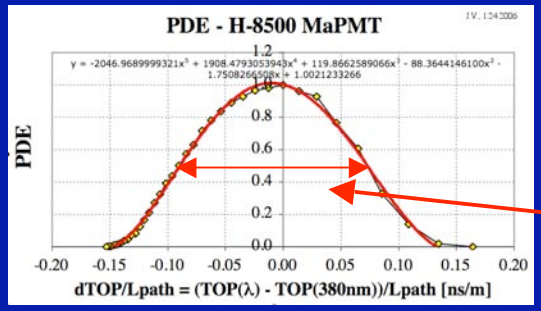






For Bialkali: $\sigma(n_g)/n_g \sim 0.013$





σ(TOP/Lpath) ~ 60 ps/m

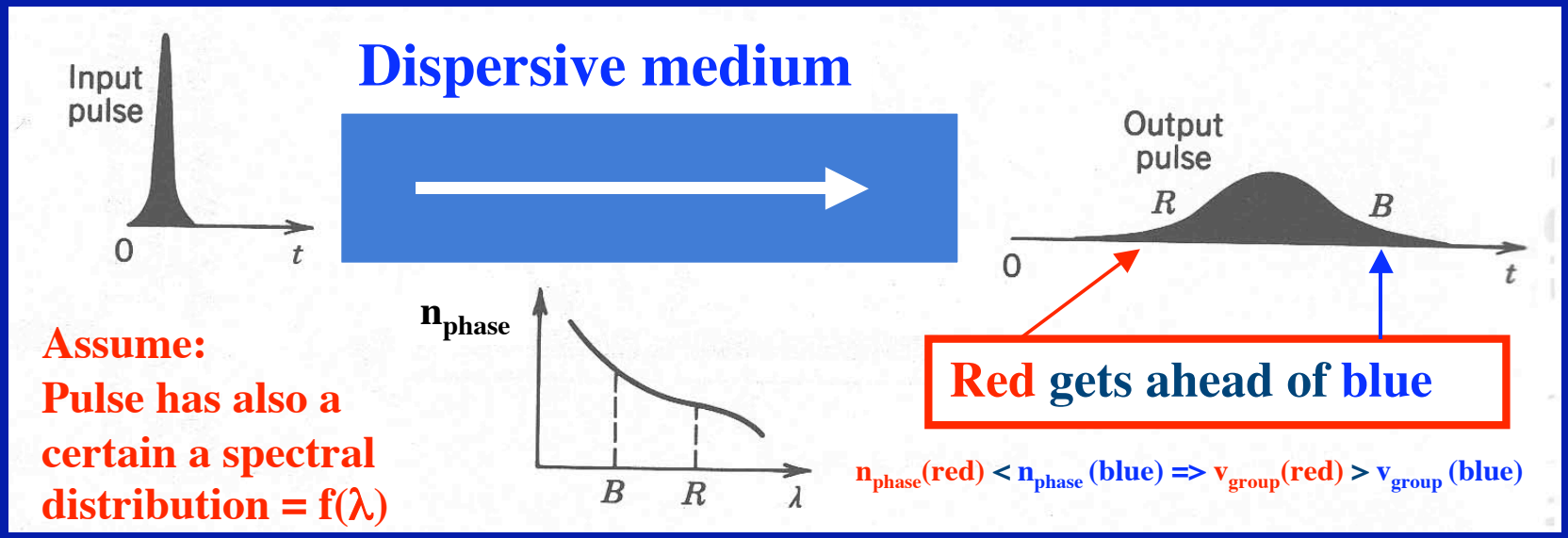
σ(TOP) ~ 500 ps for Lpath = 7m

PDE = Probability detection efficiency

Chromatic effects in FDIRC prototype

- Chromatic broadening of a light pulse in dispersive medium
- Example of ΔTOP & ΔTOP/Lpath in FDIRC data
- Chromatic correction in practice
- Final effect on data

Chromatic dispersion of light impulse



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

$$t \equiv TOP = L_{path} / v_{group} = L_{path} [n_{phase} - \lambda * dn_{phase}/d\lambda] / c \quad = \text{time-of-propagation}$$

$$\boxed{dt = L \ \lambda \ d\lambda / c * |- d^2 n_{phase}/d\lambda^2|}$$

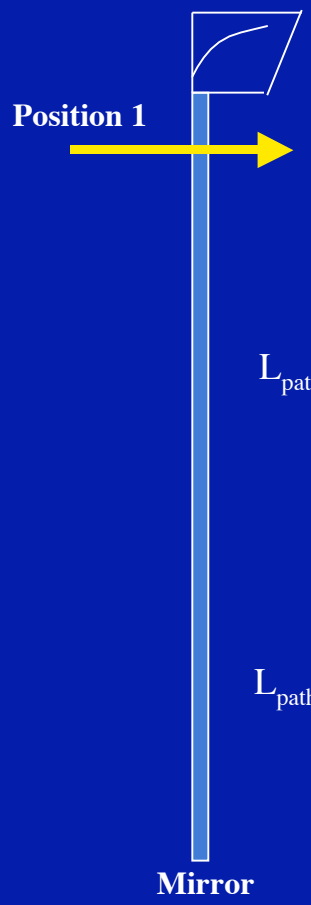
dt is pulse dispersion, fiber length **L**, wavelength bandwidth **dλ**, refraction index **n(λ)**,
n_g is typically a few % larger than **n** for photons in a Bialkali photocathode wavelength range

- **Chromaticity of the mefium can easily dominate the timing resolution.**

Chromatic broadening observed clearly in FDIRC prototype

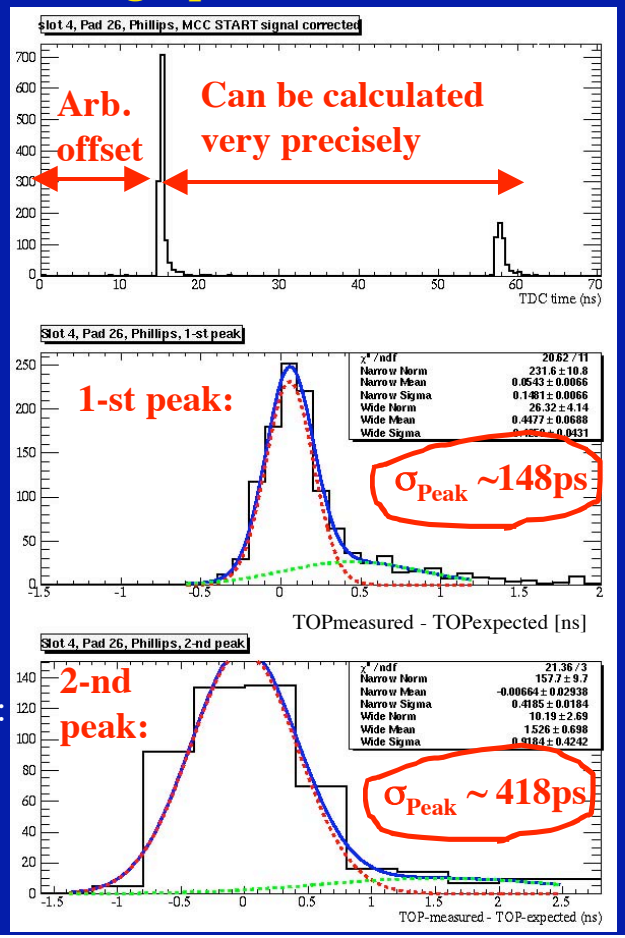
J.V., "Beam test FDIRC" log book #5, page 19-33, 2008, Run 4, position 1, 10GeV e^-

Slot 4, **single pixel** time distribution:



L_{path} ~ 1-1.5 m:

L_{path} ~ 10-12 m:



$$TOP = L_{path}\, n_{group}/c$$

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

One can clearly observe the chromatic time broadening as a function of photon path length

$$TOP\_expected = TOP_{bar\_expected} + TOP_{focusing\_piece} + t0_{TTS,\ cables,\ electronics,\ etc.}$$

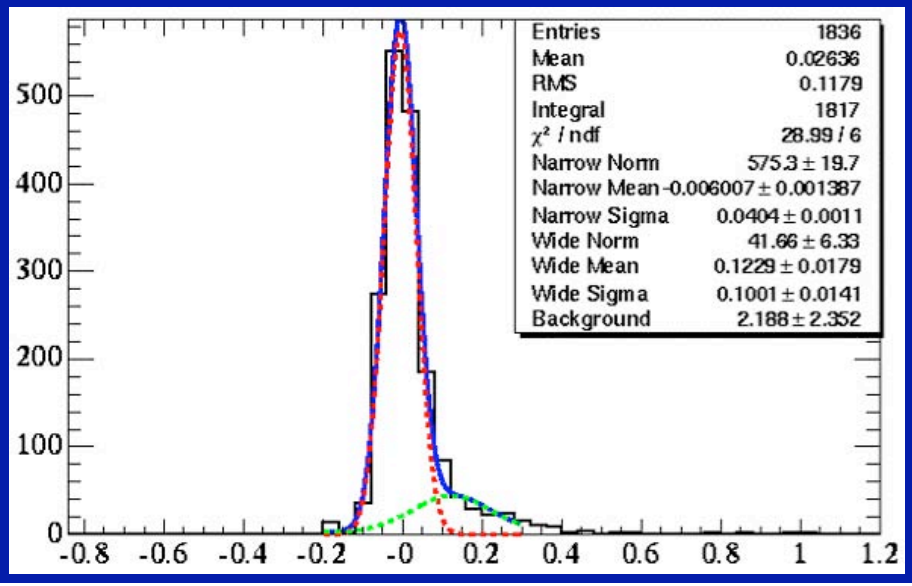
ΔTOP = TOP_measured - TOP_expected [ns]

Note: In a real experiment $TOP\_expected = TOP_{bar\_expected} + TOP_{focusing\_piece} + TOF_{track} + t0_{bunch\ length,\ TTS,\ electronics,\ etc.}$

Example of Chromatic growth in FDIRC prototype

$$TOP = L_{path}\, n_{group}/c \;\; \Rightarrow \;\; \sigma_{TOP}/TOP \sim \sqrt{[(\sigma_{Lpath} / L_{path})^2 + (\sigma_{ng} / n_g)^2]}$$

FDIRC prototype beam test data analysis:



Measured chromatic growth rate: ~ 40ps/m

$$\Delta TOP/Lpath = (TOP_{measured} - TOP_{expected})/Lpath \text{ [ns/m]}$$

- **This time dispersion growth rate is bad for the TOF counters, however, we can use it to correct the chromatic dispersion of θ_c angle.**
- **We can call it "tagging color by time".**

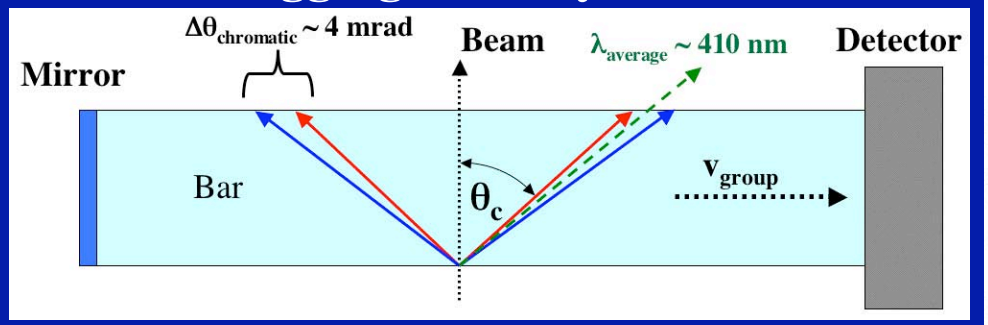
Correlation of "$d\theta_c$ vs dTOP/Lpath" to do the chromatic correction

J.F. Benitez, I. Bedajanek, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff. K. Suzuki, J. Schwiening, J. Uher and J. Va'vra, "Development of a Focusing DIRC," IEEE Nucl.Sci, Conf. Rec., October 29, 2006, and SLAC-PUB-12236, 2006 and SLAC-PUB-12803, 2007

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

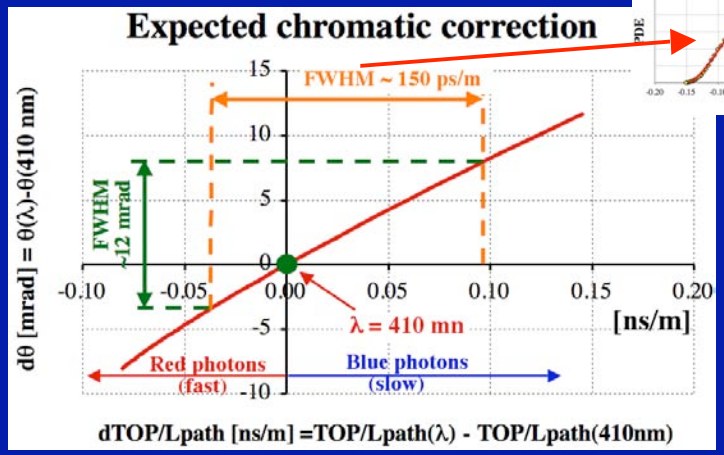
Propagation of photons is controlled by n_{group} ($v_{group} = c_0/n_{group} = c_0/[n_{phase} - \lambda * dn_{phase}/d\lambda]$): v_{group}(red) > v_{group} (blue)

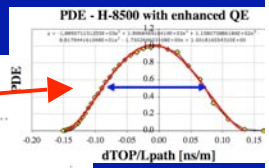
Tagging color by time:



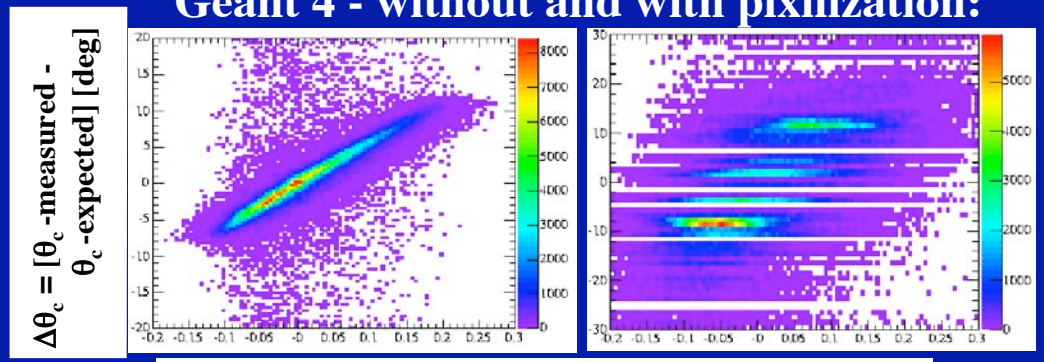
$TOP / Lpath = 1/v_{group}(\lambda)$

Excel calculation:



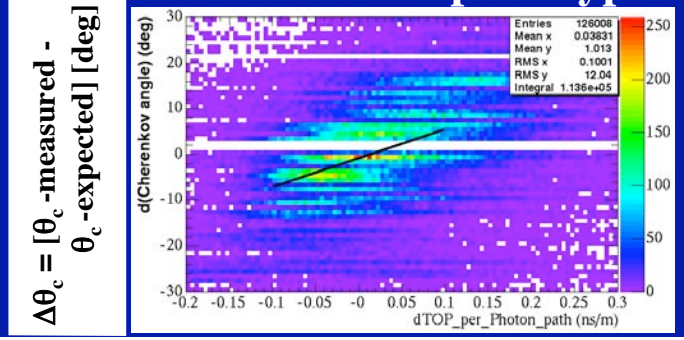


Geant 4 - without and with pixilization:



$\Delta TOP/Lpath = (TOP(\lambda) - TOP(\sim 400nm)/Lpath$ [ns/m]

Data from the prototype:



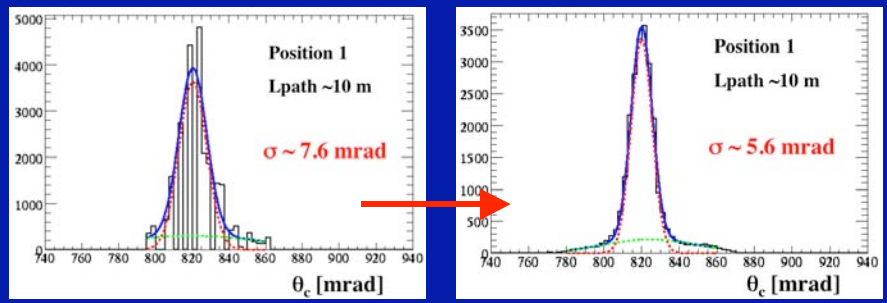
$\Delta TOP/Lpath = (TOP_{measured} - TOP_{expected})/Lpath$ [ns/m]

