Lessons learned from DIRC & FDIRC developments at SLAC

J. Va'vra, SLAC

FDIRC ≡ Focusing DIRC

Abstract

- **BaBar DIRC and FDIRC developments were successful.**
- **However, to be successful, it was necessary to make many tests.**
- **In this talk I will mention a few of them.**

Time history of DIRC & FDIRC development

- **1992-93: Blair Ratcliff publishes the first two DIRC papers.**
- **1993-96: BaBar DIRC prototypes I & II were tested.**
- **1993: BaBar collaboration was formed.**
- **1994: BaBar collaboration chose DIRC as a PID option.**
- **1995: BaBar TDR with DIRC in it was submitted.**
- **1995-2002: BaBar DIRC R&D – it was necessary to answer some crucial issues, such as a radiation damage of quartz and glues, quartz refraction index periodicity, required polishing quality, internal reflection coefficient, etc.**
- **Lesson #1: Finishing TDR does not mean that all is understood.**
- **1997-1999: Construction of DIRC bar boxes.**
- **1099-2008: BaBar experiment was taking physics data.**
- **2003-2014: FDIRC R&D performed, motivated by the SuperB experiment.**

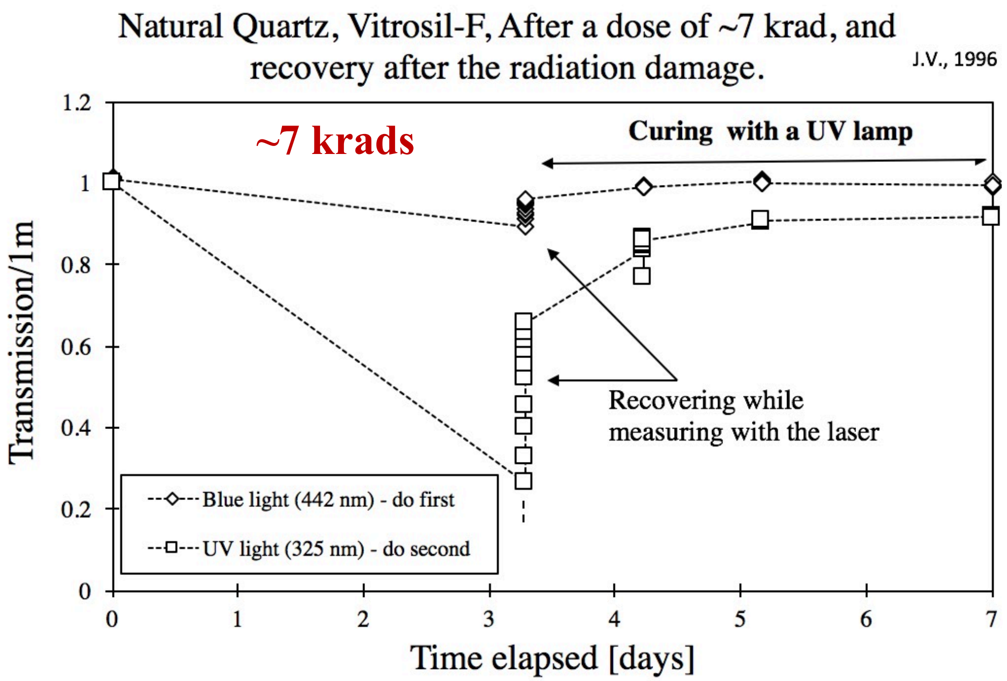
A lot of R&D steps were needed to go from a proof of principle to a final DIRC detector

1. Penetrate iron or not ? A crucial decision contributing to DIRC success.
2. Define pin hole camera optics, and select photon detector.
3. Electronics development.
4. Transmission through Fused silica bars and optical glues.
5. Radiation hardness studies of Fused silica and various other materials.
6. Effect of pollution from various materials on the internal reflection coefficient.
7. Transmission study of water.
8. Water corrosion study of PMT glass and other materials sitting in highly purified water.
9. Effect of large photon fluxes over many years on Epotek-301-2 optical epoxy.
10. Internal reflection coefficient as a function of wavelength and required surface polish quality.
11. What contributes to Cherenkov angle tails ? Is it Fused silica scintillation, or is Epotek-301 refraction index mismatch to quartz, or other effects ?
12. Periodic variation of refraction index within Fused silica.
13. Understanding of kaleidoscopic effects in Cherenkov rings due to squareness of radiator bars.
14. Water tightness of bar boxes.
15. Study of mechanical precision of bars.
16. Study of edge quality of bars.
17. Develop a procedure to minimize mechanical stresses on bars when in bar boxes in various positions.
18. Software: (a) data analysis and (b) MC codes.
19. DIRC background in BaBar.
20. How to keep bars in a clean environment for many years ?
21. FDIRC challenge: understanding of new fast pixilated detectors, optics choice, electronics choice, etc.

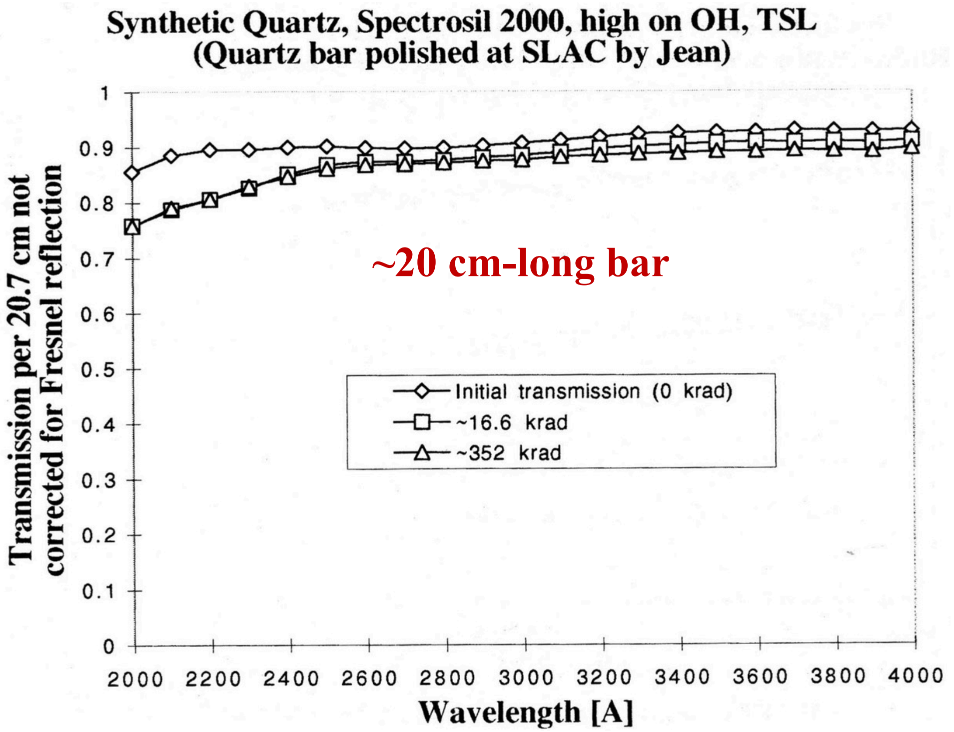
What type of quartz to use ?

X. Sarazin, M. Schneider, J. Schwiening, R. Reif and J. Va'vra, DIRC Note # 39, 1996

Natural quartz:



Spectrosil 2000:

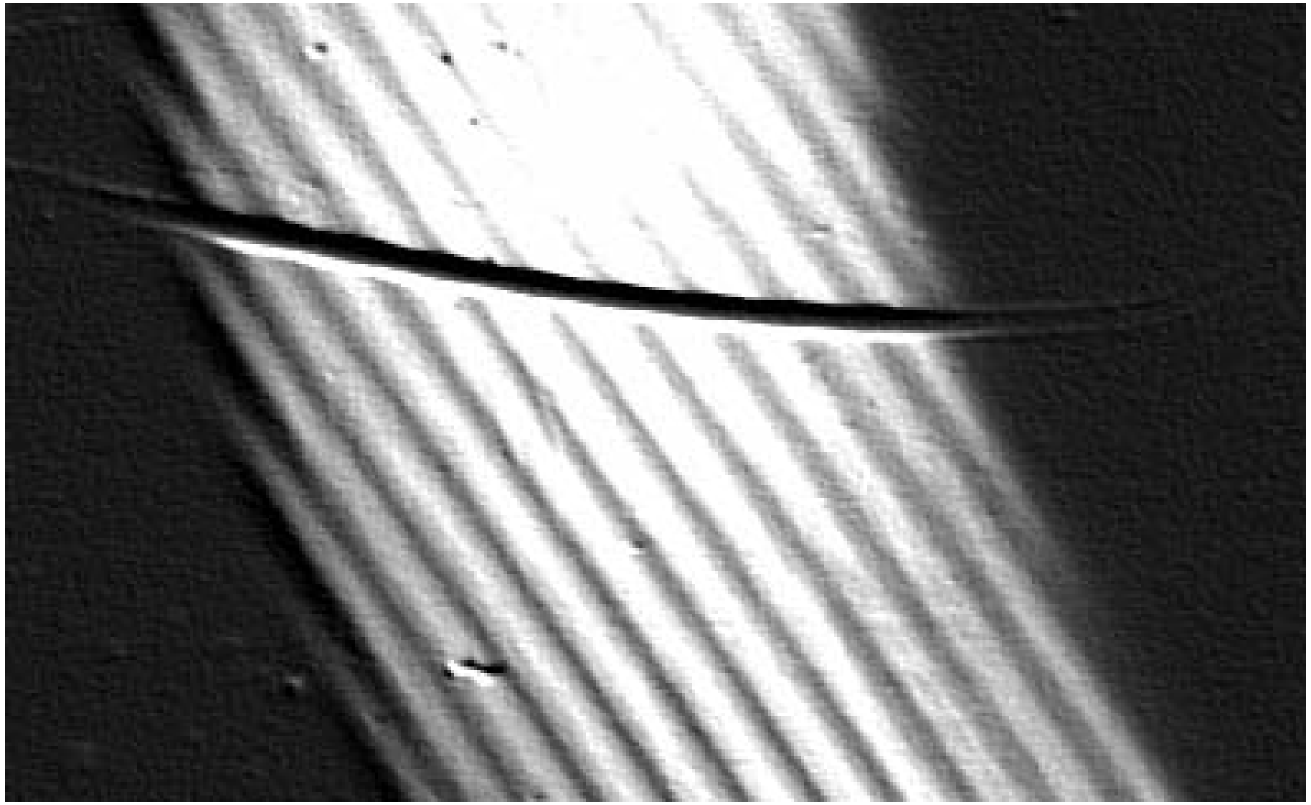


- **DIRC, according to TDR, was supposed to have the natural quartz.**
- **Lesson #2: We had to switch to Fused silica because of the radiation damage. We also had to test radiation damage of various glues.**

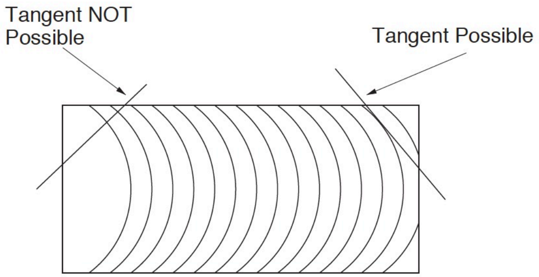
A new “unplanned discovery”: Periodicity of the refraction index

J. Cohen-Tanugi, M. Convery, B. Ratcliff, X. Sarazin, J. Schwiening, J. Va’vra, NIMA 515 (2003) 680

Surface image observed under a microscope with 100 μm wire:
(Suprasil Standard quartz)



Layering in quartz ingot:



- **This effect can be easily recognized with a laser pointer looking for a diffraction pattern.**
- **Lesson #3: Layering in quartz ingots can cause periodicity of the refraction index. Had to search for the fused silica material which does not have it.**

Important contribution to DIRC: measurement of internal reflection coefficient

J. Cohen-Tanugi, M. Convery, B. Ratcliff, X. Sarazin, J. Schwiening, J. Va'vra, NIMA 515 (2003) 680

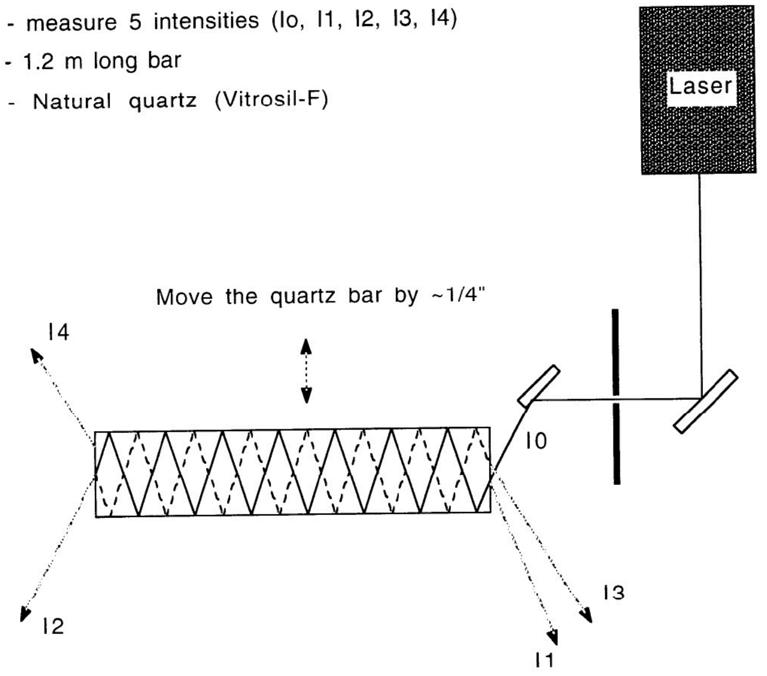
H. Krueger, M. Schneider, R. Reif, J. Va'vra, DIRC note #18, **1996**:

REFLECTION TEST#1

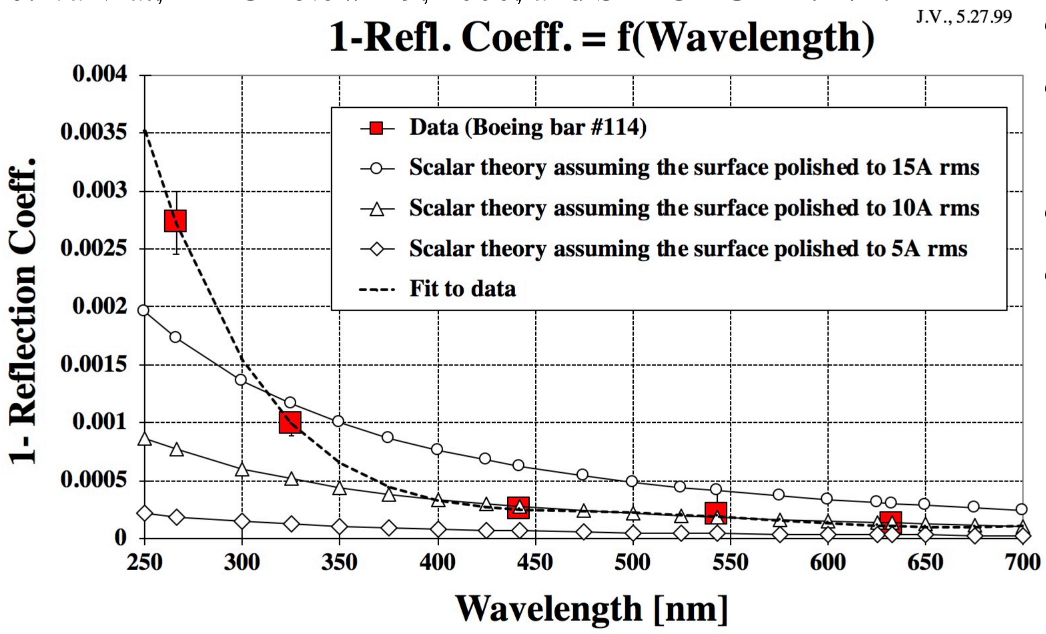
H.K., J.V., 8.31.95

Measurement of the internal reflection coefficient using a "calorimetric" technique

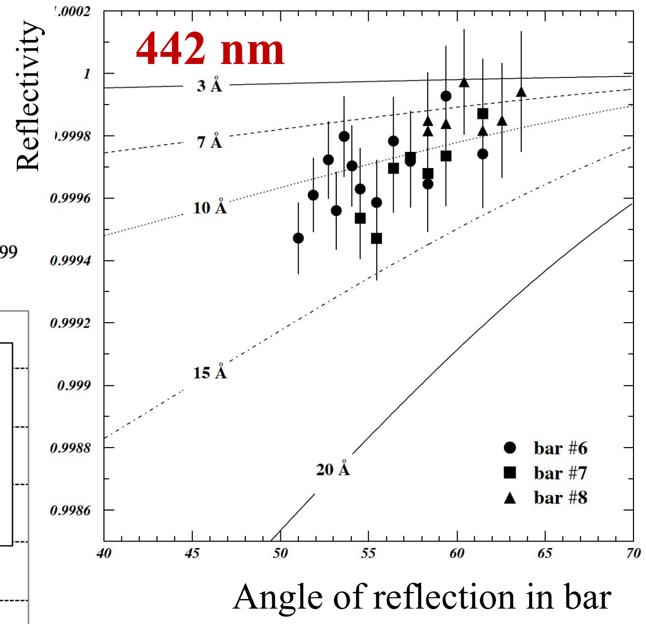
- blue or UV light (448 or 325 nm)
- measure 5 intensities (Io, I1, I2, I3, I4)
- 1.2 m long bar
- Natural quartz (Vitrosil-F)



J. Va'vra., DIRC note #129, **2000**, and SLAC-PUB-17471:



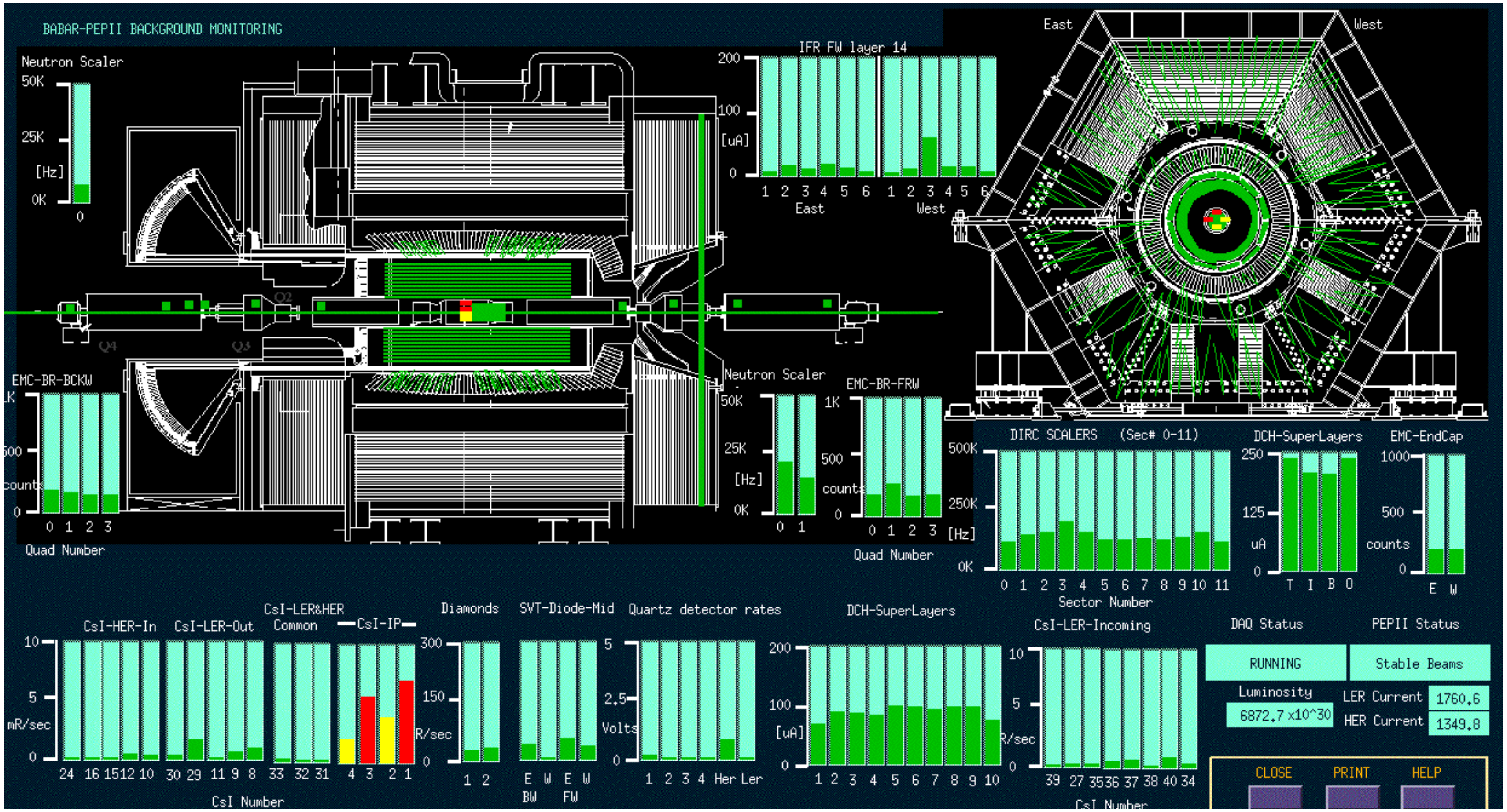
J. Schwiening, DIRC note #40, **1996**:



- **The method was invented by a summer student H. Krueger, a visitor from Germany.**
- **The method was also used in the bar pollution tests.**
- **Lesson #4: Reflection coefficient agrees with the scattering theory in the DIRC bandwidth.**

Active display to show BaBar/DIRC background

G. Vasileiadis (BaBar display and VSAM readout), J. Va'vra (provided background detectors along the beam line)

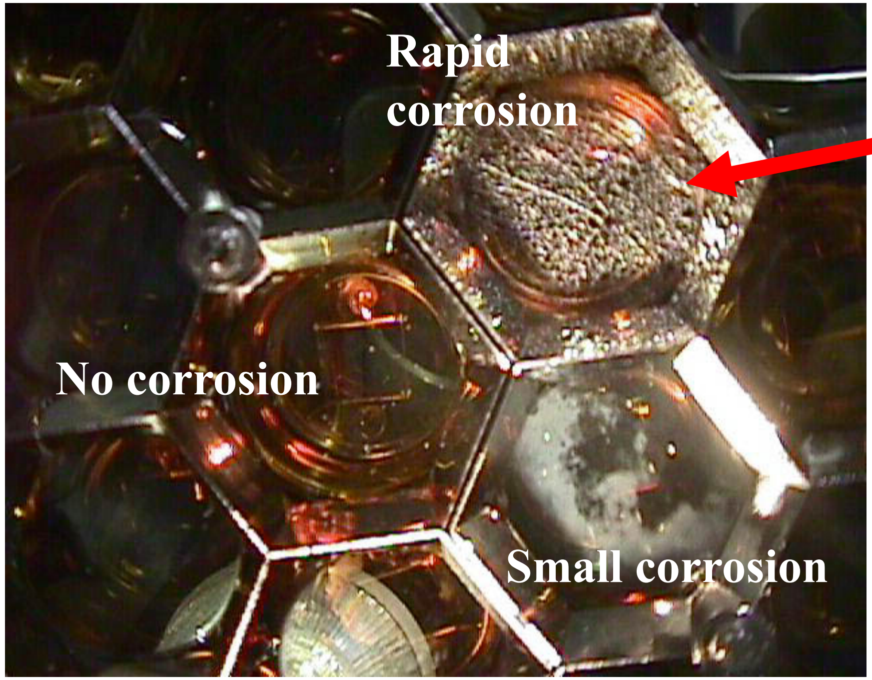


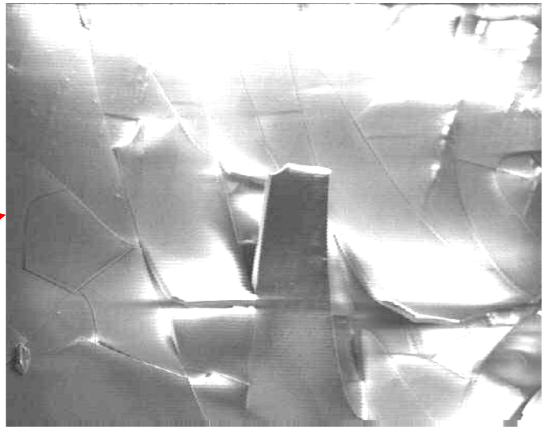
- **Lesson #5: DIRC backround was not predicted by initial background group studies ! There was a very large effort to find sources and erect effective shielding. We were lucky that we could do it.**
- DIRC's photon camera, with 6000 liters of water, was sensitive to neutron and electromagnetic background.
- **This display was very useful interactive tool to judge the background situation.**

Corrosion of PMT glass in ultra-pure water

P. Bourgeois and J. Va'vra, DIRC Note #136, 2000 and SLAC-PUB-8877

"A near panick" after 1 year of operation (1999):