Chromatic correction

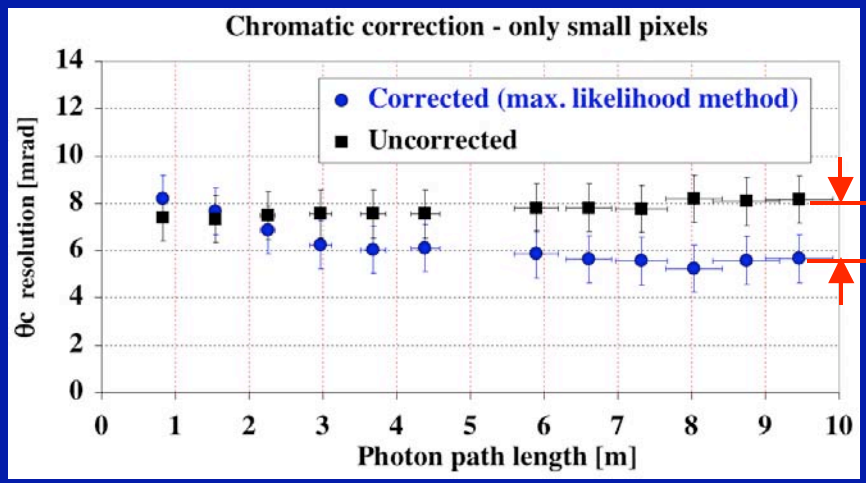
J.F. Benitez, I. Bedajanek, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff. K. Suzuki, J. Schwiening, J. Uher and J. Va'vra, "Development of a Focusing DIRC," IEEE Nucl.Sci, Conf. Rec., October 29, 2006, and SLAC-PUB-12236, 2006 and SLAC-PUB-12803, 2007

FDIRC prototype beam test data - example of 3mm pixels only:

Correction off: **Correction on:**



To be able to do this one has to measure the photon timing to σ ~200 ps



$\sigma \sim \sqrt{(8^2 - 6^2)} \sim$ ~ 5.3 mrad (consistent with expectation for the chromatic error)

- **The chromatic correction starts working for Lpath > 2-3 meters. Since bar penetrates the magnet, it is already 1-2m longer, so this correction will help.**
- **This is the first RICH detector ever to do the chromatic correction by timing !!!**

Example: Errors for FDIRC prototype

J. Va'vra, Based on test beam results with 3 mm pixels

Angular errors:

- **Cherenkov angle $\Delta\theta_c$ (3mm pixels)**

Imaging:

$\Delta\theta_{\text{bar size}} \sim 0$ mrad *

$\Delta\theta_{\text{3mm pixel size}} \sim 2.5\text{-}3$ mrad *

Photon propagation in bar:

$\Delta\theta_{\text{Photon transport in bar}} \sim 2\text{-}3$ mrad

Ring fringes due to rectangular bars:

$\Delta\theta_{\text{Photon transport in bar}} \sim 0\text{-}9$ mrad

External tracking:

$\Delta\theta_{\text{Track direction}} \sim 1$ mrad

Cherenkov ring production:

$\Delta\theta_{\text{Track multiple scattering in bar}} \sim 1$ mrad

$\Delta\theta_{\text{Chromatic}}$ (Lpath) $\sim 2 - 5.5$ mrad *

Total:

$\Delta\theta_{\text{Total expect}} \sim 6 - 7$ mrad *

Timing errors in test beam:

- **ΔTOP:**

Detector:

$\Delta TOP_{\text{MaPMT TTS}} \sim 150$ ps *

$\Delta TOP_{\text{TDC}} \sim 100/\sqrt{12} \sim 30$ ps *

External trigger:

$\Delta TOP_{\text{Trigger \& DCH to}} \sim 50$ ps *

External tracking:

$\Delta TOP_{\text{Track TOF}} \sim$ negligable

Bunch length:

$\Delta TOP_{\text{Bunch length}} \sim$ negligable

Total:

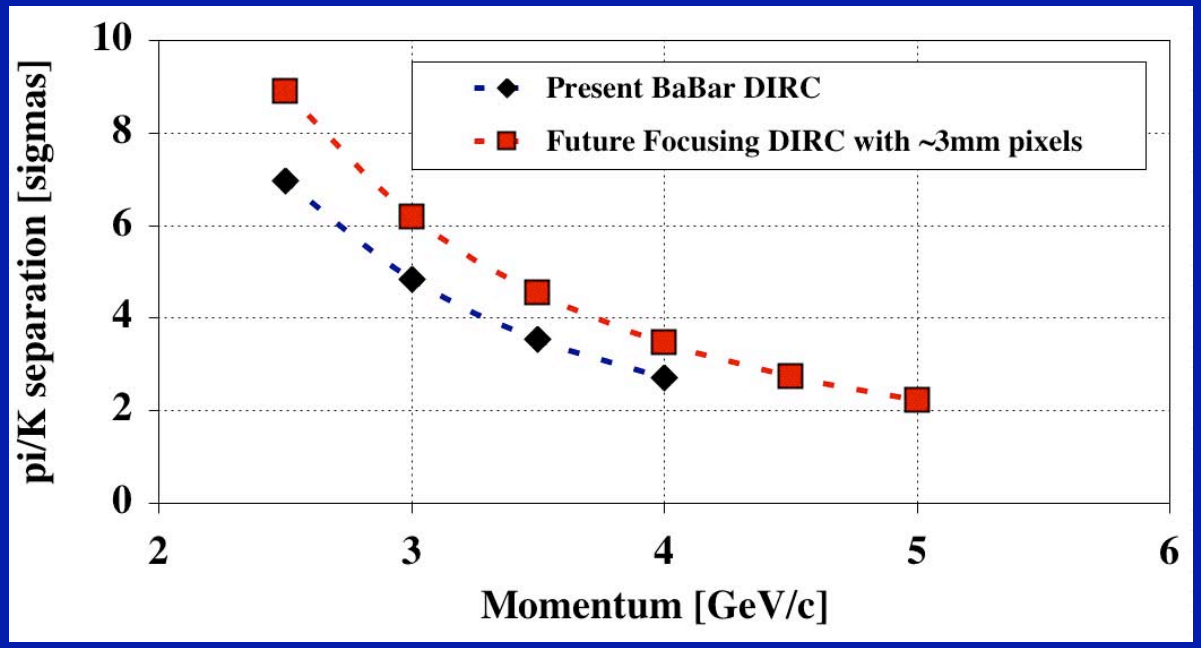
$\Delta TOP_{\text{Total expect}} \sim 200$ ps *

* **Improved compared to BaBar DIRC**

Expected final performance at incidence angle of 90°

J.F. Benitez, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff. J. Schwiening, J. Va'vra, L. Ruckman, and G.S. Varner, Nucl. Instr. & Meth., A595(2008)104-107

Expected performance of a final device:



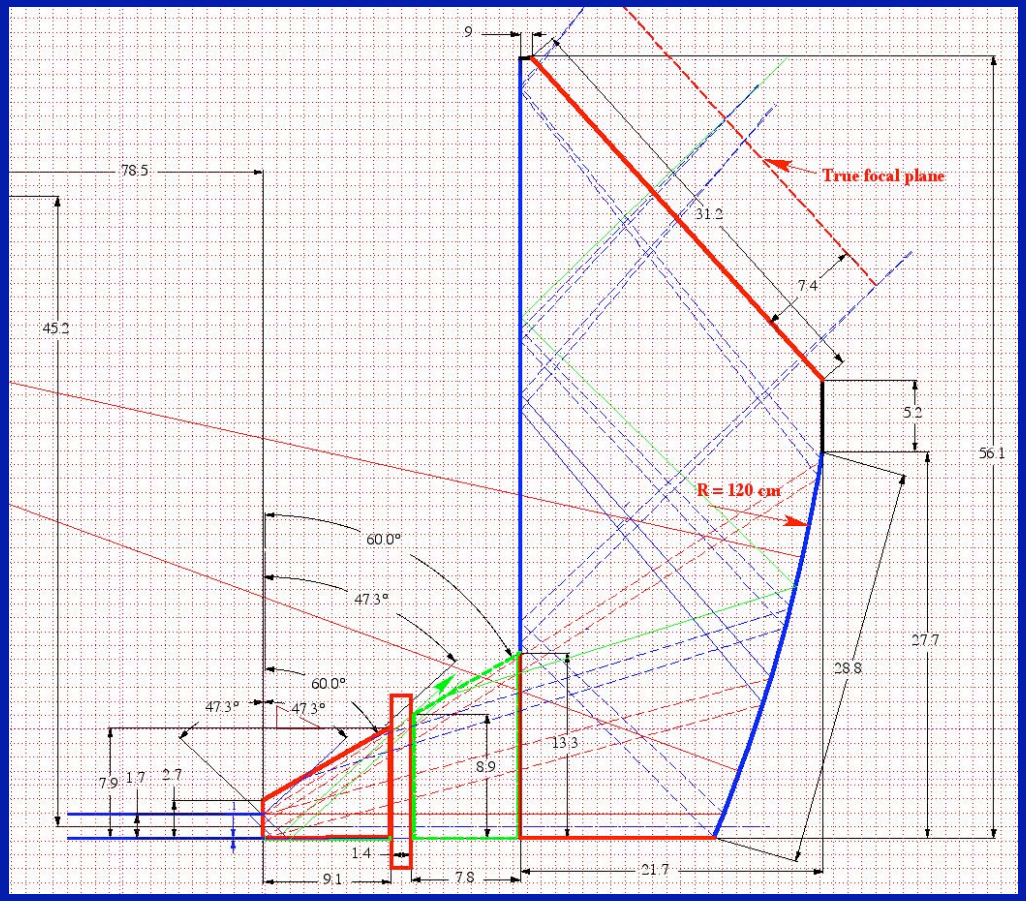
- Prototype's **Npe(measured)** and **Npe(expected)** are consistent within **~20%.**
- **BaBar DIRC design with ET PMTs**: **No ~ 30 cm^{-1}**, and **Npe ~ 27**.
- **SuperB with Hamamatsu H-9500 MaPMTs**:

  We expect **No ~ 31 cm^{-1}**, which in turn gives **Npe ~ 28** for 1.7cm-thick fused silica bar, and better performance in **pi/K** separation than the present BaBar DIRC.

SuperB FDIRC

Going for preliminary quotes to get a feel for the cost and a difficulty to make it

J. Va'vra, SLAC-PUB-13763, 2009



BaBar:

- BaBar wedge was designed for pin hole focusing and 1.2 m distance to PMTs. The wedge was not designed for a focusing optics.

SuperB:

- Add a micro-wedge to remove a 6 mrads angle at the wedge bottom.
- Add another wedge to rotate all photons pointing up and direct them better to the cylindrical mirror.
- Use double-folded mirror optics to stay away from the magnet, and have a good access to detectors.
- Use underfocusing to reduce the size.
- **The entire detector has ~30,000 pixels, using either H-9500 or H-9500 MaPMTs.**
- **MC program prediction: $\sigma_{\theta c}$ ~ 9mrads, without the chromatic correction, which could reduce the resolution further by 1-2 mrads.**
- **We now have a mechanical design and the first quotes for the optical piece - it is doable and affordable.**

Read more about the FDIRC work

- Benitez, I. Bedajanek, D.W.G.S. Leith, G. Mazaheri, B.N. Ratcliff, K. Suzuki, J. Schwiening, J. Uher, and J. Va'vra, SLAC-PUB-12236, October 2006.
- J. Va'vra, J. Benitez, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff, J. Schwiening, and K. Suzuki, presented at Vienna conference, 2007; SLAC-PUB-12803, March 2007.
- J. Benitez, D.W.G.S. Leith, G. Mazaheri, B.N. Ratcliff, J. Schwiening, J. Va'vra, L. Ruckman, and G. Varner, Nucl. Inst. & Meth., A595(2008)104-107.
- J. Va'vra, "Simulation of the FDIRC optics with Mathematica", SLAC-PUB-13464, October, 2008.
- C. Field, T. Hadig, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff, J. Schwiening, J. Uher and J. Va'vra, "Development of photon detectors for a fast focusing DIRC," Nucl. Instr.&Meth., A553(2005)96-106.
- C. Field, T. Hadig, M. Jain, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff, J. Schwiening, and J. Va'vra, "Novel photon detectors for focusing DIRC prototype," Nucl. Instr.&Meth., A518(2004)565-568.
- J. Va'vra, "Focusing DIRC design for SuperB", SLAC-PUB-13763, October 2009

- **FDIRC prototype was the 1-st RICH detector ever to perform the chromatic correction by timing.**

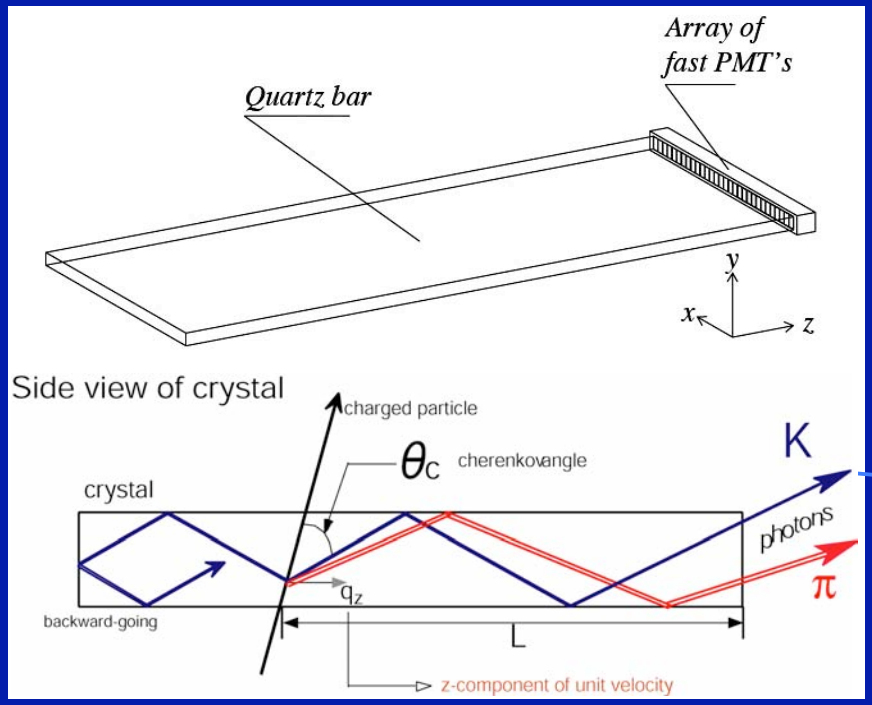
TOP counter

- Principle of TOP counter
- Chromatic effects
- TOP counter for Super Belle

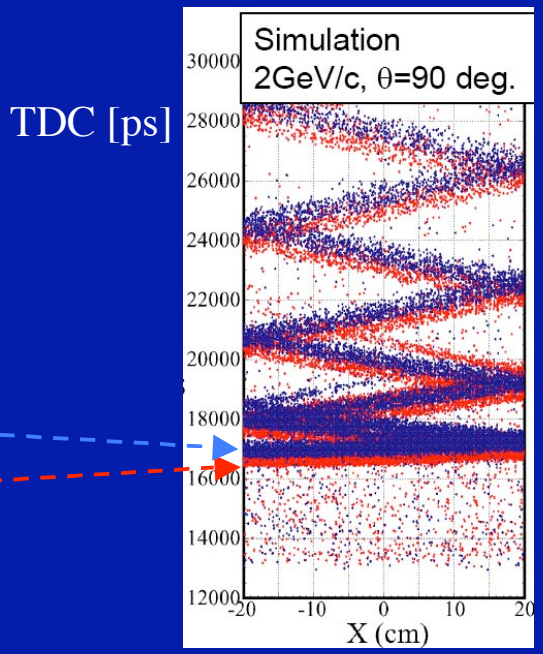
Principle of TOP counter

M. Staric, K. Inami, P. Krizan, T. Iijima, Nucl. Instr. & Meth., A595(2008)252,
M. Akatsu et al., Nucl. Instr. & Meth., A440(2000)124 and
K. Inami, RICH workshop, Giessen, Germany, 2009

TOP counter idea:



MC simulation of the Cherenkov ring and TOP distribution in a single pixel:



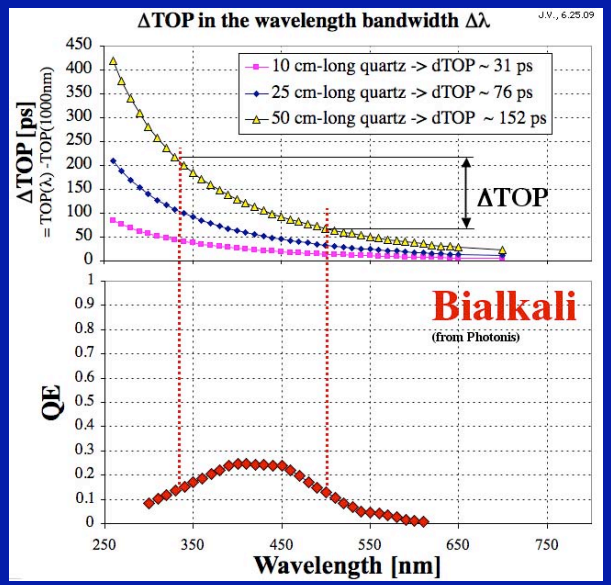
- **Initial version of TOP counter: Measure time very well (σ_{TTS}~ 35 ps) and the x-coordinate only (σ_x ~ 1.5mm). In addition measure t_o as best as possible, and track TOF.**
- **Will this simple scheme work ?**

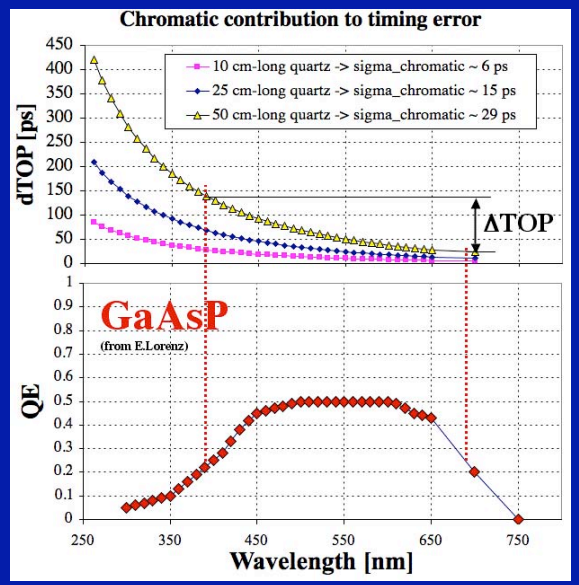
Chromatic broadening of TOP for different PC

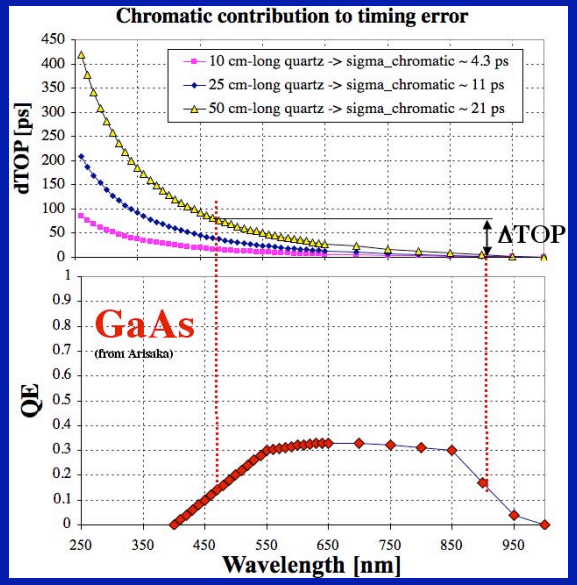
J.Va'vra, Q.E.&Tr&n - overall.xls spreadsheet

$$TOP(\Phi, \theta_c, \lambda) = [L_{total\ photon\ path}(\Phi, \theta_c)/[c/n_g(\lambda)], \text{ where } n_g = n_{phase} - \lambda * dn_{phase}/d\lambda$$

Determine TOP spread for three photon path lengths: 10, 25 and 50 cm:







$$\sigma_{Chromatic} \sim \Delta TOP/\sqrt{12}$$

- $\sigma_{Chromatic}$ gets smaller as λ gets more red.
- $\sigma_{Chromatic}$ ~ 5ps fro Lpath = 10 cm, and ~ 480ps for Lpath = 10 meters for GaAsP.

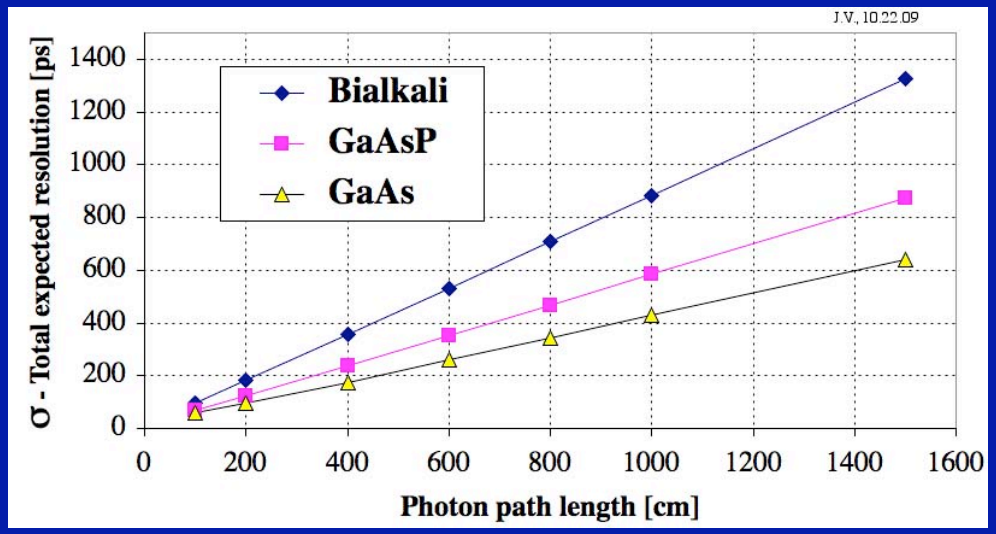
Chromatic error can dominate timing in TOP counter for long path lengths

J. Va'vra, TOF_counter_Npe.xls spreadsheet

$$\sigma_{Total} \sim \sqrt{[\sigma^2_{Electronics} + \sigma_{Chromatic}^2 + \sigma_{TTS}^2 + \sigma^2_{Track} + \sigma^2_{to}]}$$

$\sigma_{Electronics}$ - electronics contribution ~ 10 ps
$\sigma_{Chromatic}$ - chromatic term = f (photon path length) ~ 5 ps - 1.5 ns for path lengths 10cm - 15 meters
σ_{TTS} - MCP-PMT transit time spread ~ 35 ps
σ_{Track} - timing error due to track length L_{path} (poor tracking in the forward direction) ~ 5-10 ps
$\sigma_{t\,o}$ - start time dominated by the SuperB crossing bunch length ~ 20-25 ps at best

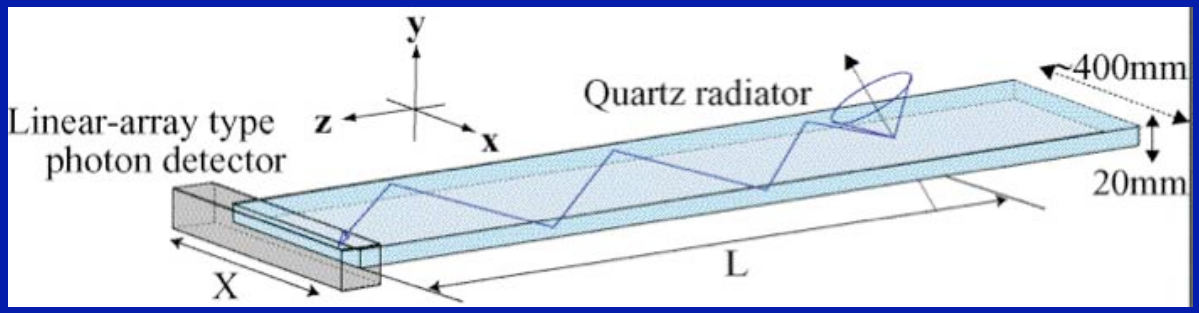
Expected final resolution:



- **Chromatic error dominates the timing resolution for long photon path lengths**
- **Red-sensitive photocathodes do help a lot. But they are difficult to make.**

TOP counter: measuring TOP only

(My naive simple estimate for pedagogical purpose only)



Assume:

4 GeV/c, n = 1.47, Total photon path in quartz = L_{path} ~ 2 meters,
SL-10 MCP-PMT with Bialkali or GaAsP photocathodes, σ_{TTS} (SL-10) ~ 40 ps

Cathode	ΔTOP = TOP(π) - TOP(K) After 2 meters	σ $(TOP)_{single\ photon}$ after 2 meters (dominated by chromaticity)	Npe Measured (from K.Inami)	σ $(TOP)_{track}$ = σ $(TOP)_{single\ ph}/\sqrt{Npe}$	Separation at θ_{dip} = 90° [TOP(π)- TOP(K)]/σ $(TOP)_{track}$ If we use it as a TOF counter only without imaging
Bialkali	~105 ps	~ 181 ps	~ 16	~ 45 ps	~ 2.3 sigmas
GaAsP	~105 ps	~ 123 ps	~ 16	~ 31 ps	~ 3.4 sigmas

- **PID with TOP measurement only works only for small photon path lengths.**
- **Bialkali PC is substantially worse than GaAsP PC.**

TOP counter: measuring x & TOP only

B. Ratcliff, ICFA Inst. Bulletin, http://www.slac.stanford.edu/pubs/icfa/spring01/paper2/paper2a.html, 2001

For $\theta_{dip} = 90^o$: $TOP = L_{path} / v_g = L_{path}\, n_g / c = L_{bar}\, n_g / (k_z\, c)$

$\tan \alpha_x = k_x / k_z$

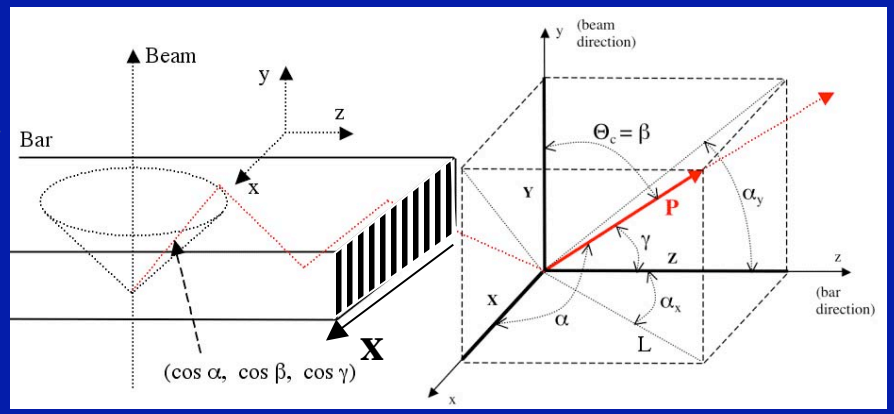
$\sin \theta_c = k_z * \sqrt{(\tan^2 \alpha_x + 1)}$

$k_x = \sin \phi_c \sin \theta_c$

$k_y = \cos \theta_c$

$k_z = \cos \phi_c \sin \theta_c$

Imaging with x & TOP:



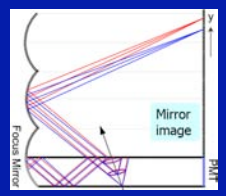
$$\sigma^2_{\theta c} \sim \tan^2 \theta_c \left[(\sigma(n_g)/n_g)^2 + (\sigma(TOP)/TOP)^2 + \sigma^2(\alpha_x) \tan^2 \alpha_x\right]$$

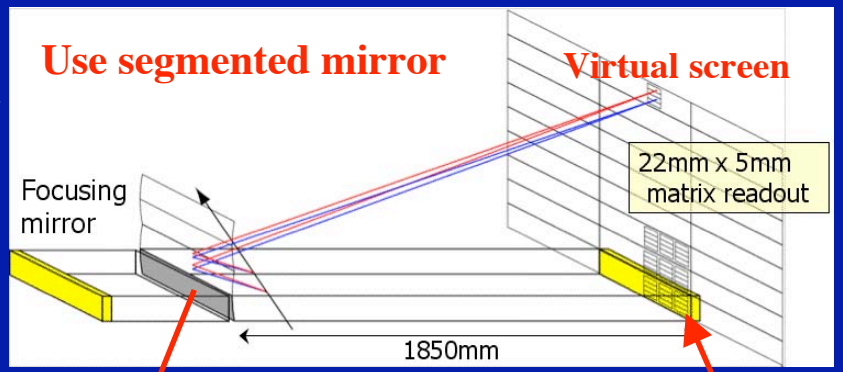
- **Is measuring TOP & α_x sufficient ?**
- Putting numbers into the above equation: $L_{path} = 2$ m, $\sigma_{TTS} \sim 40$ ps, $\sigma(n_g)/n_g \sim 0.013$ for Bialkali photocathode (see lecture I), $\sigma(TOP)/TOP \sim 0.0039$, and $\sigma(\alpha_x) \sim 0.005$, one obtains $\sigma_{\theta c} \sim 15$ mrads for Lpath > 1.5 meters.
- **<u>This is not good enough.</u> Therefore, proponents suggested: (a) use red-sensitive photocathodes, such as GaAsP, to reduce the chromatic error, (b) a UV filter to cut off low wavelengths, (c) add a mirror segmentation, which is a "cheap way" to do the y-pixillization (measurement of α_y).**

3 Solutions are being considered at present

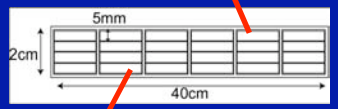
K. Inami, Giessen Cherenkov detector workshop, 5.11.2009

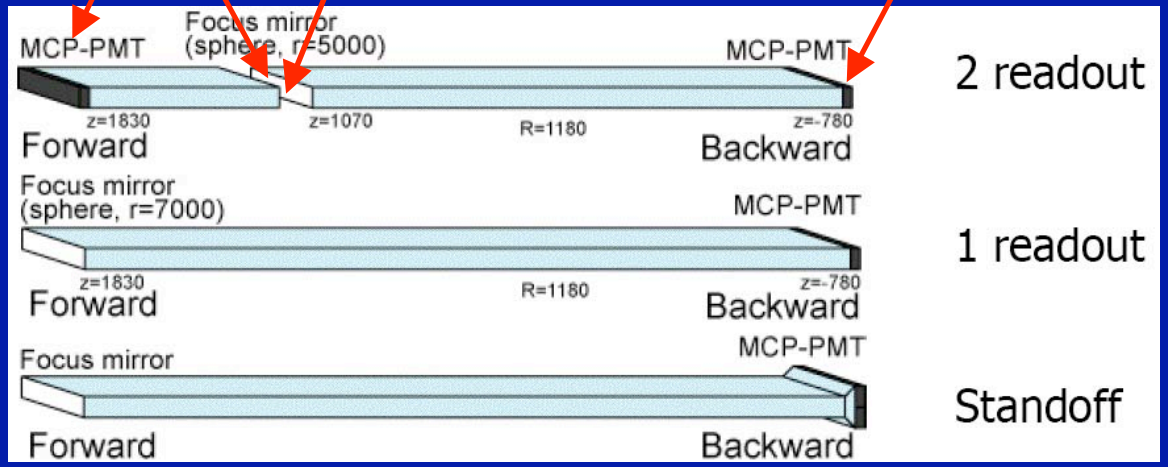
Segmented mirror:





SL-10:

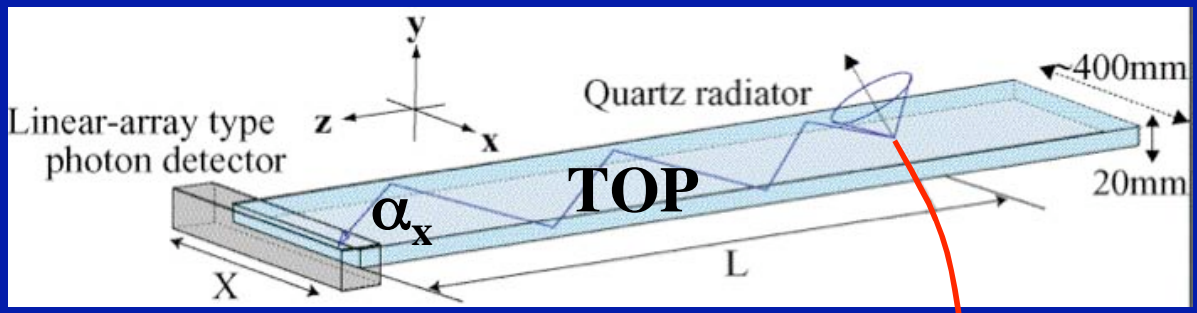




My comments:

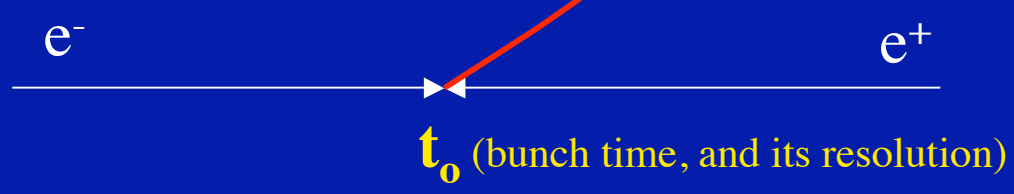
- **The segmented mirror produces the same effect as the "pixelized FDIRC," but with much smaller number of pixels. They work on backward going photons only.**
- **To make the TOP counter to work as a TOF counter in the forward direction, they have to achieve $\sigma_{TTS} \sim 40$ps and $\sigma_{to} \sim 25$ps. A very tall order !! This is, however, essential to achieve a similar performance as FDIRC.**
- **My worry would be a possible rate load on a single pixel. FDIRC will share this load among 30,000 pixels.**
- **Proponents proposed GaAsP PC. Very difficult and expensive photocathode to consider.**
- **UV filters are fine, but one is also losing signal, which may be a problem in a high background environment.**

PID in TOP counter is a complicated likelihood function of these variables: TOF, TOP, TTS, UV filter, α_x , α_y, t_o, p, θ_{track}



TOF of a track

(plays an important part for tracks close to detector)

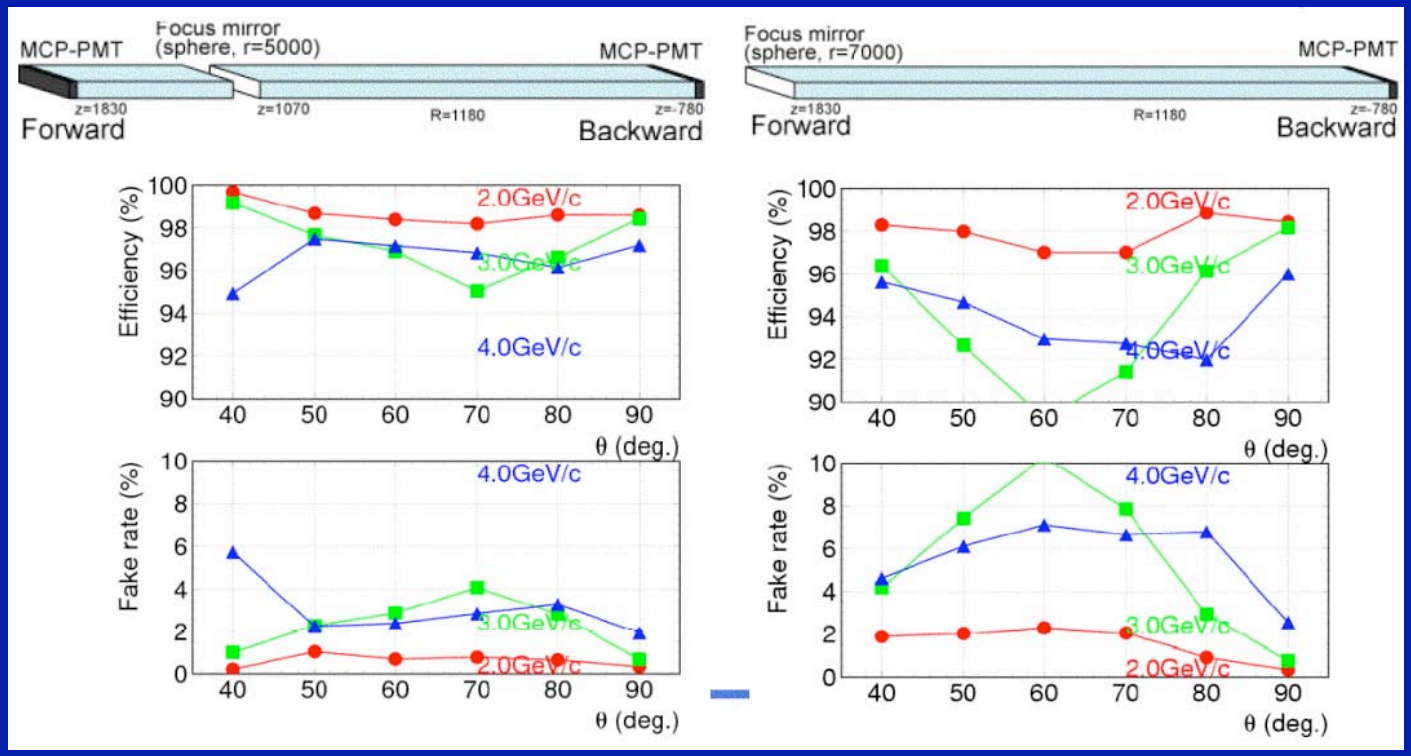


- **Although the counter's principle is simple, there is no simple formula to understand this counter; one has to have a MC to predict its performance.**

TOP counter: A solution with multi-alkali PC

K. Inami, Giessen Cherenkov detector workshop, 5.11.2009

π/K PID (Multi-alakali, 350nm filter): **MC study**



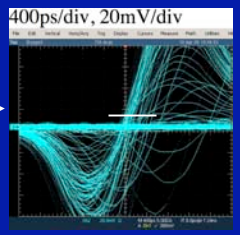
- **Do not have a separation prediction for this particular design.**
- **For GaAsP photocathode: π/K separation ~ 3 sigma at 4 GeV/c.**

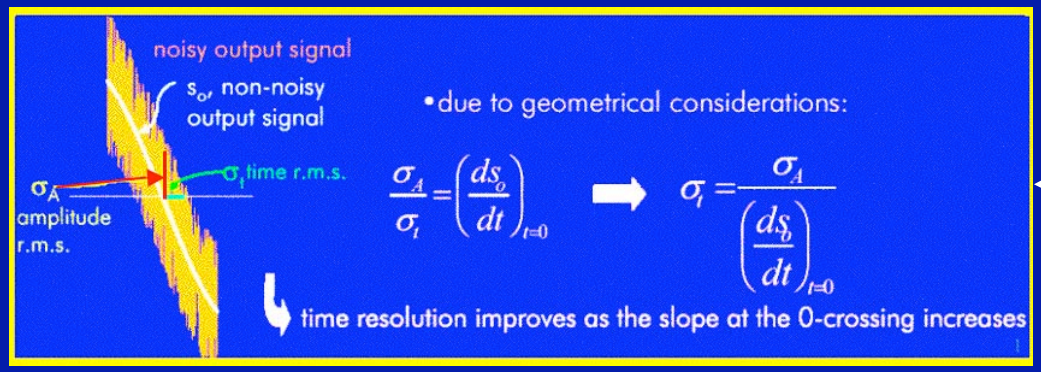
SuperB Forward TOF

- Timing strategies
- Beam & laser bench tests
- Detectors
- SuperB TOF system

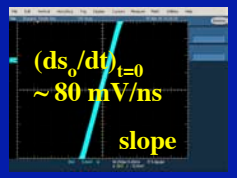
Timing strategies

- **Constant-fraction-discriminator (CFD):**
  - Timing point set at ~15% of amplitude typically - done in hardware => it is fast.
  - Less sensitive to pulse height than ordinary discriminator.
  - However, it still needs an off-line ADC correction to get the best5 resolution.



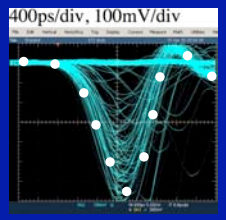


Example: HPK amplifier



$\sigma_t \sim \sigma_A/(ds_o/dt)_{t=0} \sim$ 1mV/(40mV/500ps) ~ 12.5 ps

- **Waveform sampling:**
  - typically 2.5-4 GSa/s, or 400 ps/bin - 250 ps/bin.
  - Use a software spline interpolation to get to a 10 ps/bin range.
  - Timing methods:
    - a) CFD algorithm in software, timing point is usually 15-25% of peak amplitude
    - b) Create a reference pulse by fitting a quadratic function to leading edge.
      Step the reference pulse through a given spline-interpolated pulse and find a χ^2 minimum.

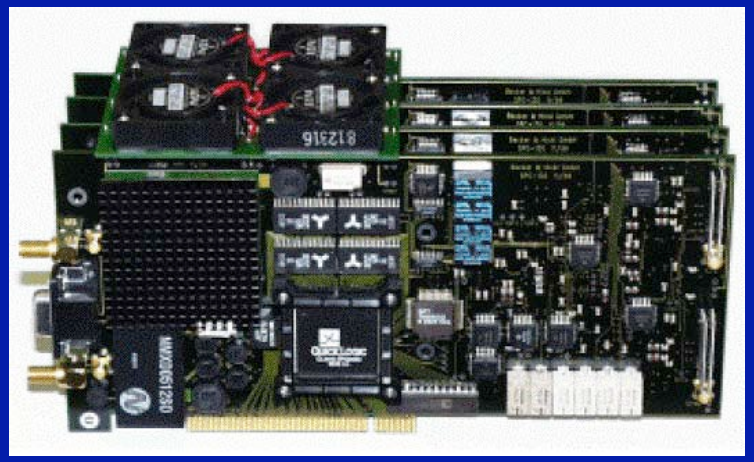


Initial interest sparked by Nagoya beam tests

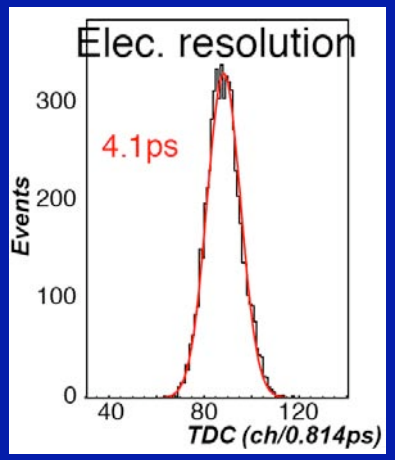
K.Inami et al., Nagoya Univ., Japan - SNIC conference, SLAC, April 2006

MCP-PMT:

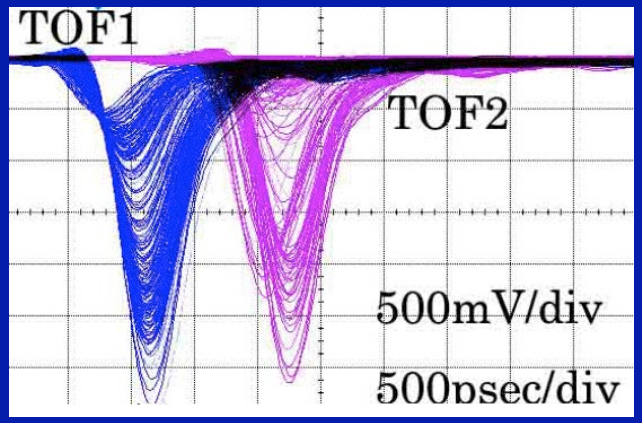
Amp/CFD/TDC:



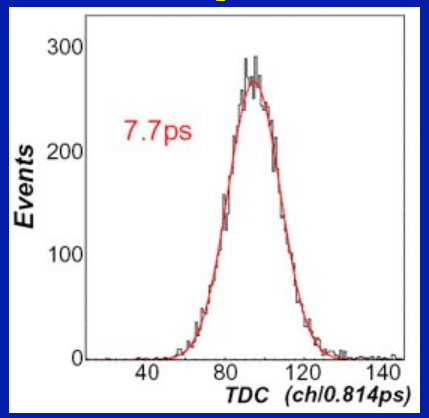
Electronics resolution:



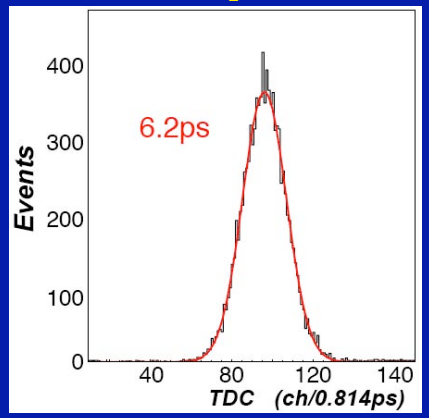
Use two identical TOF detectors in the beam (Start & Stop):



Test beam resolution with ~3 mm quartz radiator (N_{pe}~ 20):

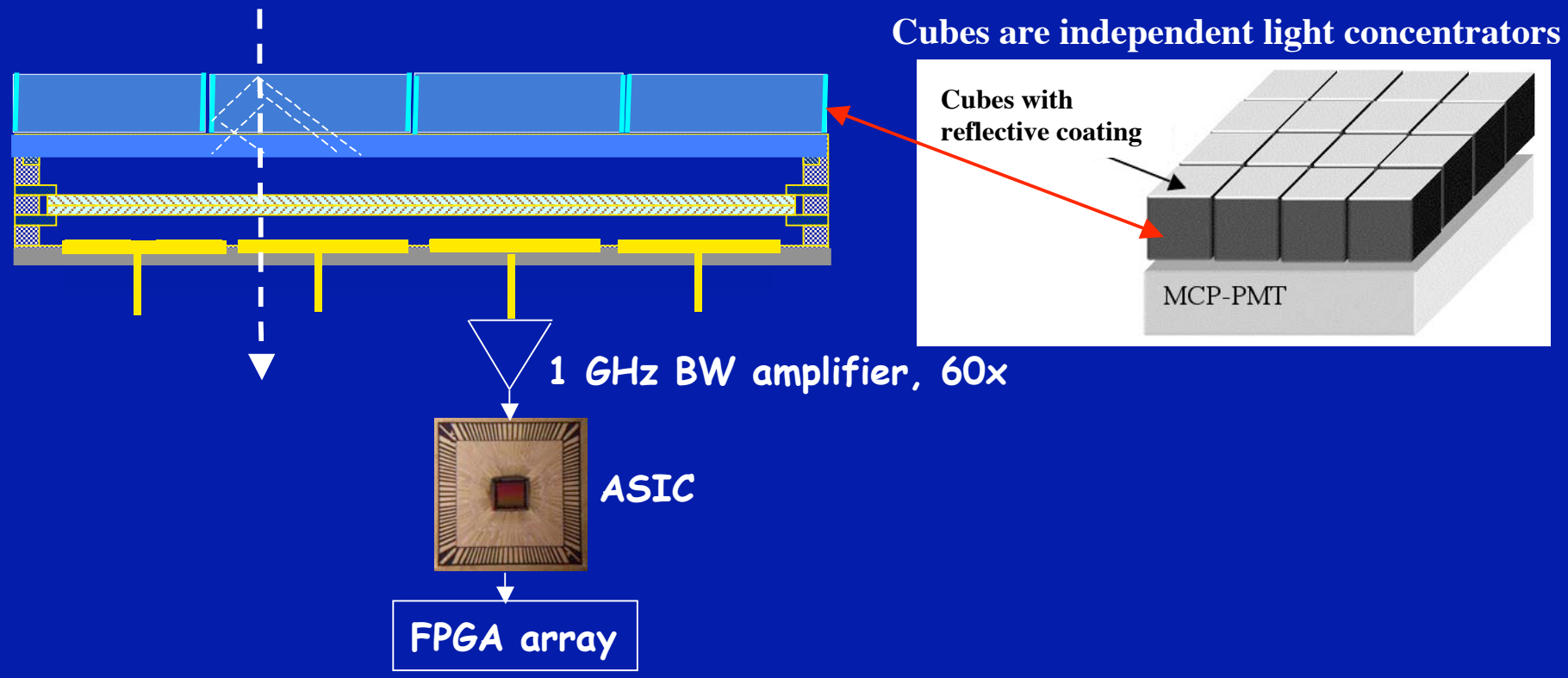


Test beam resolution with ~13 mm quartz radiator (N_{pe}~ 50):



"Pixilated" TOF counter

J.Va'vra, http://www.slac.stanford.edu/~jjv/activity/Vavra_Forward_TOF_geometry.pdf, Perugia, June 2009
http://www.slac.stanford.edu/~jjv/activity/Vavra_Forward_TOF_update.pdf, SLAC, October 2009