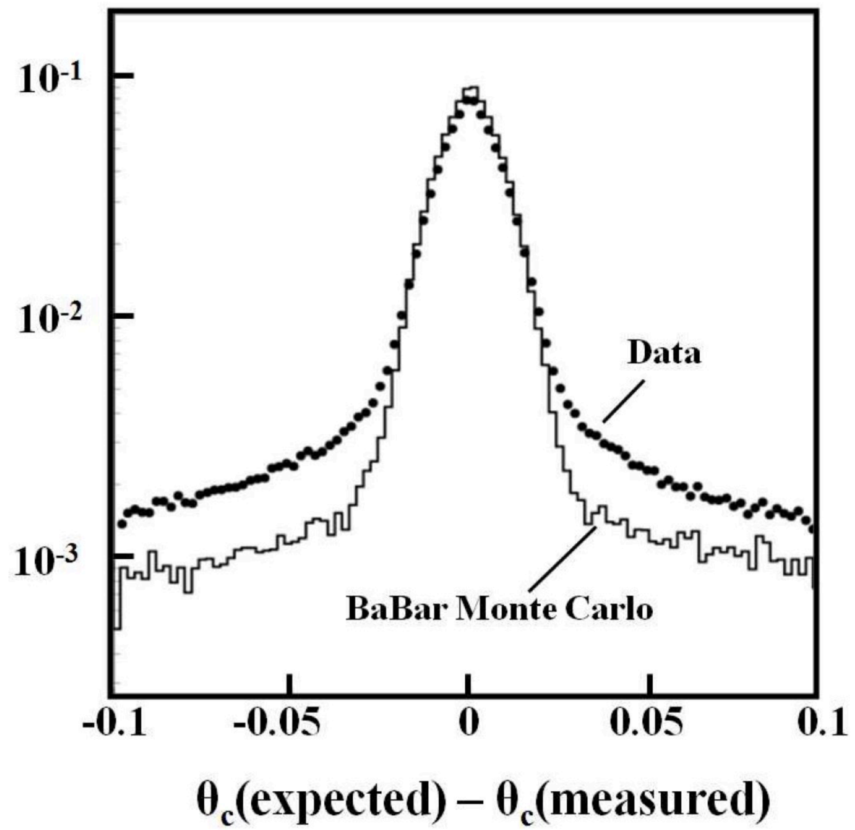


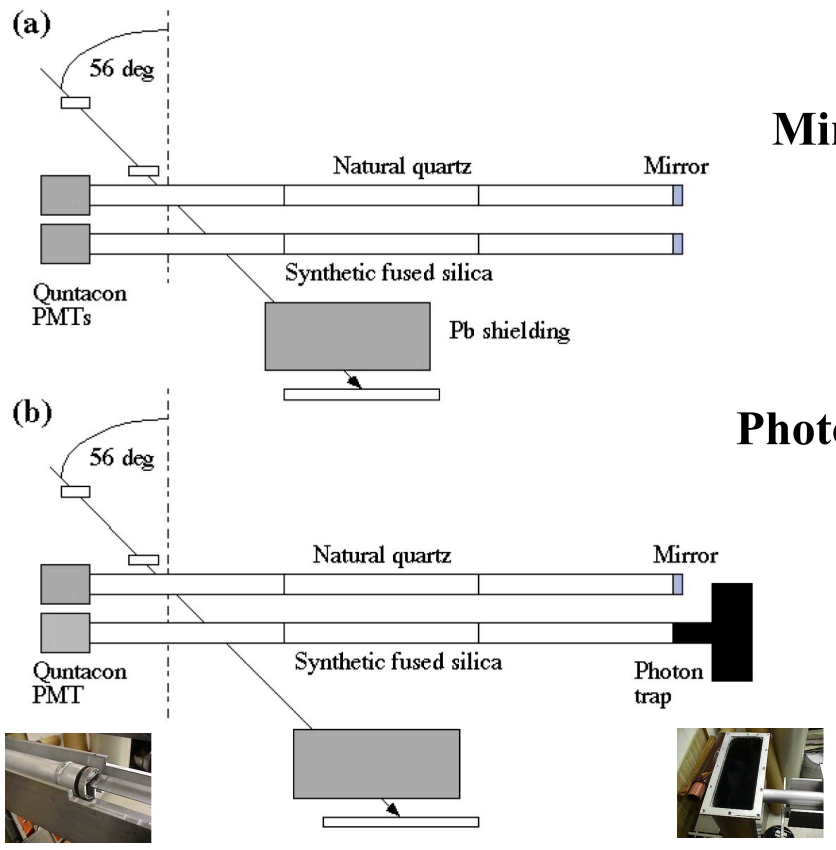
- **About ~50 PMTs were affected by a rapid corrosion, the rest by some corrosion (Water optical coupling helped to reduce the effect of milky surfaces).**
- **Lesson #6: Do not underestimate chemistry ! The PMT glass corrosion depends on a very delicate balance of various glass ingredients. In all samples with heavy corrosion, Zn element was completely missing in the PMT glass.**

Does quartz scintillates ?

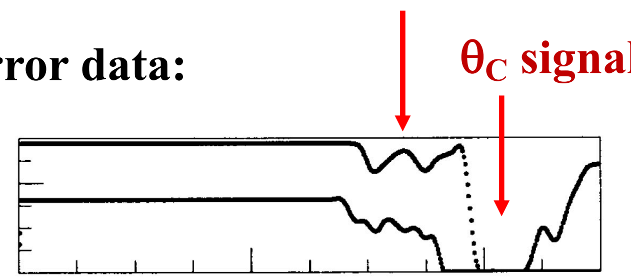
K. Yarritu, S. Spanier and J. Va'vra, DIRC note #141, **2003** & SLAC-PUB-17469

Motivation: BaBar DIRC di-muons:



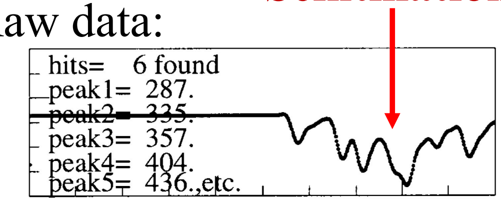


Mirror data:

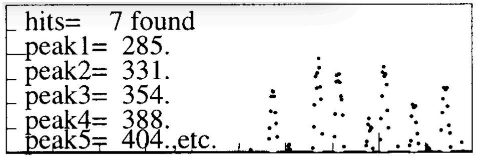


Photon trap data:

Raw data:



After deconvolution:

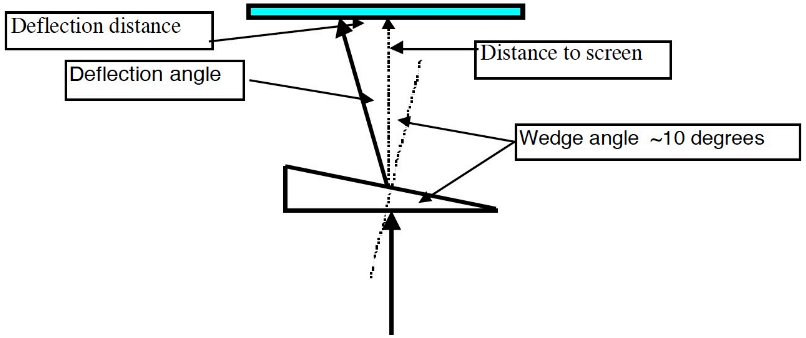


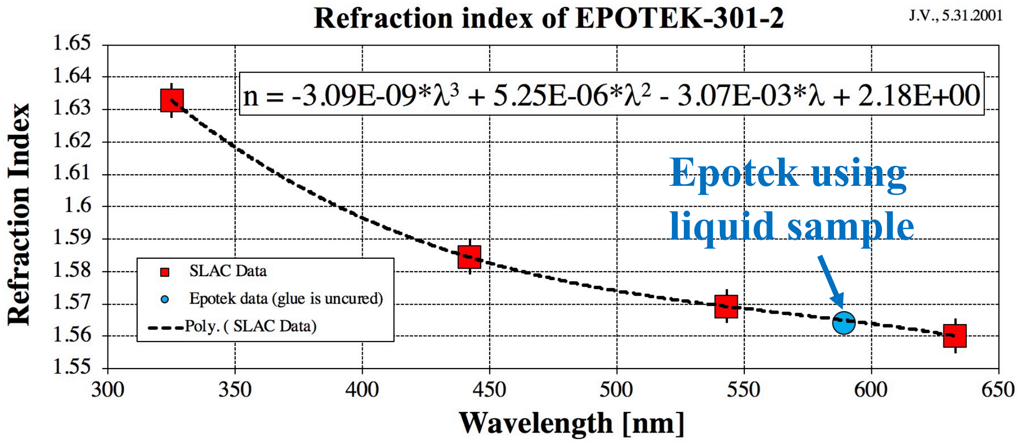
- **Scintillation rate in natural quartz bar is the about same as in the Fused silica bar.**
- **Lesson #7: We found that the scintillation contributes less than 1% of the Cherenkov signal, have to look for some other effect to explain tails – see next slide.**

Does glue/quartz interface scattering follows the Fresnel law ?

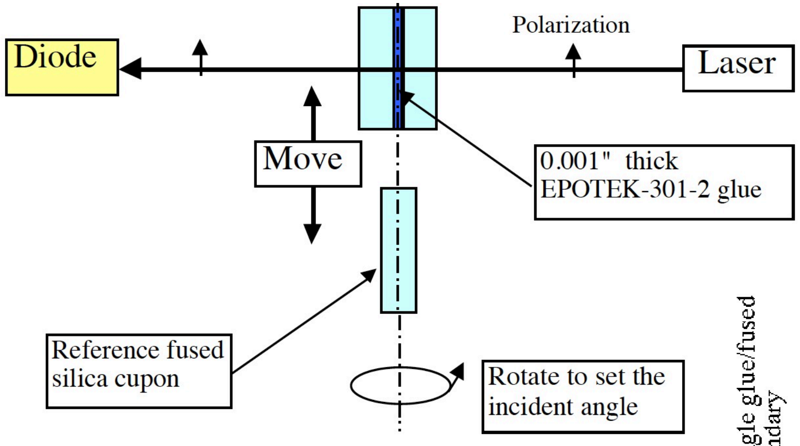
J. Va'vra, DIRC Note # 140, **2001** & SLAC-PUB-17470 & IEEE Trans., Vol. 49, No. 4, 2002

Setup to measure refraction index:



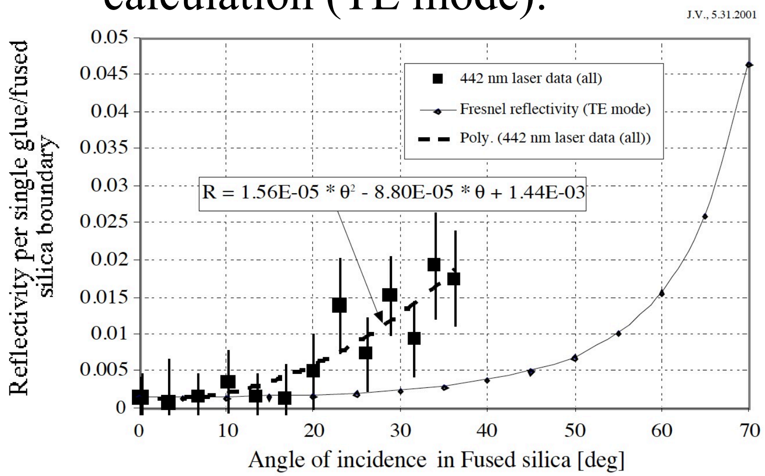


Setup to measure glue reflectivity of a 0.001"-thick sample, as used in DIRC to glue two bars together:



(Laser is polarized)

Compare data with the Fresnel calculation (TE mode):

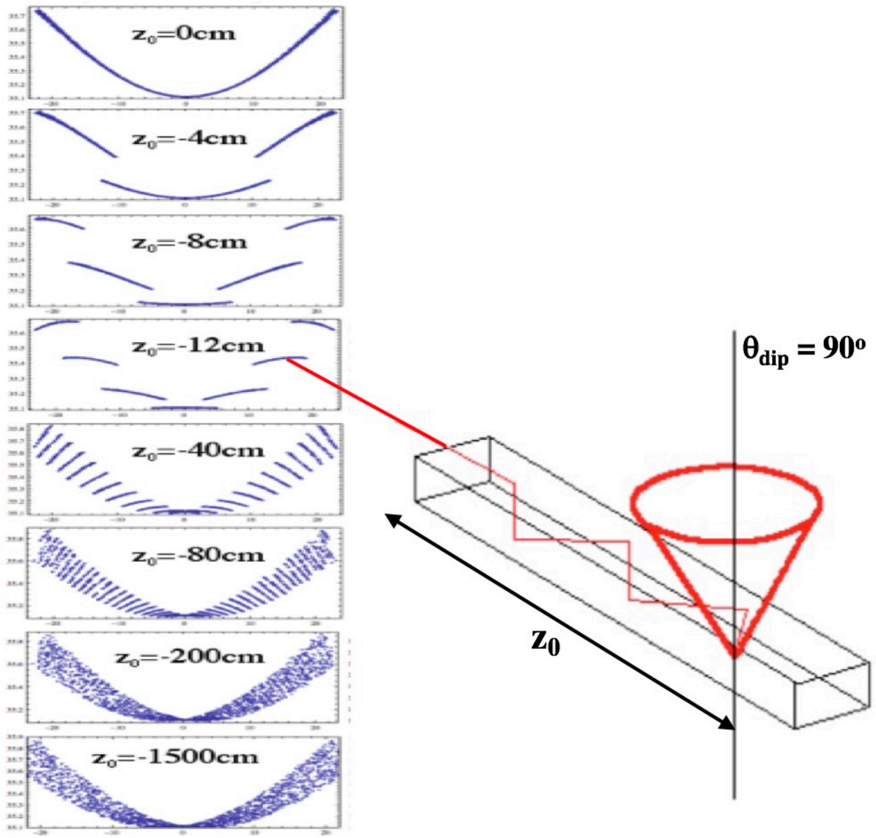


- **Lesson #8: Reflectivity of glue/quartz interface is much larger than what the Fresnel theory predicts, but did not explain tails, although it helped. <u>Perhaps, reflections from the stressed glue/fused silica interface or from quartz polished surfaces are more complex than we think ?</u>**
- **I leave it as a challenge to future DIRC-ers.**

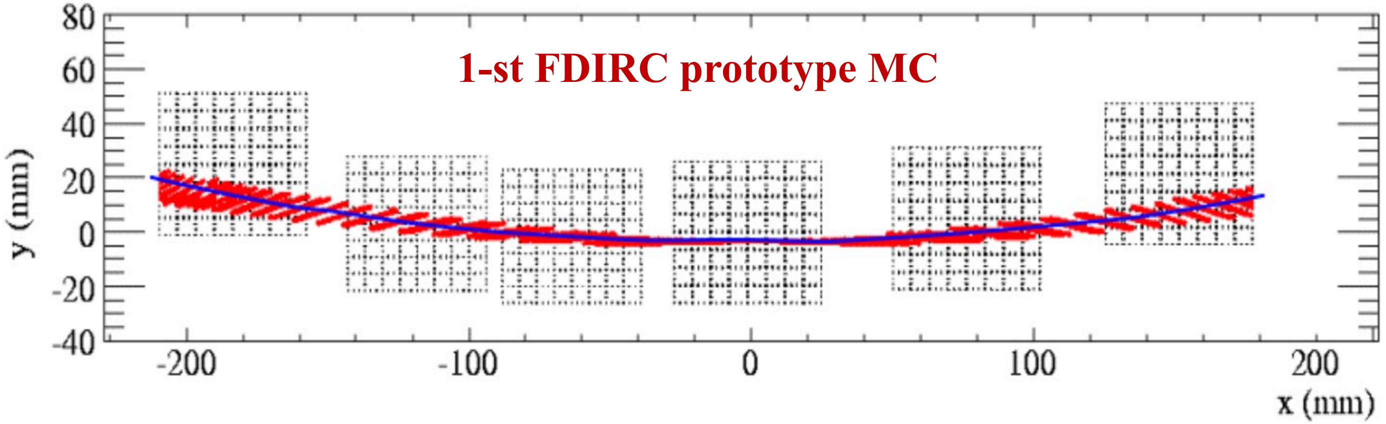
DIRC bars cause a kaleidoscopic structure of the Cherenkov ring

J.Va'vra, Mathematica code, SLAC-PUB-13464, 2008

Vary z_0:



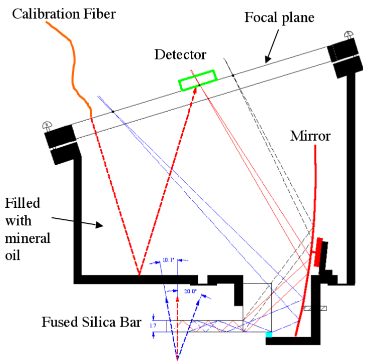
J. Benitez et al., NIMA 595 (2008) 104.

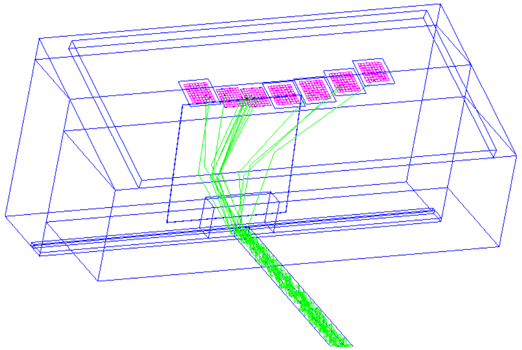


- **Lesson #9: Narrow bars break the Cherenkov ring into segments.**
- **It is a significant effect in all FDIRCs. It is less significant in BaBar DIRC because its camera is large.**

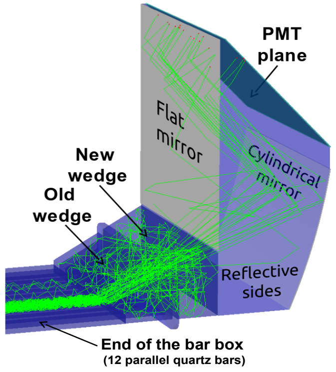
FDIRC development at SLAC

1-st FDIRC prototype:



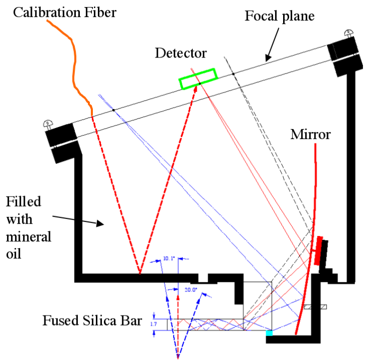


Final FDIRC prototype for SuperB:



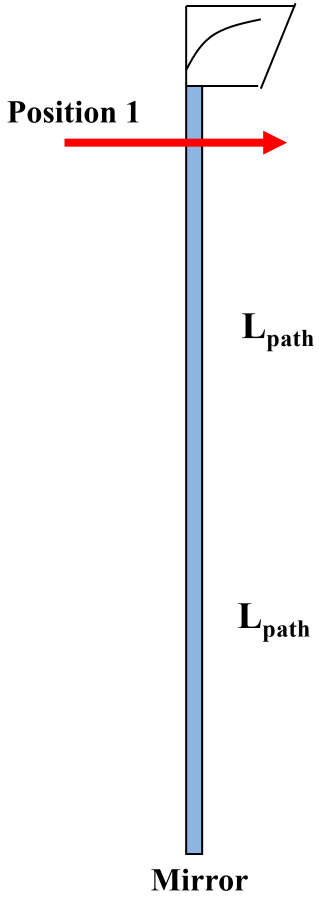
Chromatic broadening in the 1-st FDIRC prototype

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



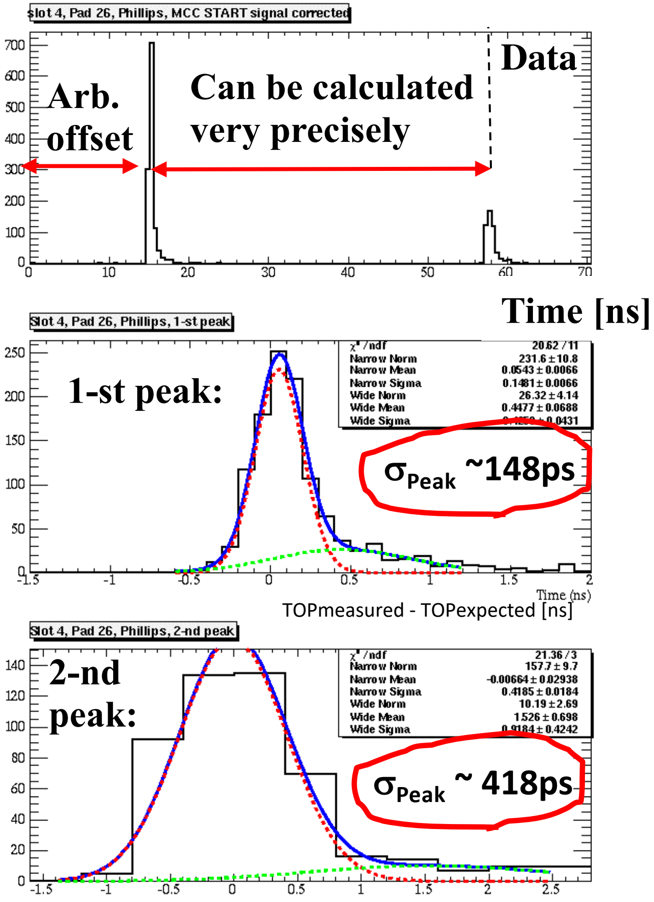
Slot 4, **single pixel** time distribution:

10 GeV electron beam



L_{path} ~ 1-1.5 m:

L_{path} ~ 10-12 m:



dTOP = TOP_measured - TOP_expected (410nm) [ns]

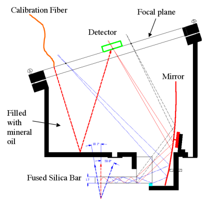
TOP = Time-of-propagation of photon in the bar

- **Lesson #10: The chromatic time dispersion is significant in DIRCs with long photon path lengths.**
- Note: A laser-based MCP photon timing resolutions was 80-100 ps per photon with the SLAC electronics.

The 1-st FDIRC test: can we do chromatic error correction ?

J. Benitez, I. Bedajanek, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff, K. Suzuki, J. Schwiening, J. Uher, L.L. Ruckman, G. Varner, and J. Va'vra,

SLAC-PUB-12236 & NIMA 595 (2008) 104



Time of propagation is controlled by n_{group} : TOP = $L_{path}\, n_{group}/c$, $TOP/L_{path} = 1/v_{group}$,

Cherenkov angle production is controlled by n_{phase} : $\cos\theta_c = 1/(n_{phase}\,\beta)$

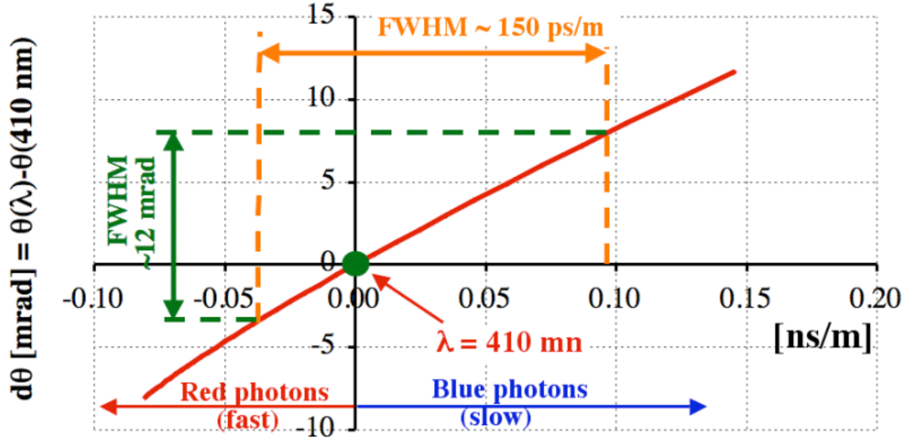
n_{phase} and n_{group} are of course related: $v_{group} = c/n_{group} = c/[n_{phase} - \lambda*(dn_{phase}/d\lambda)]$

θ_c correlates with TOP/L_{path}

θ_c (red) < θ_c (blue)

v_{group}(red) > v_{group} (blue)

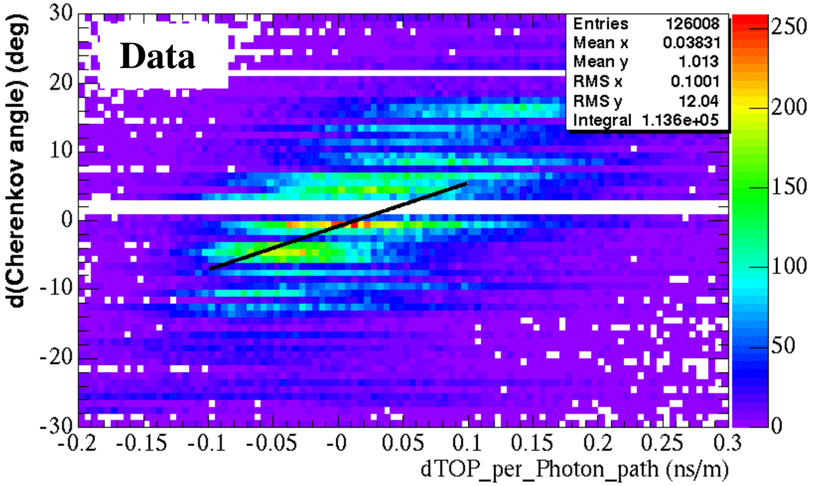
Expected chromatic correction



dTOP/Lpath [ns/m] =TOP/Lpath(λ) - TOP/Lpath(410nm)

10 GeV e^- beam:

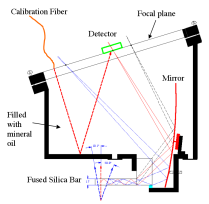
Data from the 1-st FDIRC prototype:



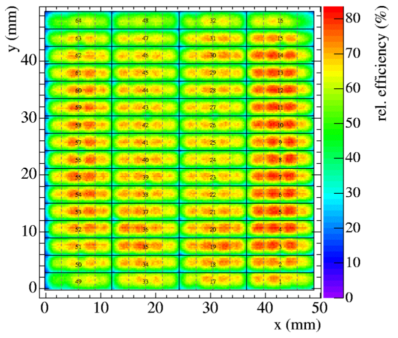
Lesson #11: Because of this correlation, one can either correct pixel-based Cherenkov angle using time, or correct TOP-based Cherenkov angle using pixels.