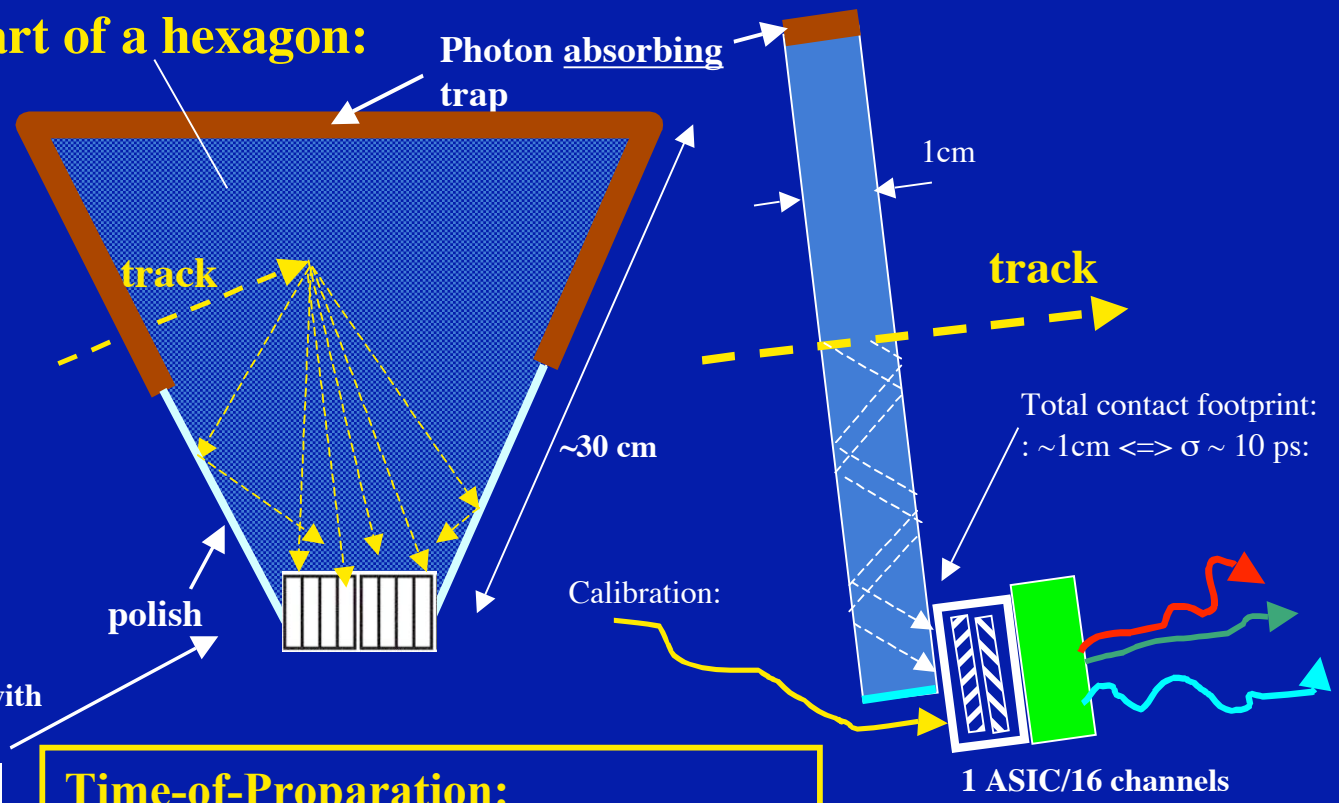
- Cherenkov light radiator: 5-10 mm thick quartz radiator cubes + 2 mm window
- Short 4 small pads together to form 16 macro-pads per detector
- Want to run MCP-PMT at low gain of ~2-5x10^4. Arguments for it: (a) smaller aging, and (b) good results in beam.

"DIRC-like" TOF detector

J.Va'vra, http://www.slac.stanford.edu/~jjv/activity/Vavra_Forward_TOF_geometry.pdf, Perugia, June 2009
http://www.slac.stanford.edu/~jjv/activity/Vavra_Forward_TOF_update.pdf, SLAC, October 2009

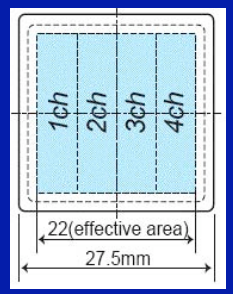
Part of a hexagon:

- Not all photons are of "equal" quality. Some we want to throw away because they are affected by the chromatic broadening.
- We do not want photons to rattle around for too long
- This design requires a high gain operation to detect single photons



Hamamatsu MCP-PMT (SL-10) with strips and a protection foil:

ϕ 10 μm holes



Time-of-Proparation:

$$TOP(\Phi, \theta_c, \lambda) = [L_{photon\ path})]/[v_g(\lambda)]$$

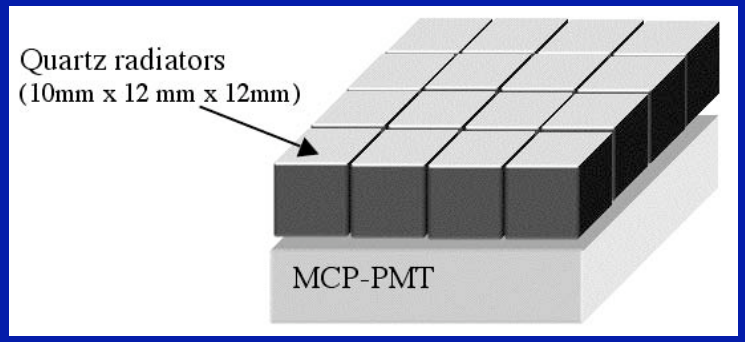
A direct photon is accepted only if:

$$TOP_i^{measured} - TOP_i^{expected} < Cut$$

Even 3 photons will do as long as they are "good" photons

Pixilated TOF counter - simple

J. Va'vra, http://www.slac.stanford.edu/~jjv/activity/Vavra_Forward_TOF_update.pdf, SLAC, October 2009



Assume:

2 GeV/c, Total particle track length ~ 2 meters, 1cm radiator => Npe ~40, Photonis MCP-PMT with Bialkali, low gain operation => σ_{TTS} ~ 120 ps

Cathode	ΔTOF = TOF(π) - TOF(K) after 2 meters	Npe 1cm-long radaitor	$\sigma(TOF)_{track}$ total contribution	Separation [TOF(π)- TOF(K)]/$\sigma(TOF)_{track}$
Bialkali	~184 ps	~ 40	**~ 25 ps**	~ 7.4 sigmas
Bialkali	~184 ps	~ 40	**~50 ps**	~ 3.7 sigmas

In case of problems

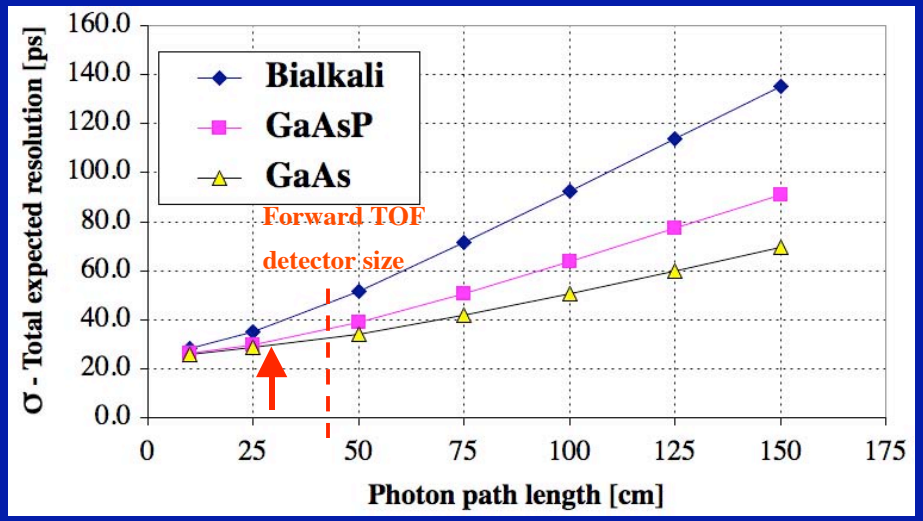
- **A good π/K separation at 2GeV/c even if only $\sigma(TOF)_{track}$ ~ 50 ps is achieved.**

"DIRC-like" TOF detector - simple

$$\sigma_{Total} \sim \sqrt{[\sigma^2_{Electronics} + (\sigma_{Chromatic} / \sqrt{(\varepsilon_{Geometrical\_loss} * N_{pe})})^2 + (\sigma_{TTS} / \sqrt{\varepsilon * N_{pe}})^2 + \sigma^2_{Track} + \sigma^2_{detector\ coupling\ to\ bar} + \sigma^2_{to}]}$$

$\sigma_{Electronics}$ - electronics contribution ~ 10 ps
$\sigma_{Chromatic}$ - chromatic term = f (photon path length) ~ 5-45 ps for path lengths 10-50 cm
σ_{TTS} - transit time spread ~ 35 ps
σ_{Track} - timing error due to track length L_{path} (poor tracking in the forward direction) ~ 5-10 ps
$\sigma_{detector\ coupling\ to\ bar}$ - timing error due to detector coupling to the bar ~ 10 ps
$\sigma_{t\ o}$ - start time dominated by the SuperB crossing bunch length ~ 20-25 ps (?)
$\varepsilon_{Geometrical\_loss}$ - loss due to a geometrical acceptance ("reject" bad photons) ~ 10%

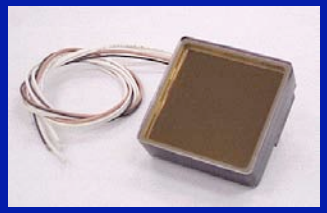
Total expected final resolution:

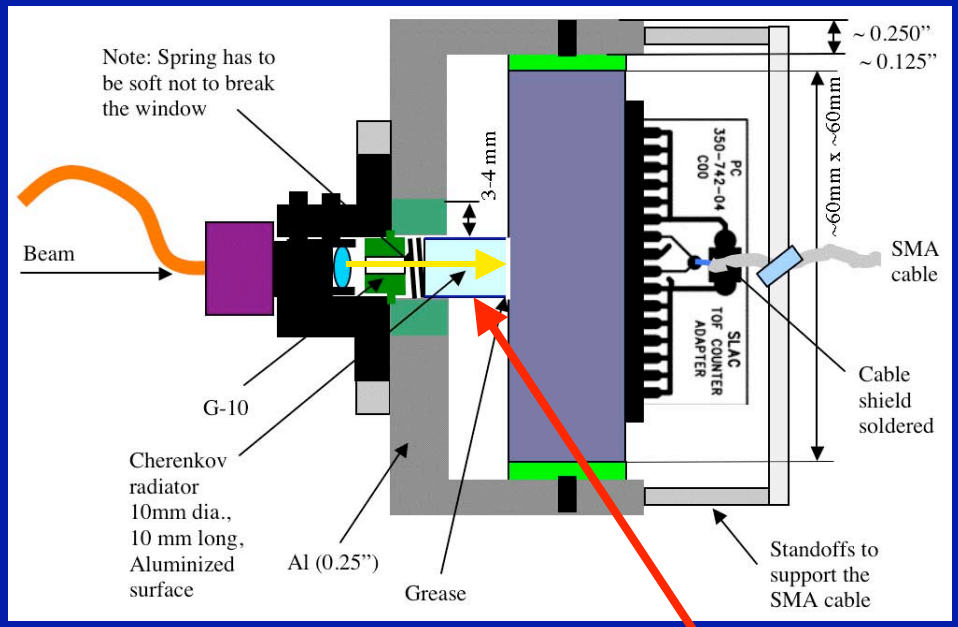


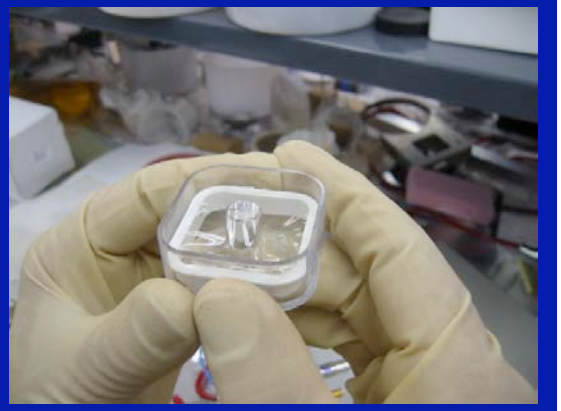
- **Bialkali photocathode will give σ_{ave}~ 40 ps on average at best.**

Pixilated TOF counter prototype

J. Va'vra et al., Nucl. Instr. & Meth., A606(2009)404-410







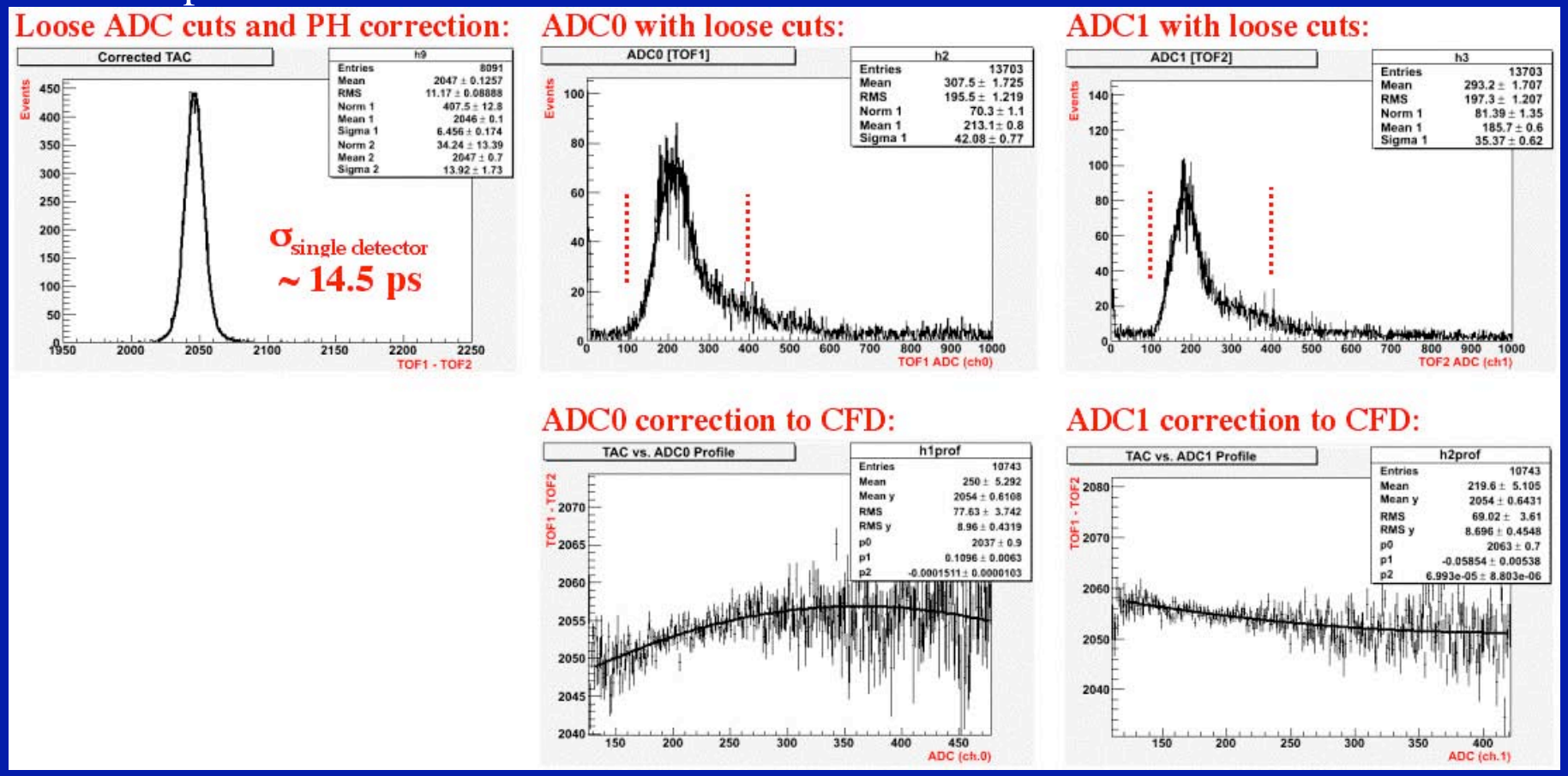
Cylindrical radiator coated with Al on its sides

- **Cherenkov light for ultra-fast response.**
- **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: (a) Fermilab test: good coating by Photonis, (b) SLAC test: poor coating.**
- **Calculation using all known efficiencies: Npe ~ 30.**
- **Calibration of the Fermilab beam test: Npe ~ 45 ± 10.**