The 1-st FDIRC prototype performance with 3mm x 12 mm pixels

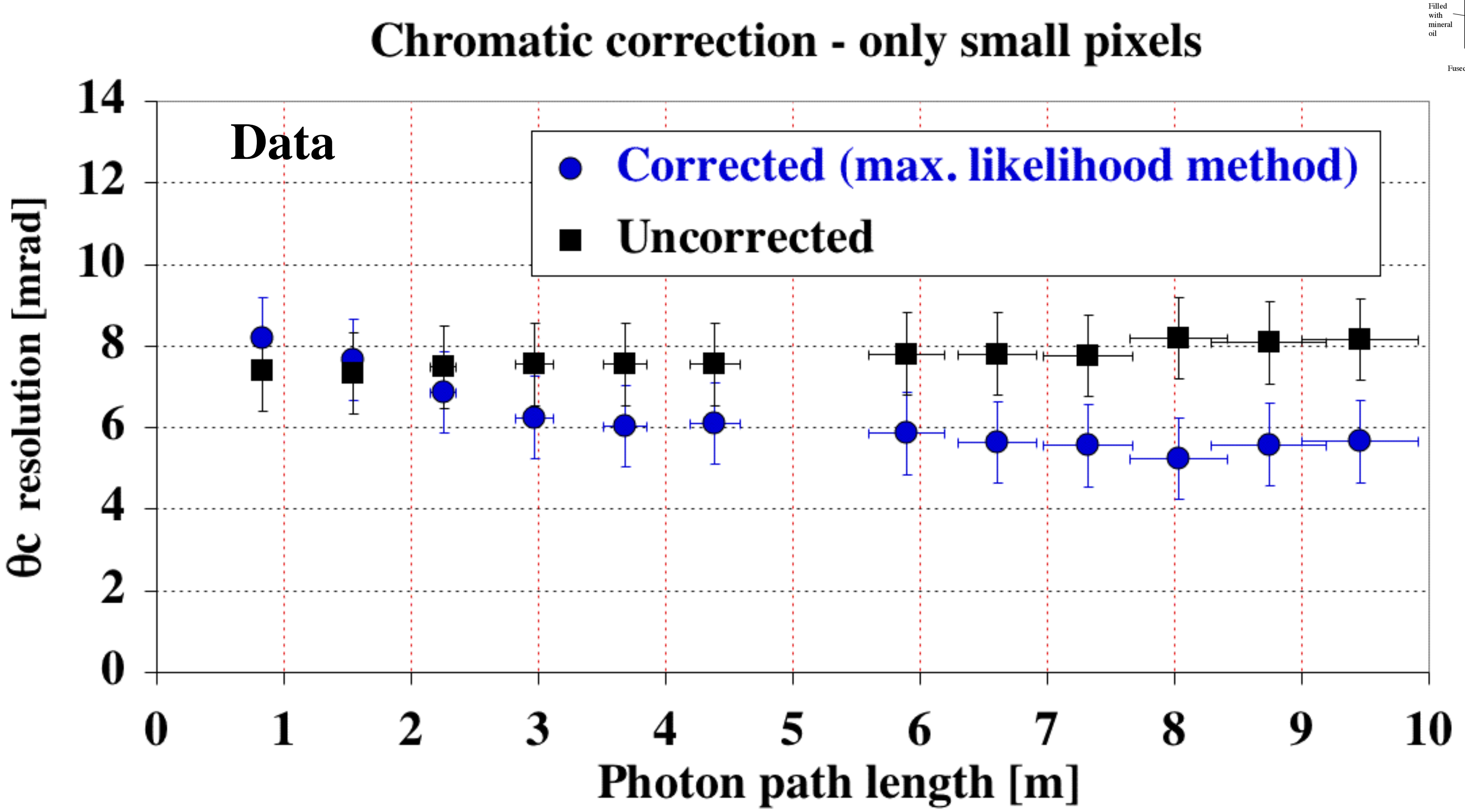
J. Benitez, I. Bedajanek, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff, K. Suzuki, J. Schwiening, J. Uher, L.L. Ruckman, G. Varner, and J. Va'vra, SLAC-PUB-12236 & NIMA 595 (2008) 104



H-9500 MaPMT:



Pixel size: **~3 mm x 12 mm**

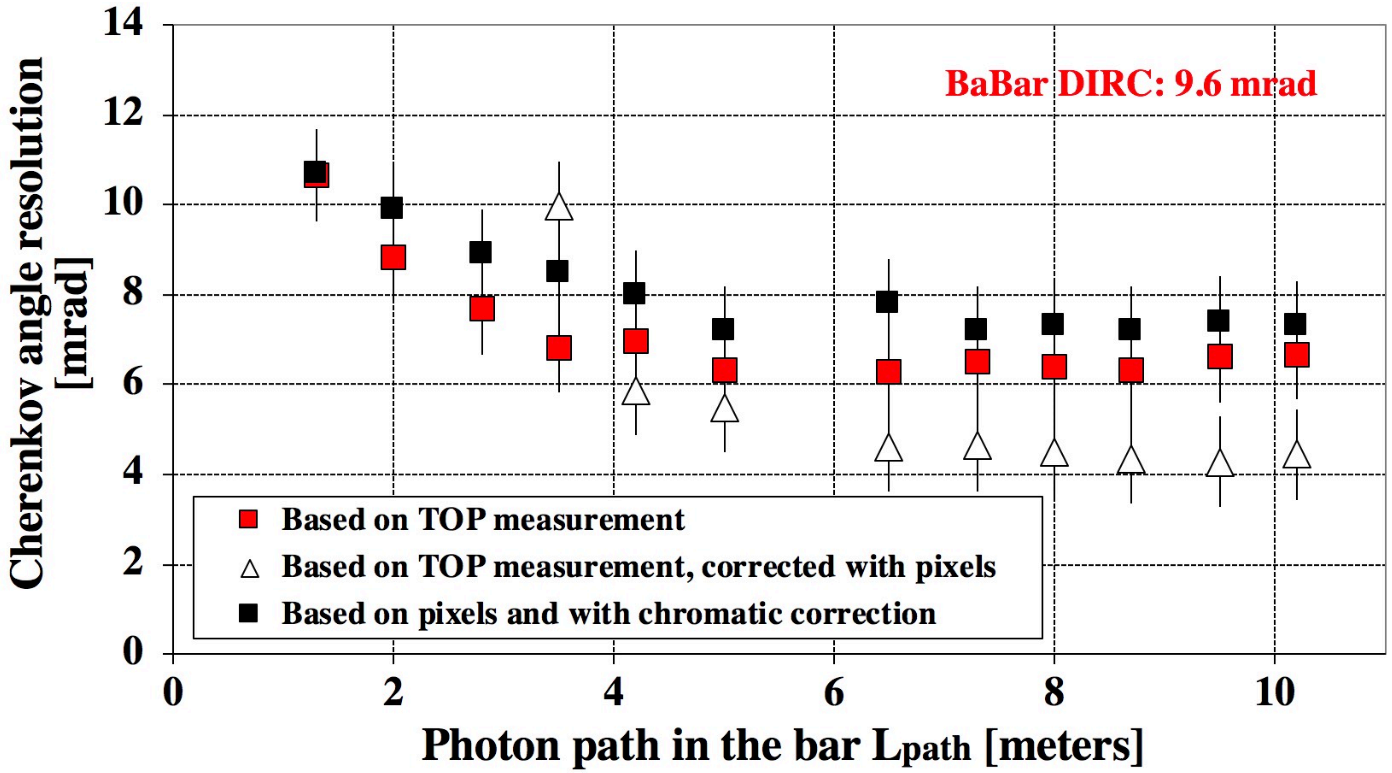


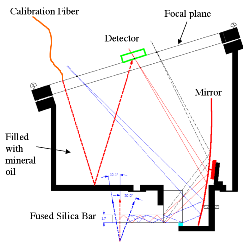
Lesson #12: The first Cherenkov detector can correct the chromatic error <u>using time,</u> if the single photon timing resolution is ~200ps.

The 1-st FDIRC prototype performance with time-based analysis

J. Benitez, I. Bedajanek, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff, K. Suzuki, J. Schwiening, J. Uher, L.L. Ruckman, G. Varner, and J. Va'vra, SLAC-PUB-12236 & NIMA 595 (2008) 104

10 GeV e$^-$ beam:

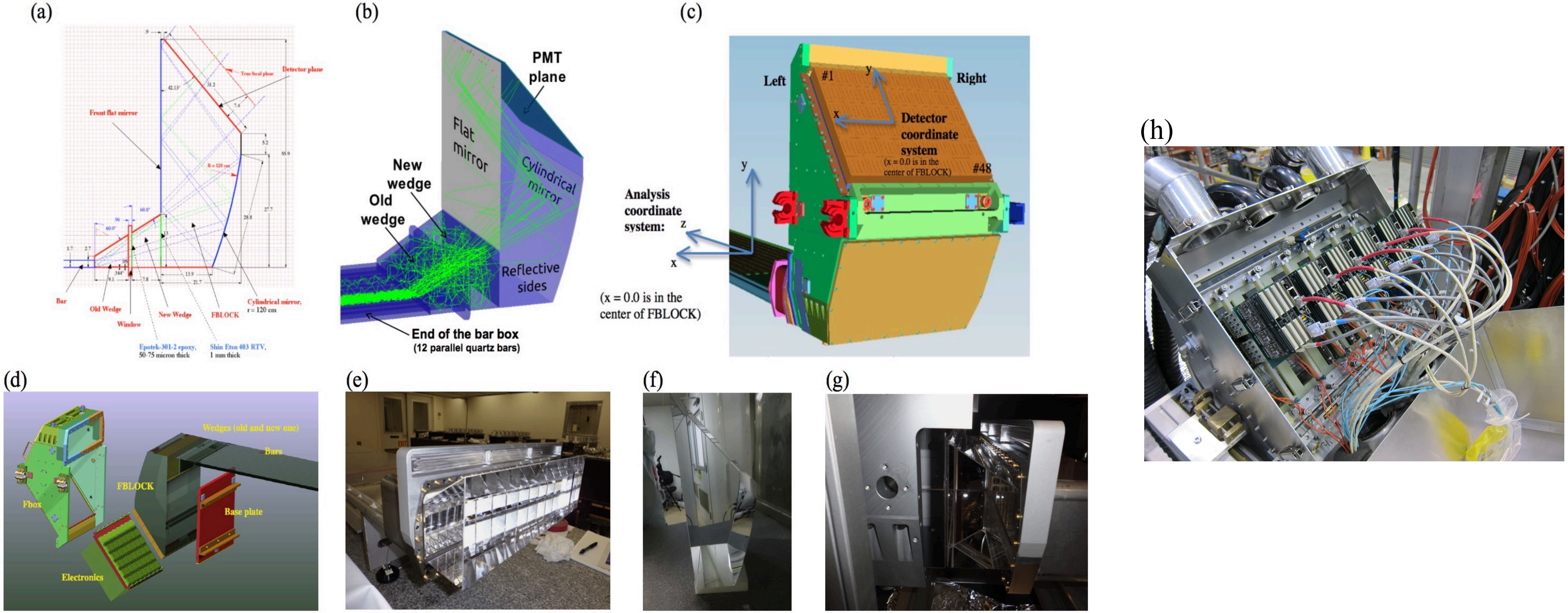




- **Lesson #13: The <u>TOP-based</u> Cherenkov angle resolution is slightly better than pixel-based resolution; <u>TOP-based</u> resolution can be further improved using the <u>pixel-based</u> correction.**
- **This correction requires that both time and the angular resolution measured well.**
- This particular plot is based on data from the 1-st FDIRC prototype instrumented with SLAC electronics, and 4 MCP-PMTs , and two H-8500 MaPMTs.

Final FDIRC prototype design

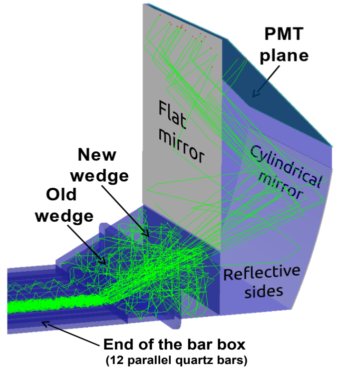
B. Dey, M.Borsato, N.Arnaud, D.W.G.S.Leith, K.Nishimura, D.A.Roberts, B.N. Ratcliff, G.Varner, J.Va'vra, NIMA 775 (2015) 112



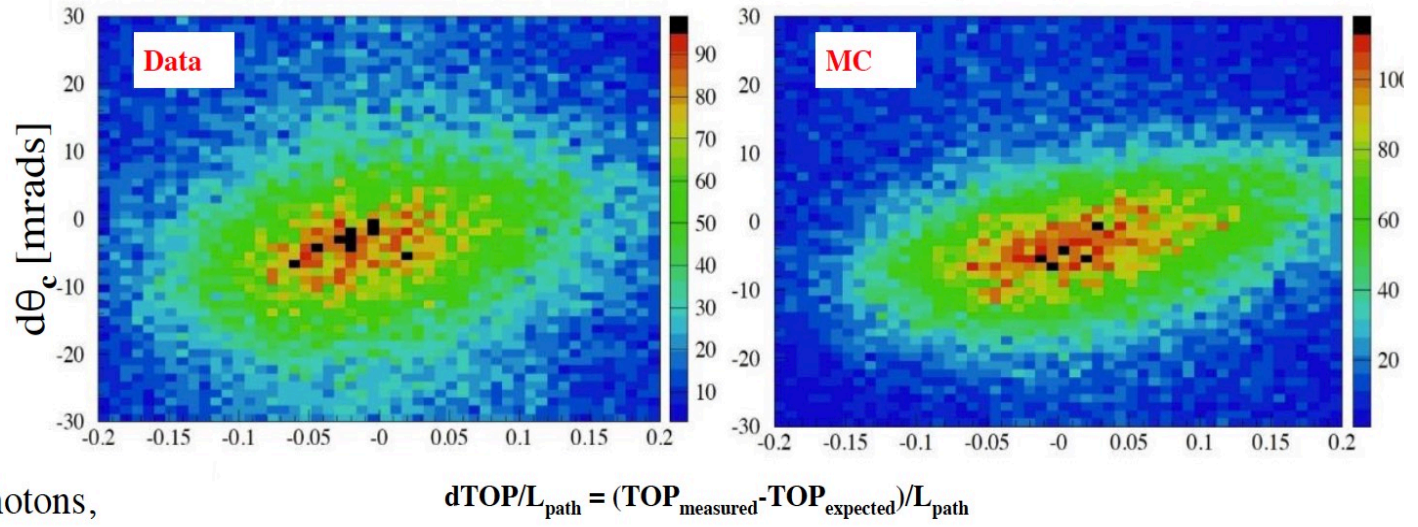
(a) FDIRC optical design. (b) A 3D simulation of photon paths in the FDIRC optics using Geant4. (c) FDIRC coordinate system. (d) Parts of the FDIRC photon camera. (e) New wedge glued to the bar box window. (f) Finished FBLOCK, made of solid Corning 7980 fused silica. (g) Details of coupling between FBLOCK, new wedge and bar box, and (h) SLAC Elantek amplifier + Hawaii IRS-3 waveform digitizing electronics read out **12 H-8500 MaPMTs – 768 pixels.**

Chromatic correction: Data vs. MC simulation for 3D tracks

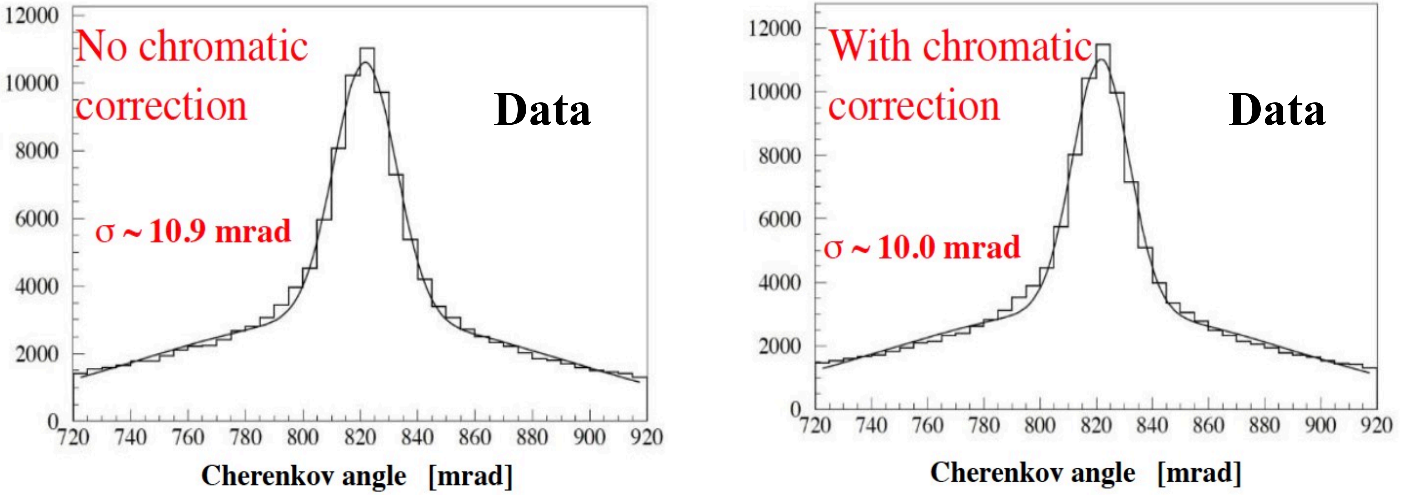
N. Arnaud, M. Borsato,, B. Dey, D.W.G.S. Leith, K. Nishimura, B.N. Ratcliff, D. Roberts, G. Varner, J. Va'vra , NIMA 775(2015)112



Tests were done in cosmic ray telescope (CRT):

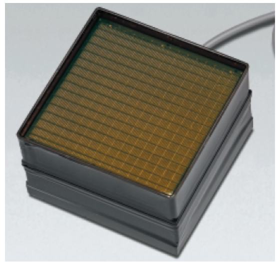


Backward photons, long paths



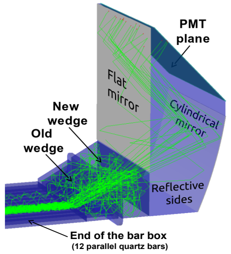
- **Lesson #14: Even with a single photon timing resolution of only σ ~ 0.5ns, FDIRC can still do very well and even correct chromatic error. This is an advantage of pixel-based technique.**

H-9500 MaPMT
3mm x 12 mm



Simulation of FDIRC design with 3 mm x 12 mm pixels

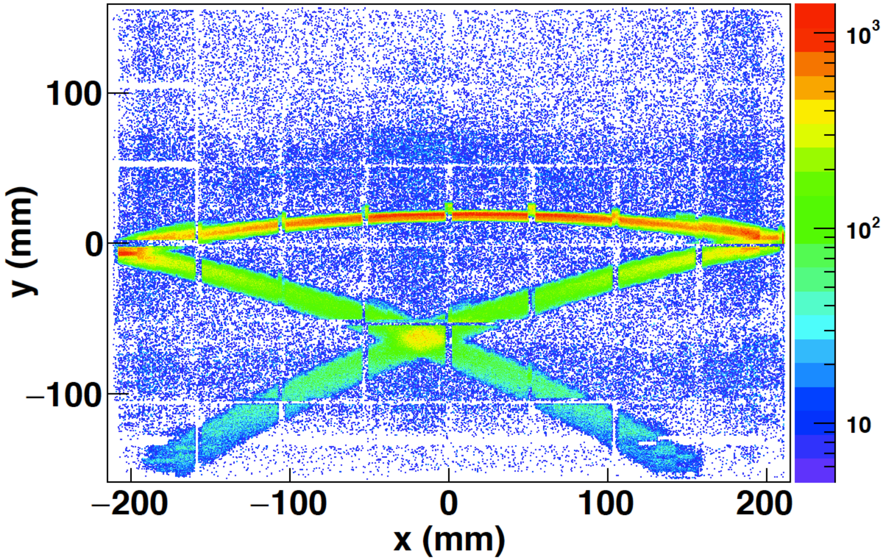
B. Dey, B.N. Ratcliffc, J. Va'vra , NIM A 876 (2017) 141

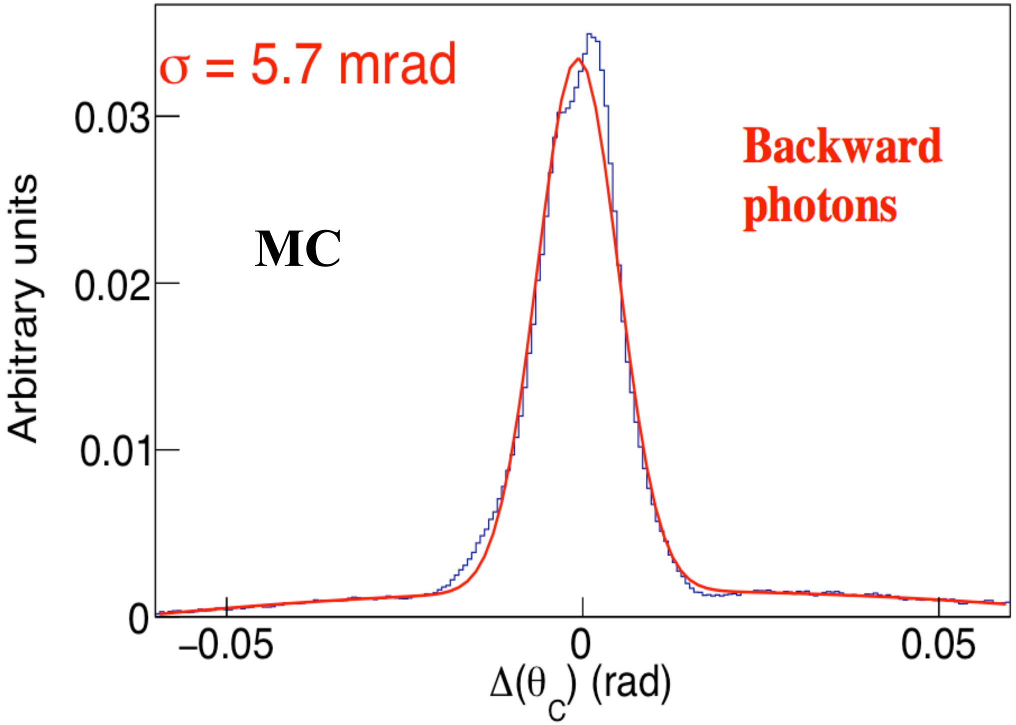


10 GeV muons & for perpendicular tracks:

Cherenkov ring x-y image in FDIRC:

(show individual hits)

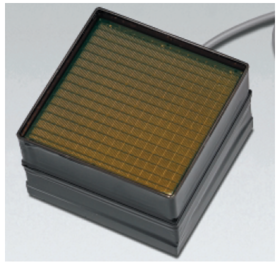




- Single photon resolutions for backward going photons: $\boldsymbol{\sigma_{\theta c} \sim 5.7}$**mrad.**
- This design assumes a BaBar bar box **without any changes**.