Beam test at Fermilab: 120 GeV protons

J. Va'vra et al., Nucl. Instr. & Meth., A606(2009)404-410

120 GeV protons:



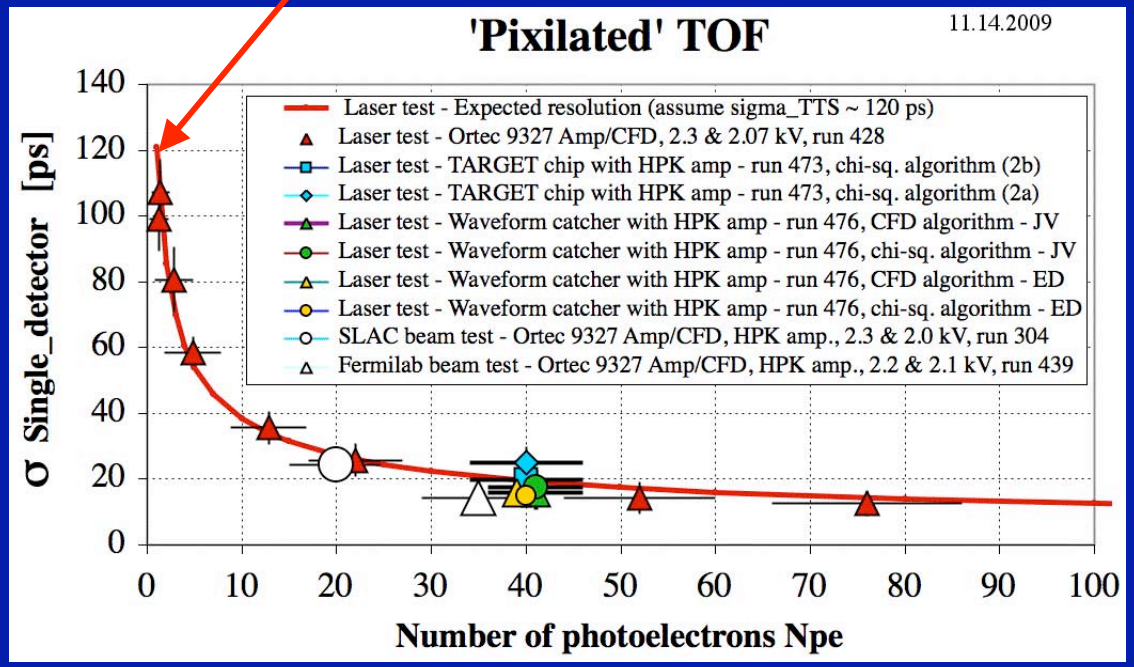
- **Additional pulse height correction to CFD timing was found necessary to obtain the best result.**

Are the results consistent with expectations ?

$$\sigma_{LASER} \sim \sqrt{[\sigma^2_{MCP\text{-}PMT} + \sigma^2_{Radiator} + \sigma^2_{Pad\ broadening} + \sigma^2_{Electronics} + \ldots]} =$$
$$= \sqrt{[(\sigma_{TTS}/\sqrt{N_{pe}})^2 + (((12000\mu m/\cos\Theta_C)/(300\mu m/ps)/n_{group})/\sqrt{(12Npe)})^2 +}$$
$$+ ((2x6000\mu m/300\mu m/ps)/\sqrt{(12Npe)})^2 + (4.7\ ps)^2]$$

For Npe = 30, σ_{TTS} ~120ps, contribution from each term: 22 ps 2.1 ps 2.2 ps 4.7 ps

Low gain operation of 2-3x10^4



Pixilated TOF scheme

- **SLAC test had smaller number of photoelectrons due to poor radiator coating.**
- **Laser test results very similar to the SLAC & Fermilab beam test results.**
- **CFD/ADC electronics is giving a very similar results as the waveform digitizing electronics with either Waveform Catcher chip (Orsay) or Target chip (Hawaii).**

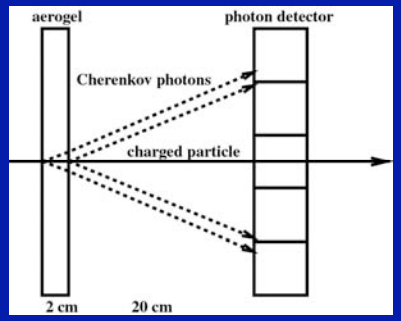
Aerogel RICH

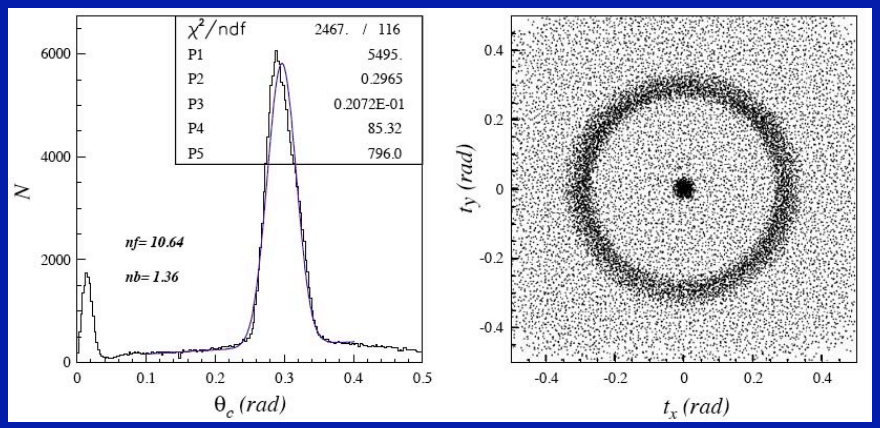
- Focusing vs. non-focusing
- Expected performance
- What detector to use ?

Principle of focusing ARICH

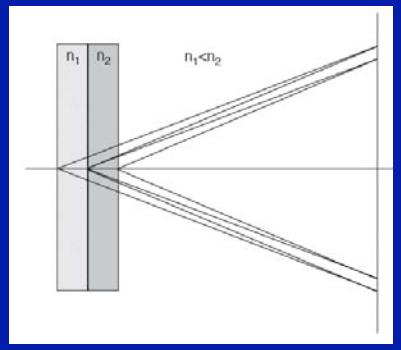
S. Korpar et al., Nucl. Instr.&Meth, A553(2005)64 and A548(2005)383

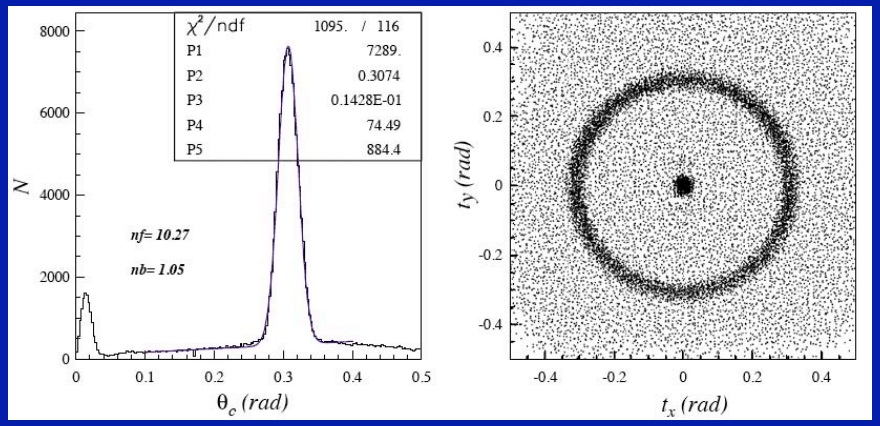
Single thick radiator





Two focusing radiators

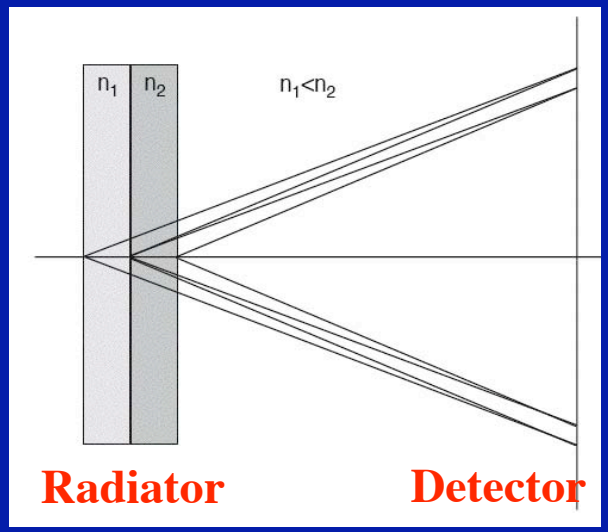




- **ARICH suffers from small number of photoelectrons (small n). The way out of it is to use a thicker radiator, which in turn leads to a poor angular resolution.**
- **<u>Solution</u>: Make the Focusing ARICH with two radiators, where $n_1 = 1.046$, and $n_2 = 1.055$ ($n_1 < n_2$).**

Proximity Focusing Aerogel RICH

P. Krizan, Aerogel RICH, http://www.phys.hawaii.edu/superb04/slides.html



Assume:

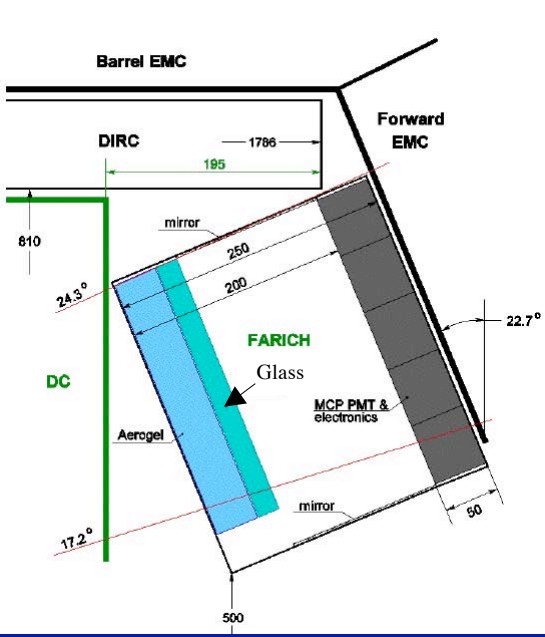
4 GeV/c, n = 1.05, radiator length = 2cm, H-8500 pixels (6 mm x 6 mm)

$\theta_c(\pi)$ [mrad]	$\Delta\theta_c = \theta_c(\pi) - \theta_c(K)$ [mrad]	$\sigma(\theta_c)_{single\ photon}$ measured	Npe measured	$\sigma(\theta_c)_{track} = \sigma(\theta_c)_{single\ photon}/\sqrt{Npe}$	Separation at $\theta_{dip} = 90^o$ $[\theta_c(\pi) - \theta_c(K)]/\sigma(\theta_c)_{track}$
308	23 mrad	~ 14 mrad	~ 10	~ 4.4	~ 5 sigmas

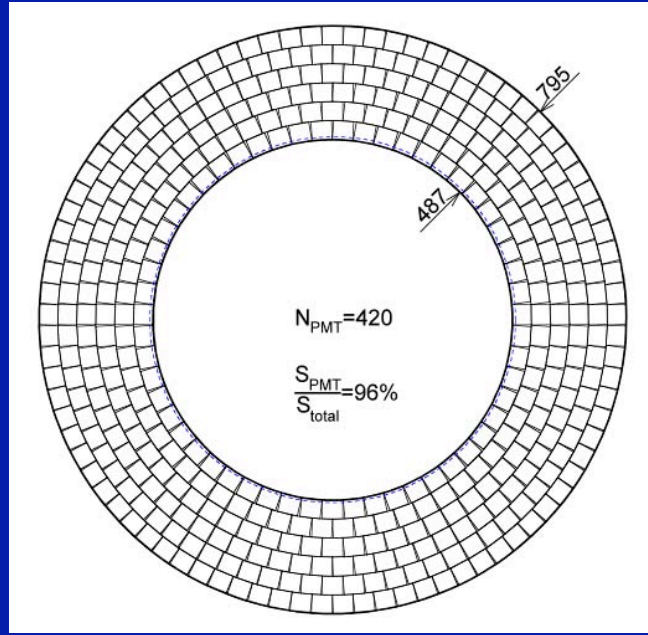
- **Clearly, excellent performance, superior to the TOF method.**

An example of the forward Aerogel RICH detector proposal for SuperB

S. Kononov et al., Novosibirsk, 2009



- Expansion gap 200 mm
- Burle MCP PMT with 3.2x3.2 mm pixels (16x16 matrix), photoelectron collection efficiency 70%, geometrical factor 85%
- 3-layer focusing aerogel, n_{max}=1.07, total thickness 30 mm
- Number of PMTs ~ 450
- Number of channels ~ 115000
- Amount of material, (X_0) = 3.5%(aerogel)+ 2.5% glass + 14%(MCP PMT)+8% (support, electronics, cables) ~ 28%

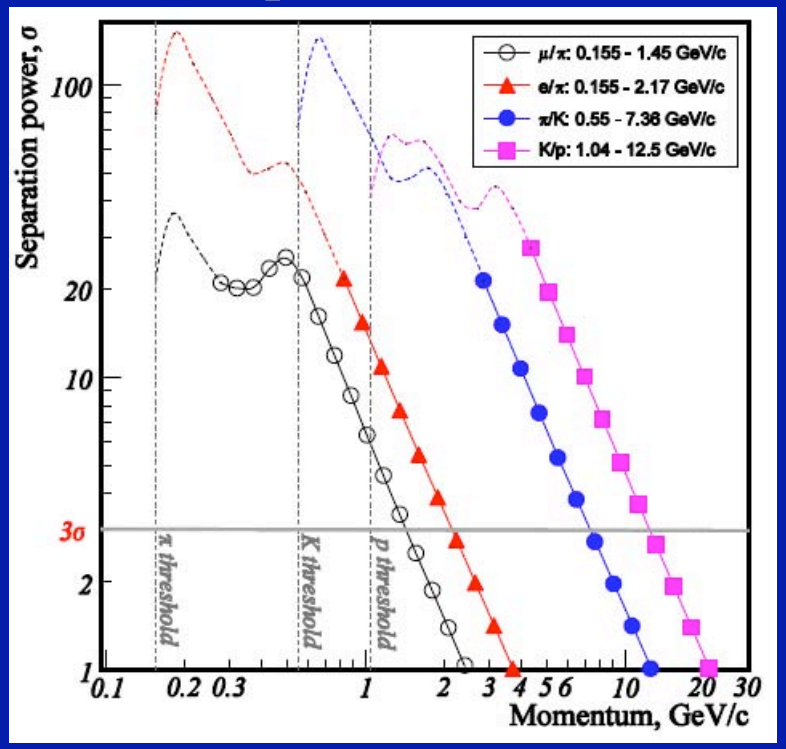


- **The system would use 450 Photonis MCP-PMTs with 10 micron holes.**
- **3-layer radiator for the focusing ARICH: two aerogel layers and water.**
- **Add glass radiator, with higher n, to improve the low momentum PID capability.**
- **However, adding more mass in front of the calorimeter, degrades its resolution.**
- **Can one handle so many MCP-PMTs operating at high gain, high rate, at 16kG ?**

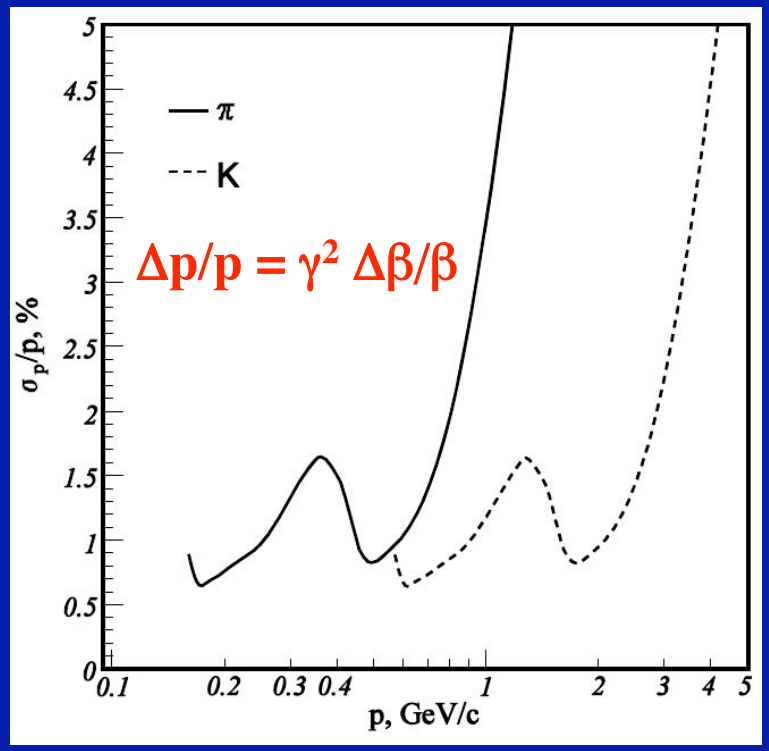
Forward Aerogel RICH expected performance

S. Kononov, E. Kravchenko et al. , Novosibirsk, 2009

Particle separation:



RICH can measure momentum:



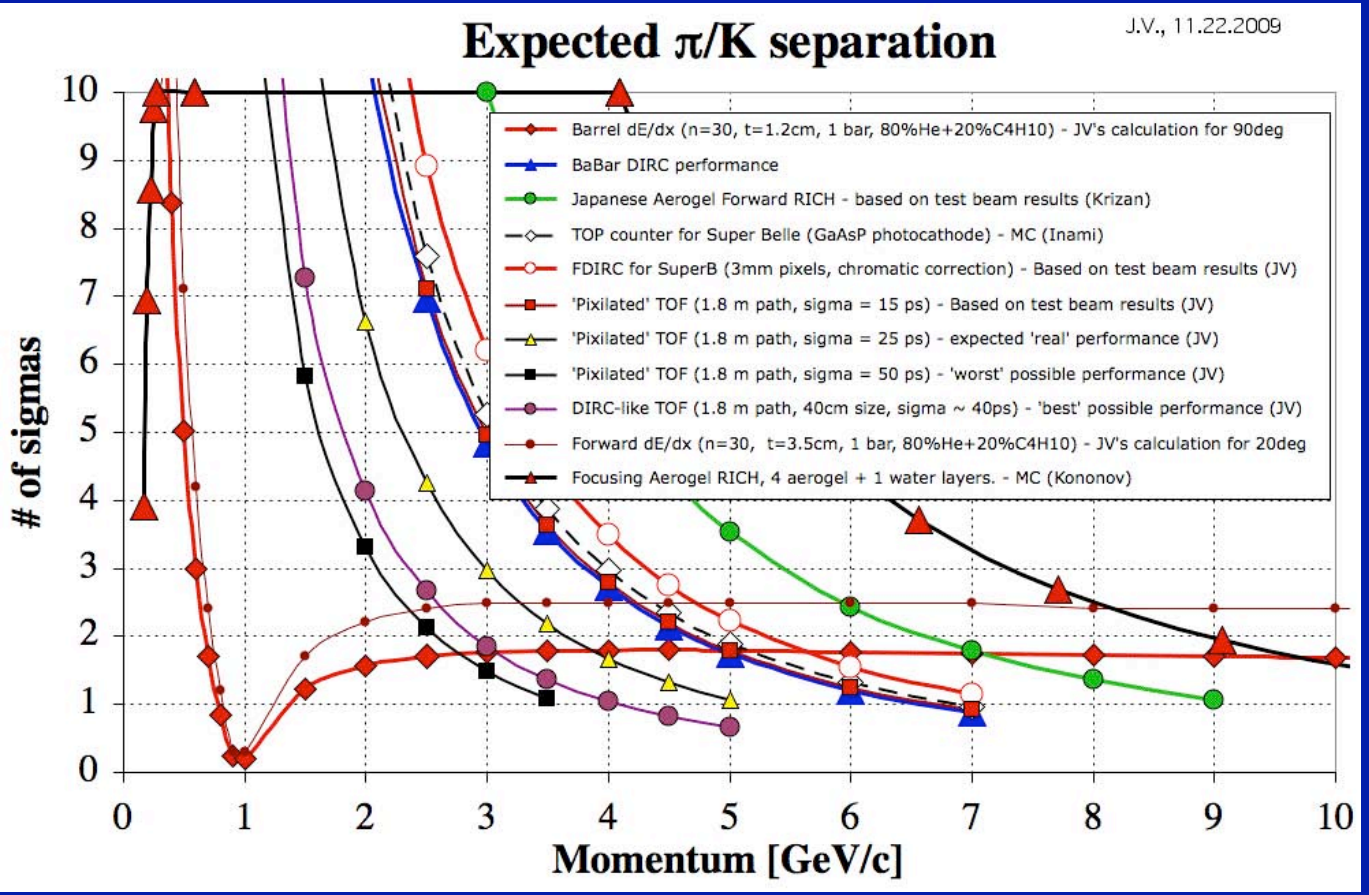
- **Clearly excellent performance up to very high momenta.**
- **Excellent π/K separation from 0.6 to 8 GeV/c.**
- **RICH can measure momentum to ~1% for low momenta tracks.**

"Ideal" SuperB PID performance

J. Va'vra, dE_dx = f(beta_gamma) study.xls spreadsheet

Example of various Super-B factory PID designs:

Calculation done for flight path length = 1.8m



- **Calculations represent an optimistic predictions based on gaussian distributions without realistic background. Should be taken as upper limit of performance.**
- **A TOF detector even with ~100ps resolution would do to fill up the dE/dx hole at ~1 GeV/c.**
- **TOP counter: GaAsP photocathode is probably not realizable, so performance will be worse.**

Summary of PID techniques for SuperB

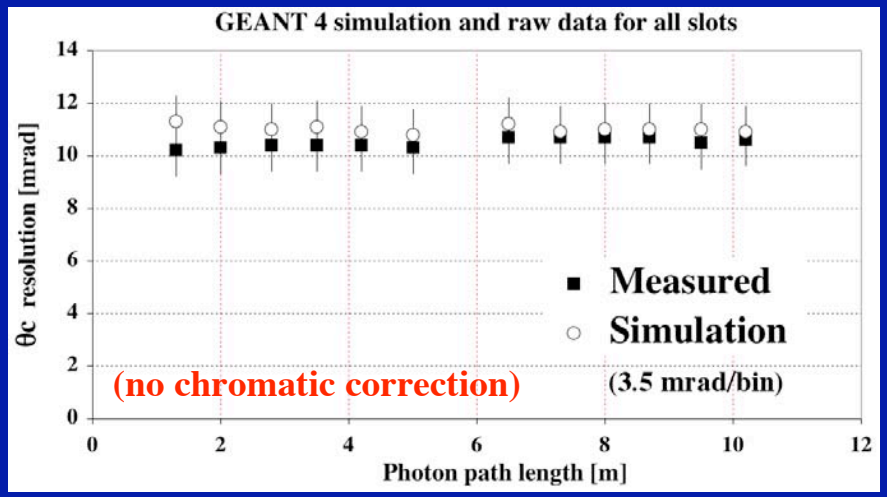
Method	My personal comment
dE/dx - charge integration	Now a standard technique; good π/K PID bellow ~0.8 GeV/c; no PID near cross-over near ~1 GeV/c; relatively poor PID performance in the relativistic rise region above 1 GeV/c
dE/dx - cluster counting	Nobody has tried it yet; possible with introduction of wave form digitizing electronics; a factor of up to 2x of improvement over the standard dE/dx technique; should be tried.
FDIRC RICH	Thanks to focusing features, the focusing optics is much smaller than the SOB in BaBar; new MaPMTs will allow compact and highly pixelized detector, thus improving the angular resolution; absence of water will make the maintenance easier; the size and much faster timing will help the background issues; a timing resolution of σ ~200ps will allow the chromatic corrections; the overall performance should be better than that of BaBar DIRC by 20-30% ?
TOP counter (latest version: pixelized)	"On-paper" performance about the same as that of FDIRC; however, the MCP-PMT detector must deliver a TTS resolution of σ ~40 ps for the scheme to operate; t0 must be also good to ~25 ps; possibly large rate load on pixels if backgrounds large; sensitive to chromatic effects; GaAsP photocathode probably will not be avaolable; timing MUST work !
Forward Aerogel RICH	Truly excellent PID performance for~0.2-10 GeV/c; one really does not need this much of performance; large number of MCP-PMTs operating at high gain in a high rate environment - as of now unexplored challenge; large number of pixels; mass in front of calorimeter.
Forward TOF (pixelized)	Good for π/K PID bellow 2-3 GeV/c; it has a better chance to work than the DIRC-like TOF scheme; large number of MCP-PMTs required; more expensive; nobody has done it on such a large scale before; aging and rate effects reduced by running a very low gain on these tubes; to reach σ ~25ps will require a large effort as everything has to be done right, including a t0 signal; to reach σ ~ 50ps is easier, still a lot of work !!
Forward TOF (DIRC-like)	Good for π/K PID bellow 2-3 GeV/c; must have tracking; very difficult data analysis; MCP-PMT have to run at high gain; aging & rate effects more difficult than in the "pixilated" TOF scheme.

Appendix

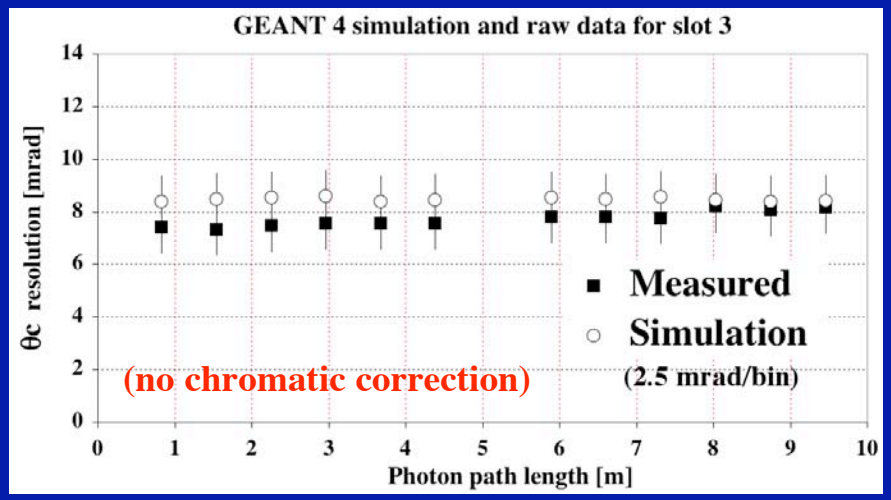
Geant 4 MC simulation for test beam condition

J.F. Benitez, I. Bedajanek, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff. K. Suzuki, J. Schwiening, J. Uher and J. Va'vra, "Development of a Focusing DIRC," IEEE Nucl.Sci, Conf. Rec., October 29, 2006, and SLAC-PUB-12236, 2006 and SLAC-PUB-12803, 2007

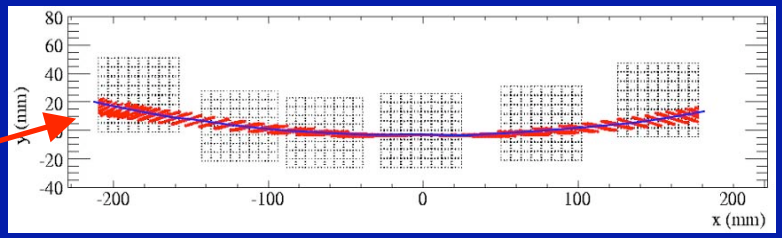
θ_c resolution - 6mm pixels:



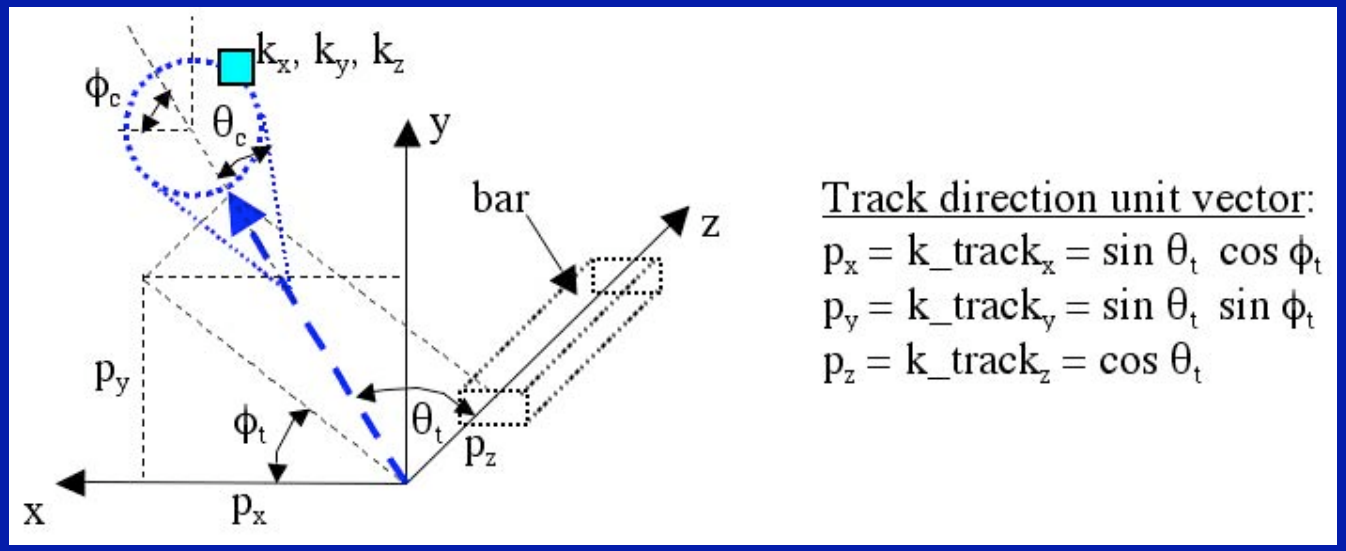
θ_c resolution - 3mm pixels only:



- **This is why we want 3mm pixels in FDIRC for SuperB**
- **<u>Main contributions to the θ_c resolution</u>:**
  - **Chromatic smearing**: ~ **2 - 5.5 mrad**
  - **6mm pixel size**: ~**5 - 6 mrad**
  - **3mm pixel size**: ~**2.5 - 3 mrad**
  - **Kaleidoscopic wiggles - could one correct them analytically ?**:
    (contribute from ~0 mrad at ring center to ~9 mrad in outer wings of the Cherenkov ring)



How to combine FDIRC with external tracking

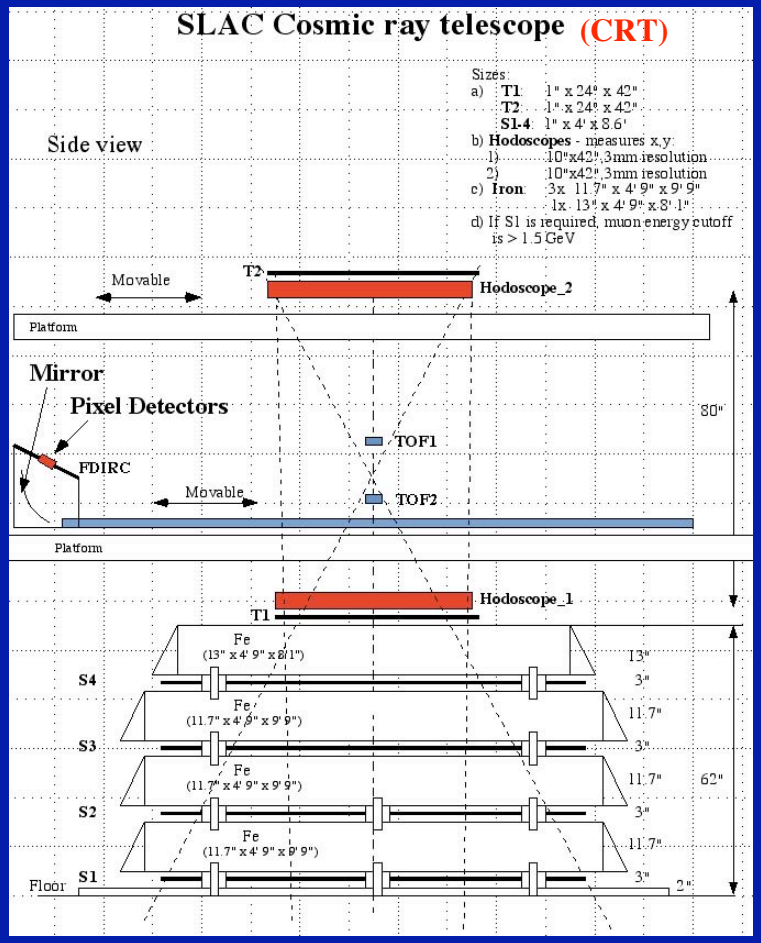


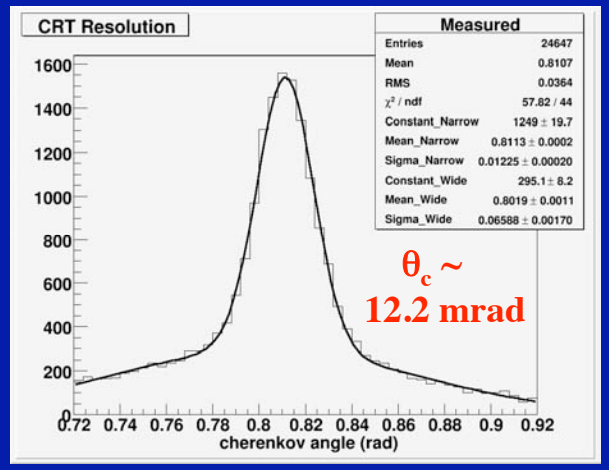
$$\cos\theta_c = k_x * k\_track_x + k_y * k\_track_y + k_z * k\_track_z$$

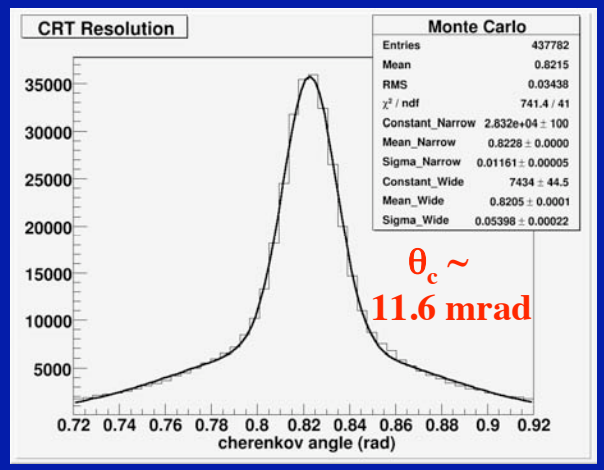
- **One has treat signs right at the production point! For example, time-of-propagation can be used to determine a sign of k_track_z. A sign of k_track_y is defined by external tracking. Some ambiguities cannot be resolved, such as a sign of k_track_x.**

Example: FDIRC prototype in CRT

J.V., "CRT log book #1, page 106, 2009, Run 4, position 3, >1.5 GeVmuons





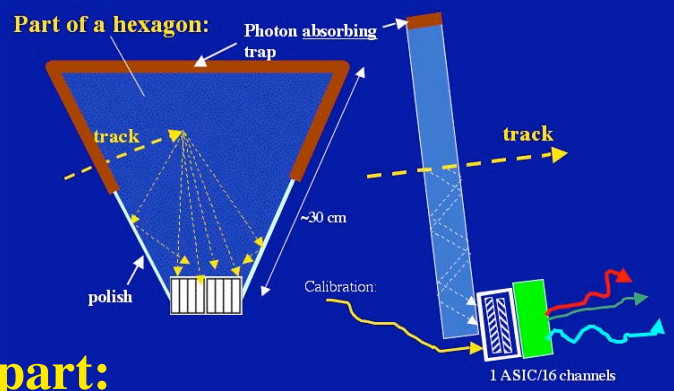


- **The only way to get a good θ_c resolution is to combine track and FDIRC direction cosines correctly, and with right signs !**

Geometry selection

J. Va'vra, http://www.slac.stanford.edu/~jjv/activity/Vavra_Forward_TOF_update.pdf, SLAC, October 2009

DIRC-like TOF



Bad part:

a) **Must be sensitive to single photoelectrons**

b) Detector has to work at **high gain** (>5x10^5).

c) Detector operates at higher rate. Therefore, the rate and aging problems are a concern. **May segment more if necessary.**

e) Chromatic effects could be important for large photon paths.

f) More complicated data analysis.