Ultimate DIRC design

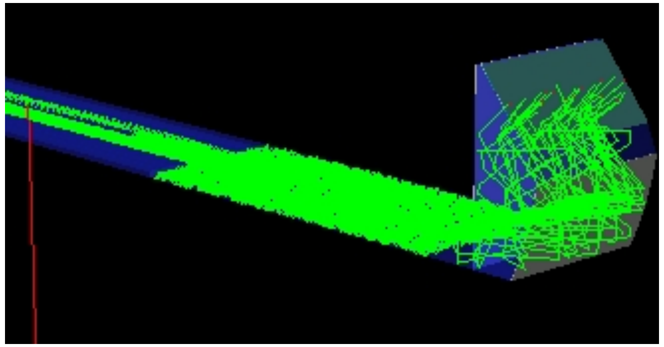
H-9500 MaPMT
3mm x 12 mm



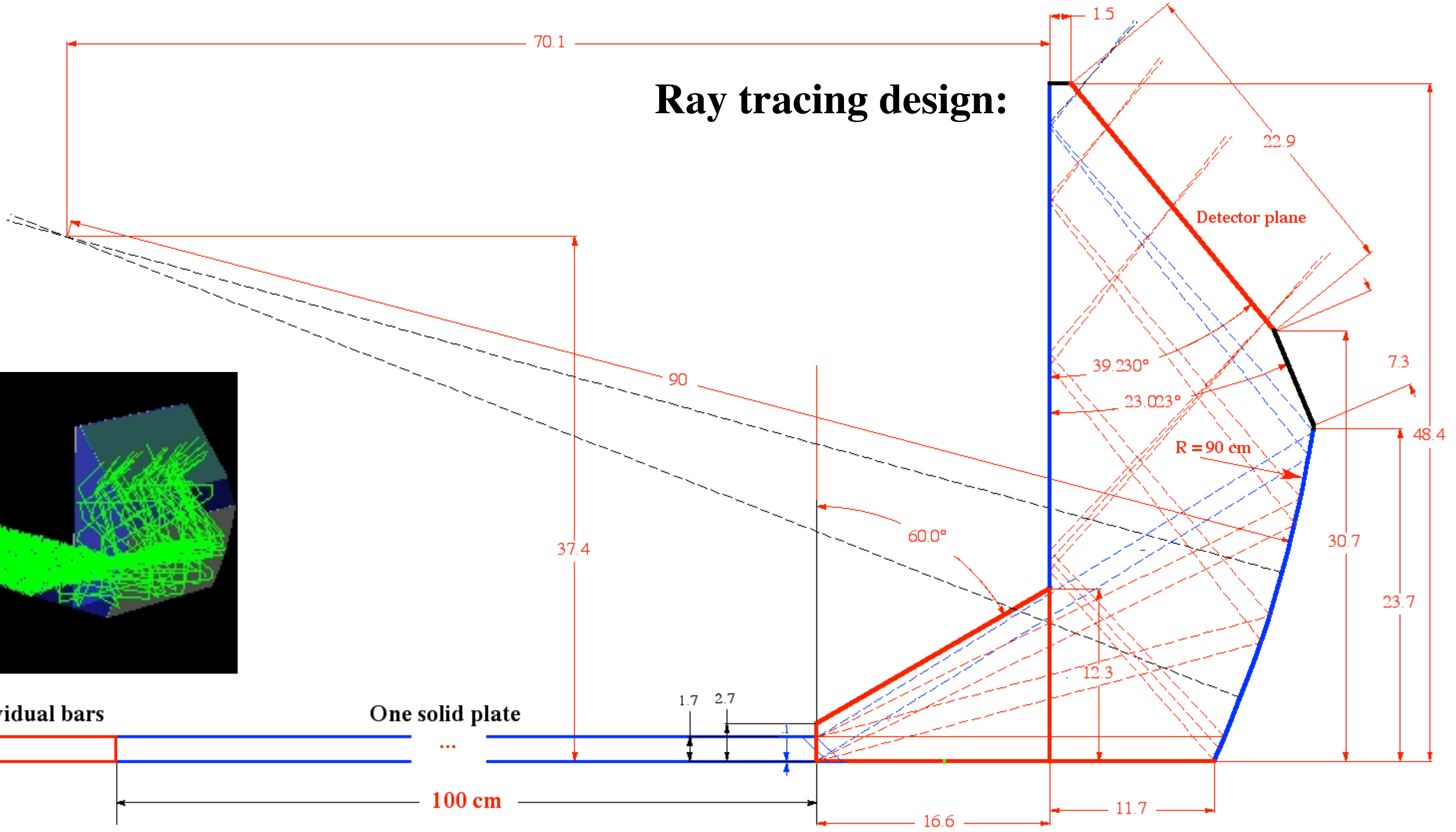
New smaller FDIRC with wide plate & bars

B. Dey, B.N. Ratcliffc, J. Va'vra , NIM A 876 (2017) 141

MC simulation:

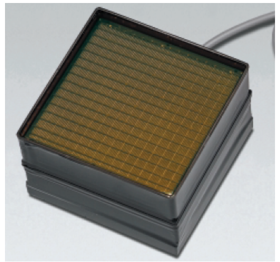


Ray tracing design:



- **This design improves the pinhole optics in the x-direction; cylindrical lens is focusing in y-direction.**
- **Babar bar box would have to be modified:** the last group of bars would be replaced by a 1m-long wide plate, and the BaBar DIRC wedge would be replaced with a new longer one.

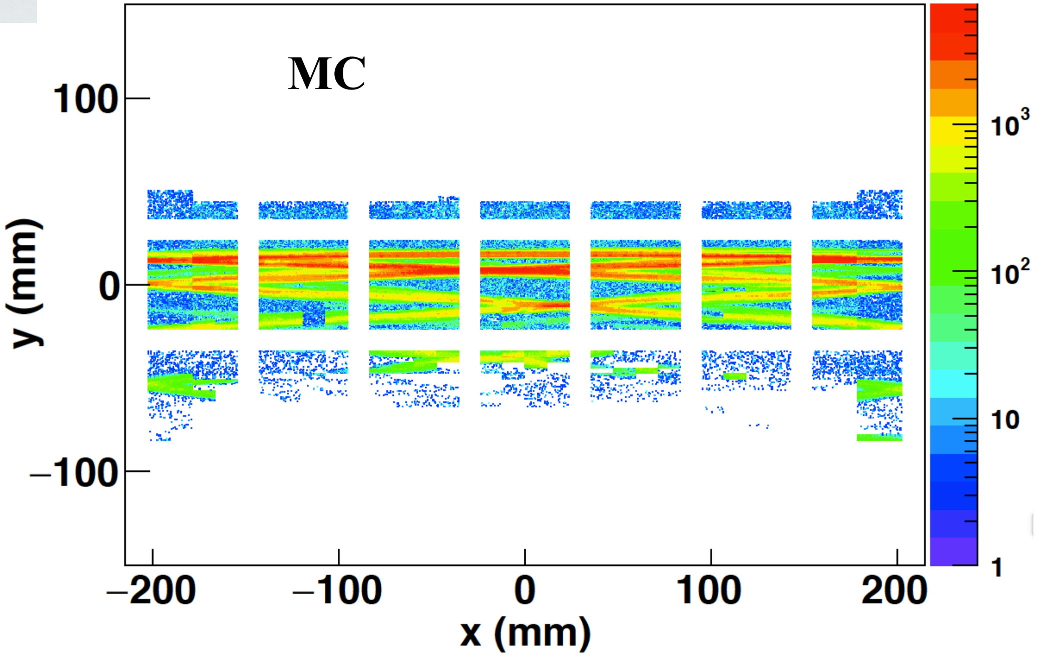
H-9500 MaPMT
3mm x 12 mm



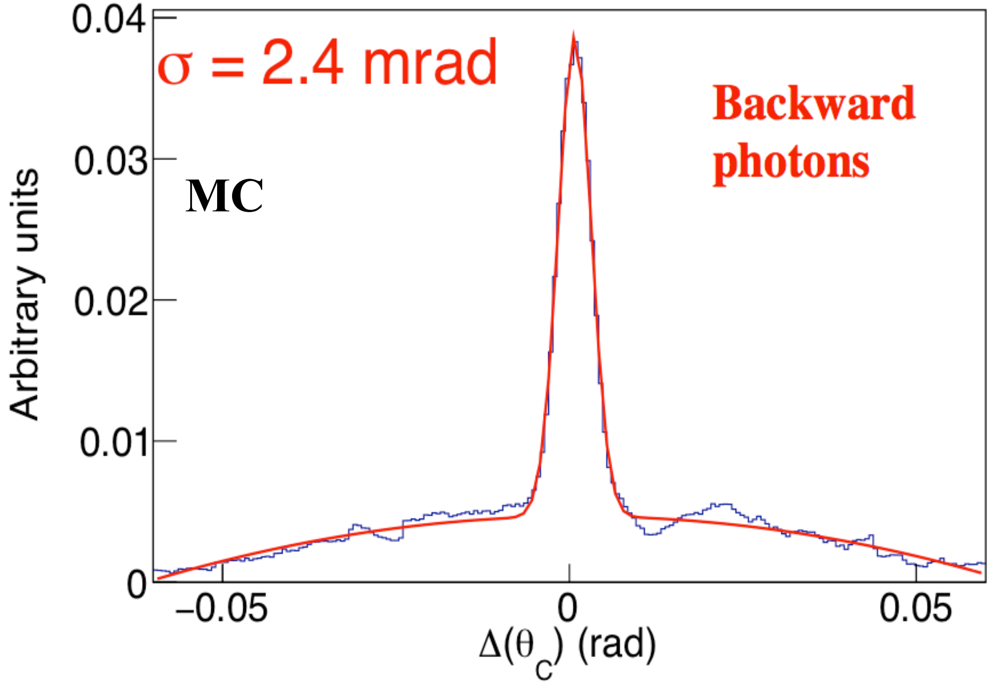
New smaller FDIRC with wide plate & bars

B. Dey, B.N. Ratcliffc, J. Va'vra , NIM A 876 (2017) 141

Cherenkov ring x-y image in FDIRC:
(show individual hits)



10 GeV muons & for perpendicular tracks:



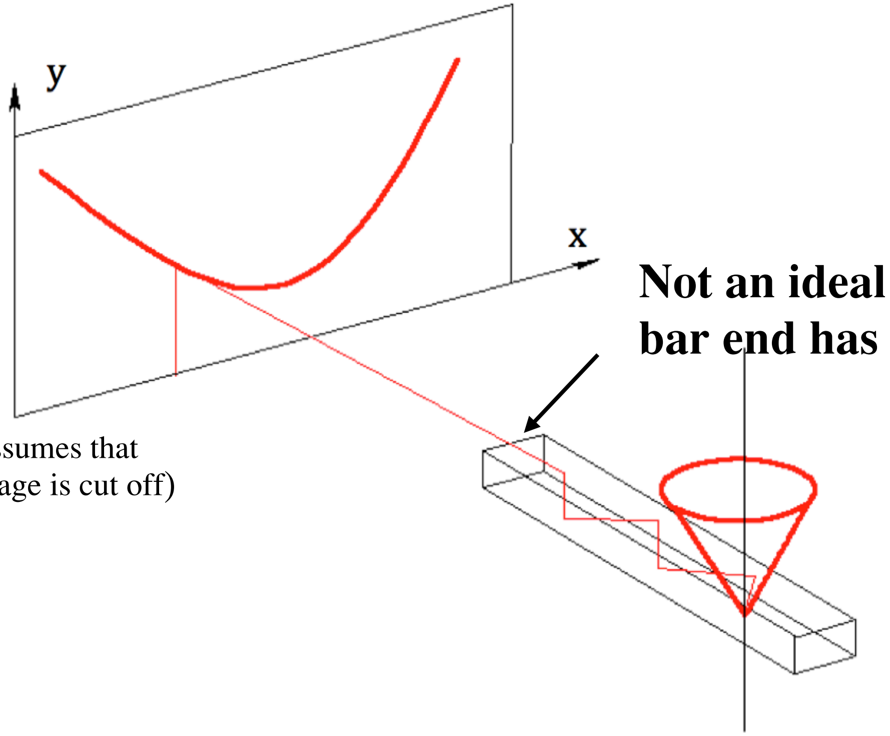
- **This result was obtained using the pixel-based analysis with the chromatic correction.**
- **We have not tried the time-based analysis with a pixel correction, as was done on slide 17.**
- **If you have such a good resolution, it pays to improve tracking.**
- **Lesson #15: This is the best DIRC design I have seen.**

Conclusion

- **BaBar DIRC was a successful detector and it was a privilege to work on it.**
- **DIRC detectors that combine precise <u>angular and time measurements</u> are likely to provide the "ultimate performance" in the future DIRC detectors.**
- **The trend is to make the focusing photon camera smaller, equipped with highly pixilated detectors. Imagination, how to arrange the "focusing" optics, has no limit. I call all these designs as "Focusing DIRCs".**

Appendix

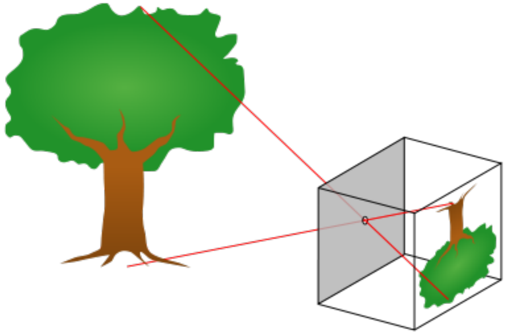
DIRC imaging principle



(Picture assumes that
bottom image is cut off)

Not an ideal pin hole, as bar end has a finite size

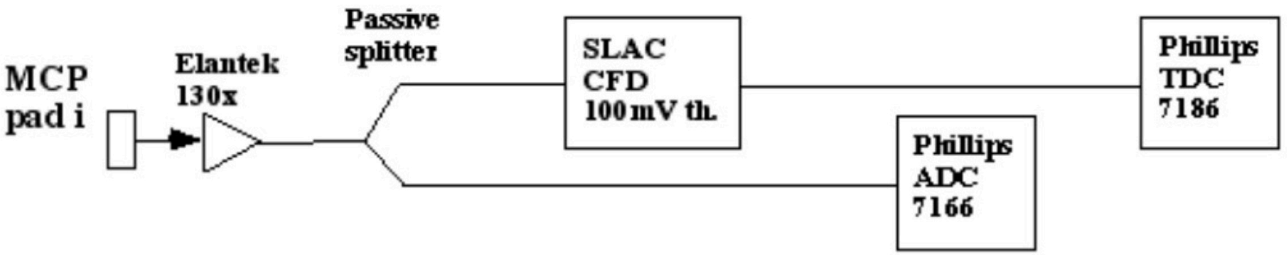
Pin hole camera principle:

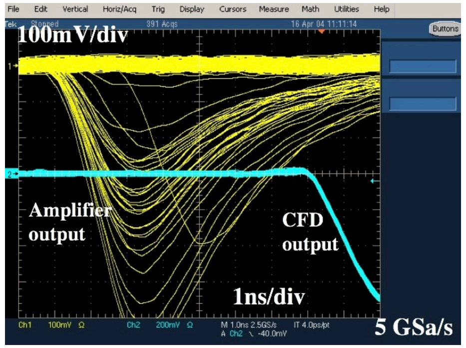


- If the pin hole is too big, or the imaging plane too close, one gets a blurred image.
- BaBar DIRC has chosen to solve this problem by using a very large photon detector size.
- I will discuss several solutions how to minimize this effect in FDIRCs.