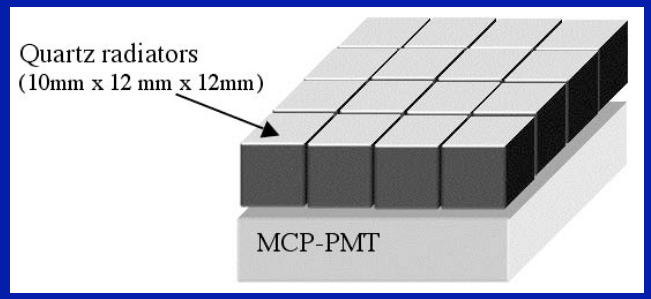
g) Quartz radiator needs a complicated & perfect **photon trap**. Without a photon trap it may act as a optical resonator !! Very crucial to success !!

Good part:

a) **VERY small number of photo-detectors (~ 50 detectors !!)**

b) Thin & uniform radiator in front of the calorimeter

Pixilated TOF



Bad part:

a) **Large number of photo-detector needed.**

b) **Too much mass in front of the calorimeter.**

c) Low gain operation => worse S/N ratio. Offset by thick radiator.

d) Expemsive.

Good part:

a) **Low gain operation (~2x10^4) - small rate of aging.**

b) **Detector "does not" see single photoelectron background.** The detector is sensitive only to tracks. Therefore the detector operates at much lower rates. Therefore, the rate and aging problems are easier to solve.

c) **Simple data analysis.**

d) The chromatic effects are not important at all.

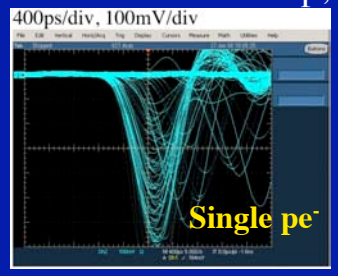
σ_{TTS} measurement with single pe's - high gain

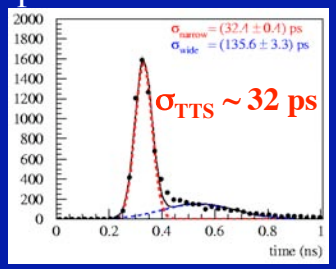
J.Va'vra et al., Nucl.Instr.&Meth. A 572 (2007) 459–462, and my log books 3 & 6, 2006 & 2008

- **Photonis Planacon**, S/N 11180401
- **10 μm MCP hole diameter**
- **2.8 kV**
- **Single pe sensitivity**

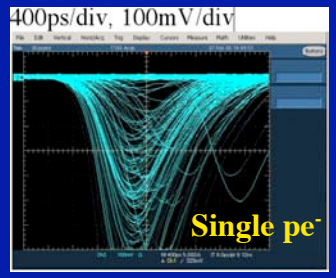
1) ~ 300 MHz BW electronics:

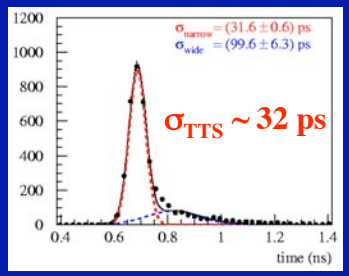
HPK C5594-44 amp, Phillips 715 CFD:



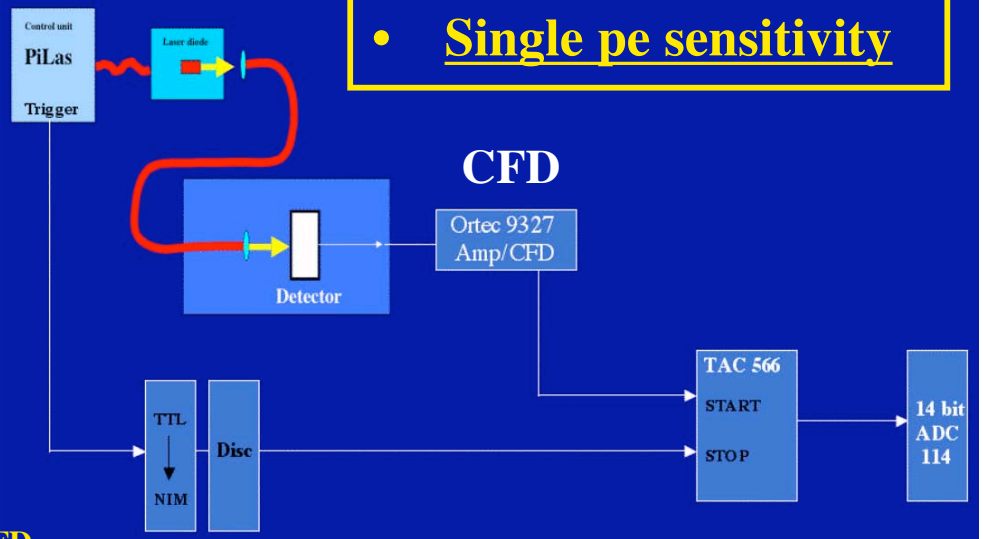


Ortec VT-120 amp.+6dB, Phillips 715 CFD :





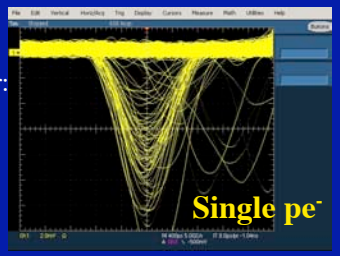
- **Slow down amplifiers by a long cable between Amp & CFD** (optimum was found to be ~20ns).

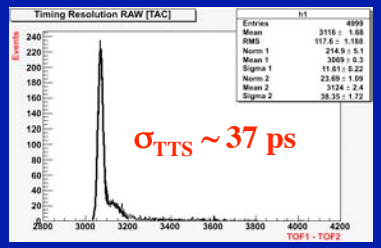


2) ~ 1 GHz BW electronics:

Ortec 9327CFD, TAC566, ADC114:

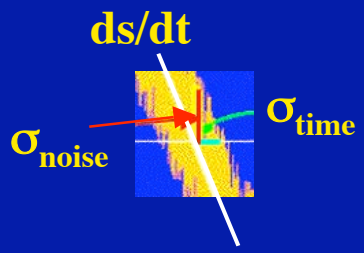
CFD monitor:





- **CFD timing:**

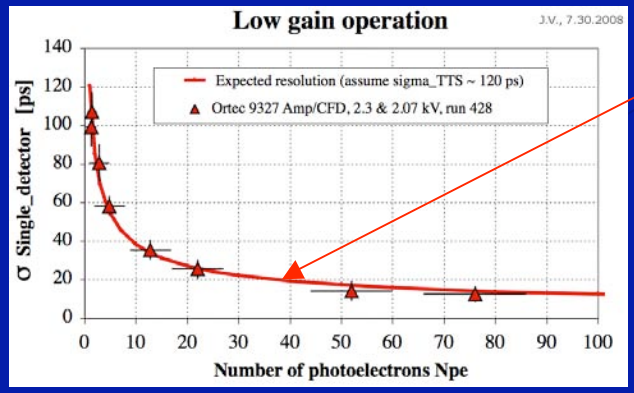
$$\sigma_{time} = \sigma_{noise} / (ds/dt)_{zero\ crossing\ point}$$



Laser test of the Fermilab electronics - low gain

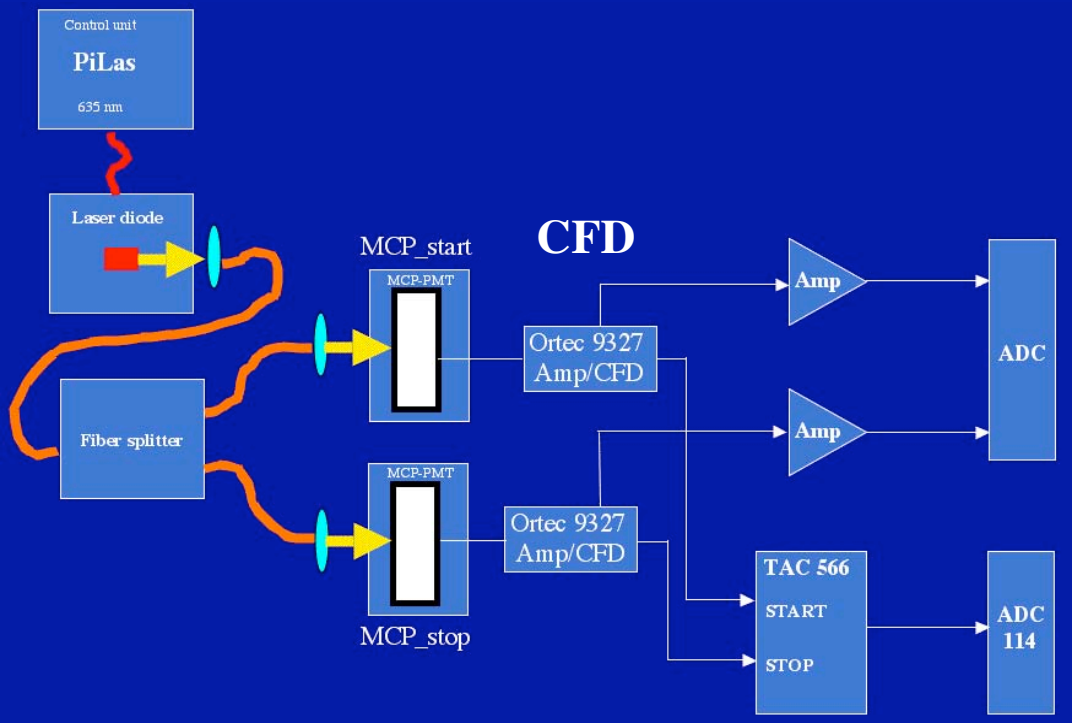
J.Va'vra et al., Nucl.Instr.&Meth. A 595 (2008) 270-273

Nominal MCP voltages, G ~$2x10^4$**:**



$$\sigma \sim \sqrt{[\sigma^2_{MCP\text{-}PMT} + \sigma^2_{Laser} + \sigma^2_{Electronics} + \ldots]} =$$
$$= \sqrt{[\sigma_{TTS}/\sqrt{N_{pe}})^2 + \sqrt{((FWHM/2.35)/\sqrt{N_{pe}})^2 + (4.2\ ps)^2}}\ ]$$

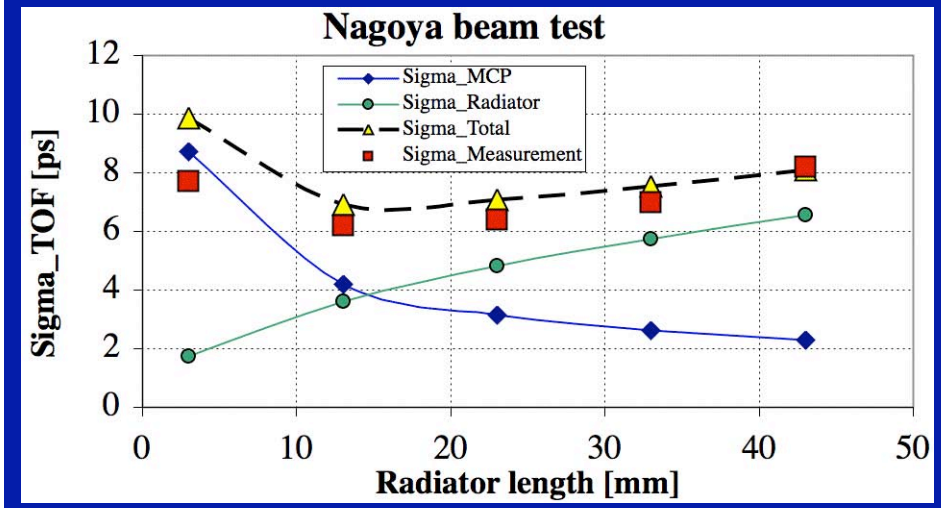
- **Photonis Planacon**, S/N 11180401 & 7300714
- **10 μm MCP hole diameter**
- **2.2 kV & 2.0 kV on MCP-PMTs**
- **Not sensitive to single pe ! Instead, linear for Npe ~ 30-50**

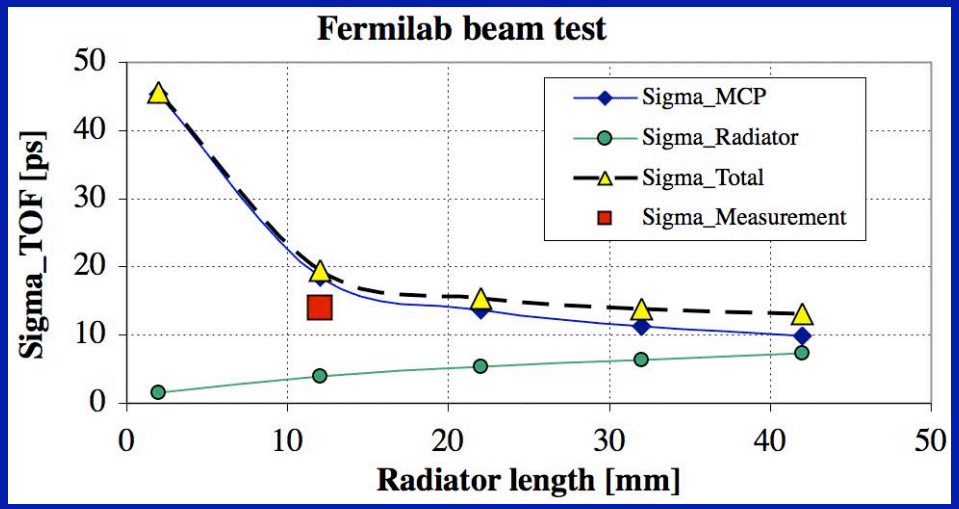


- **The same electronics as in the test beam - Ortec electronics (9327CFD, TAC566, ADC114)**
- **Extrapolating to Npe = 1, one obtains much worse σ_{TTS} ~ 110 ps.**

Radiator thickness

J. Va'vra et al., Nucl. Instr. & Meth., A606(2009)404-410





- **It appears that a length of 10 mm is optimum.**
- **This is important from point of view of a mass in front of the EMC calorimeter.**
- **There is an important difference between the two beam tests:**

  - MCP-PMT had high gain during the Nagoya beam test, enough to detect single pe's
  - MCP-PMT had low gain during the Fermilab beam test; it would not see single pe's