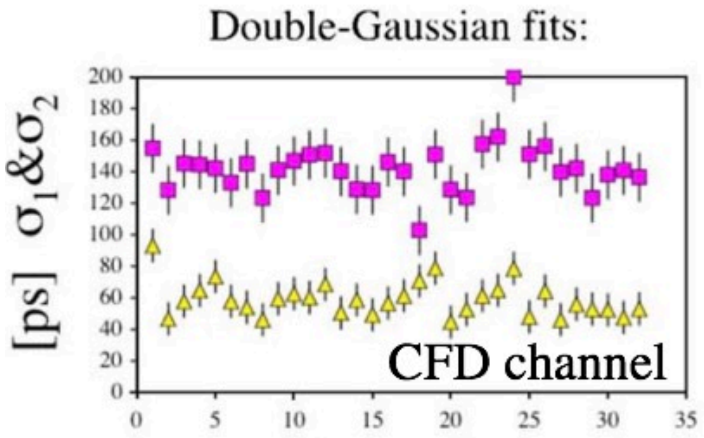
1-st FDIRC prototype used initially a simple electronics

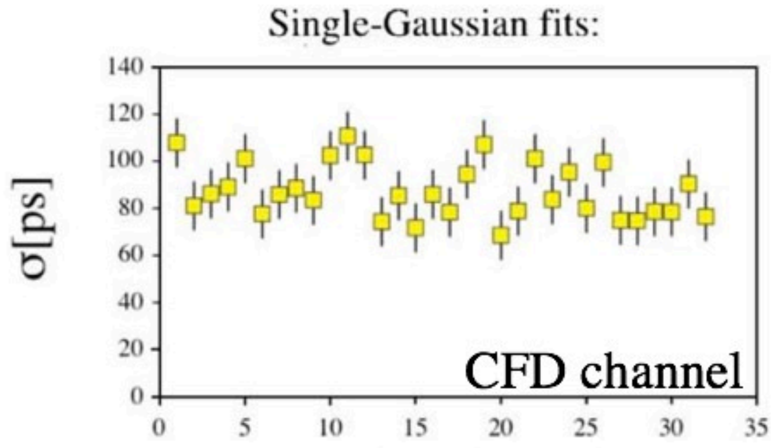
J. Benitez, I. Bedajanek, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff, K. Suzuki, J. Schwiening, J. Uher, L.L. Ruckman, G. Varner, and J. Va'vra,
SLAC-PUB-12236, 2008





Bench top laser measurements with single photons:



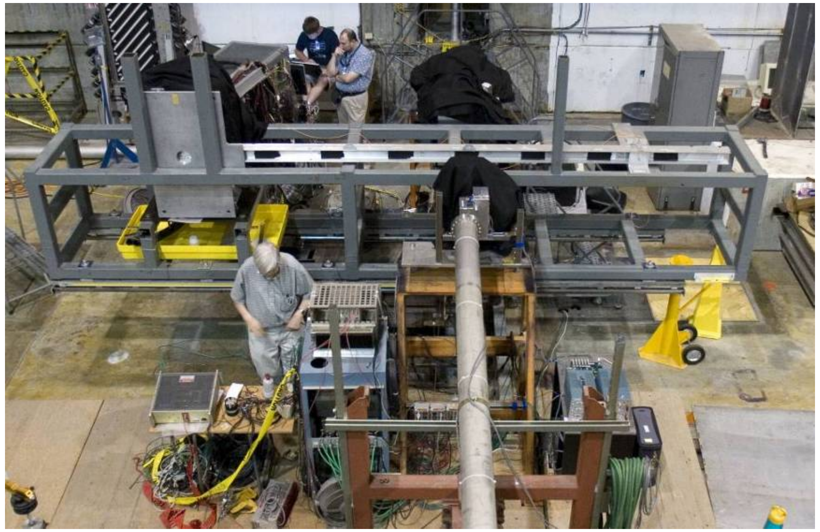


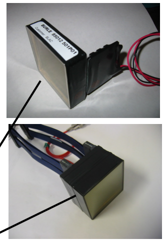
- **A typical MCP single photon timing resolutions was 80-100 ps per photon.**
- **This electronics was instrumented on ~320.**
- **Lesson #10: One can achieve a pretty good timing resolution even with a simple electronics.**

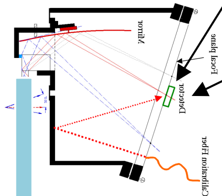
The 1-st FDIRC prototype test beam setup – 1D tracks

J. Benitez, I. Bedajanek, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff, K. Suzuki, J. Schwiening, J. Uher, L.L. Ruckman, G. Varner, and J. Va'vra,
SLAC-PUB-12236 & NIMA 595 (2008) 104

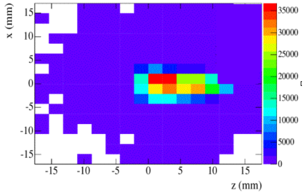
- **Beam test instrumentation:**
  - Two x-y scintillating fiber hodoscopes (σ<1mm)
  - START Quartz counter (σ ~40-45ps)
  - Time start from the LINAC RF signal
  - Lead glass to monitor beam multiplicity (very important in the SLAC's beam)
  - A tandem of two TOF counters
  - Run ~0.2 particles/pulse (need lead glass)
  - **Perpendicular tracks only**





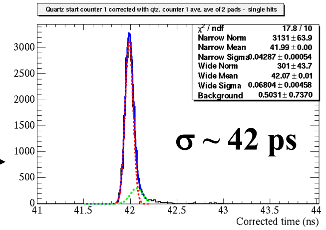


Beam spot: σ < 1mm

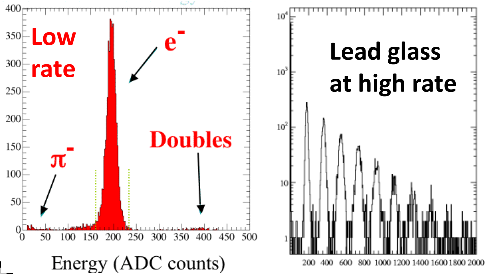


Start Quartz counter
(4-pad MCP-PMT)

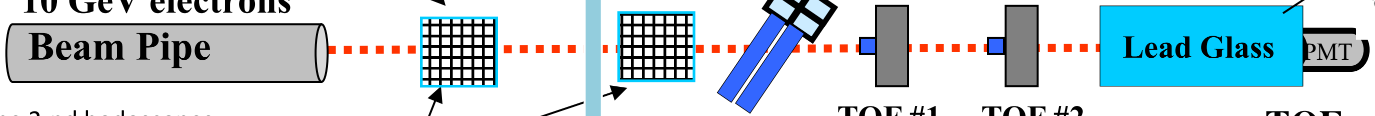
Timing relative to machine:



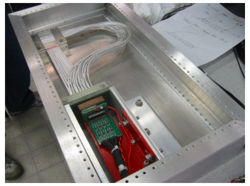
Lead glass:



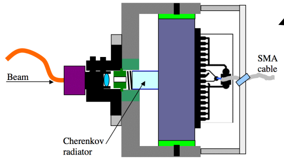
10 GeV electrons



The 2-nd hodoscopes:

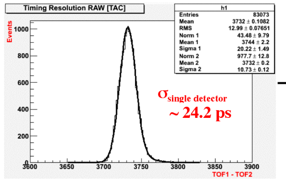


Hodoscopes #1&2 (2mm scint. fibers)

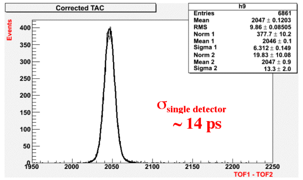


TOF counter result:

Initial result at SLAC:



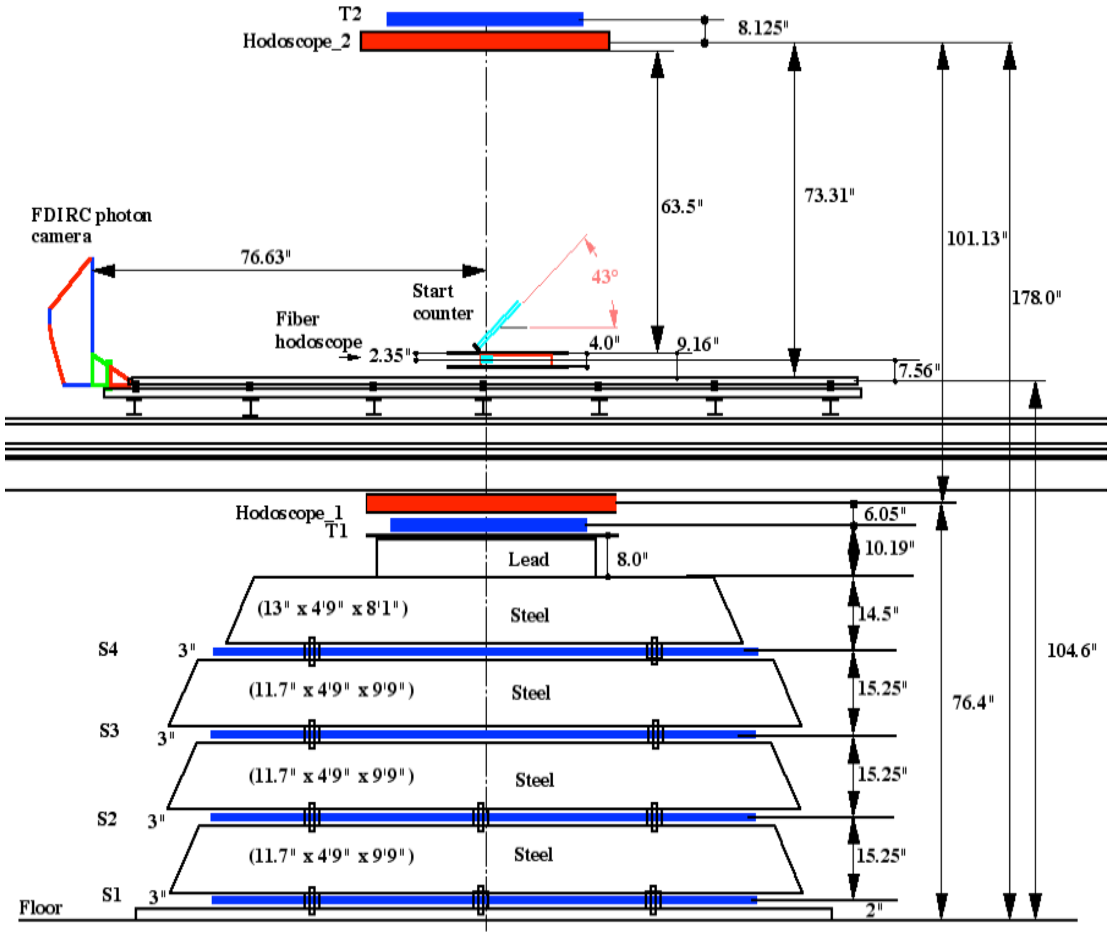
Final Result in Fermilab test beam:



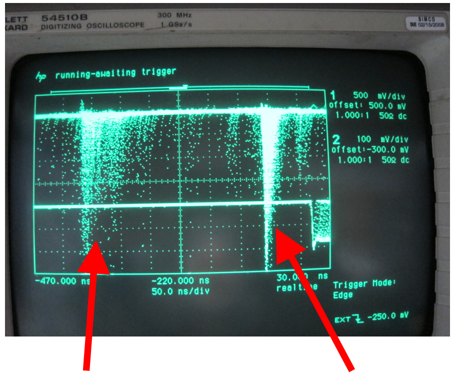
Final FDIRC prototype test in cosmic ray telescope – 3D tracks

B. Dey, M.Borsato, N.Arnaud, D.W.G.S.Leith, K.Nishimura, D.A.Roberts, B.N. Ratcliff, G.Varner, J.Va'vra NIMA 775(2015)112

CRT:



One pixel connected to scope:



- **Iron & lead absorber thick enough to provide a muon momentum cutoff of ~2 GeV.**
- **A non-uniform muon energy contributed ~1 mrad extra to the Cherenkov angle resolution.**