Cherenkov Imaging Techniques

J. Va'vra, SLAC

Plan of this talks

- **Comments about basic properties of :**
  (Refraction index, Photocathodes, Transmission of materials)
- **Examples of large Cherenkov detectors:**
  (HERA-B, DIRC, HERMES, ALICE, COMPASS, LHC-b, BTeV)
- **New ideas/trends in the Cherenkov concepts:**
  (TOP counter, Focusing DIRC)
- **Search for the new photon detectors:**
  (H-8500, MCP-PMT, fine mesh PMT, HAPD, gaseous detectors ????)

Comments about the momentum range

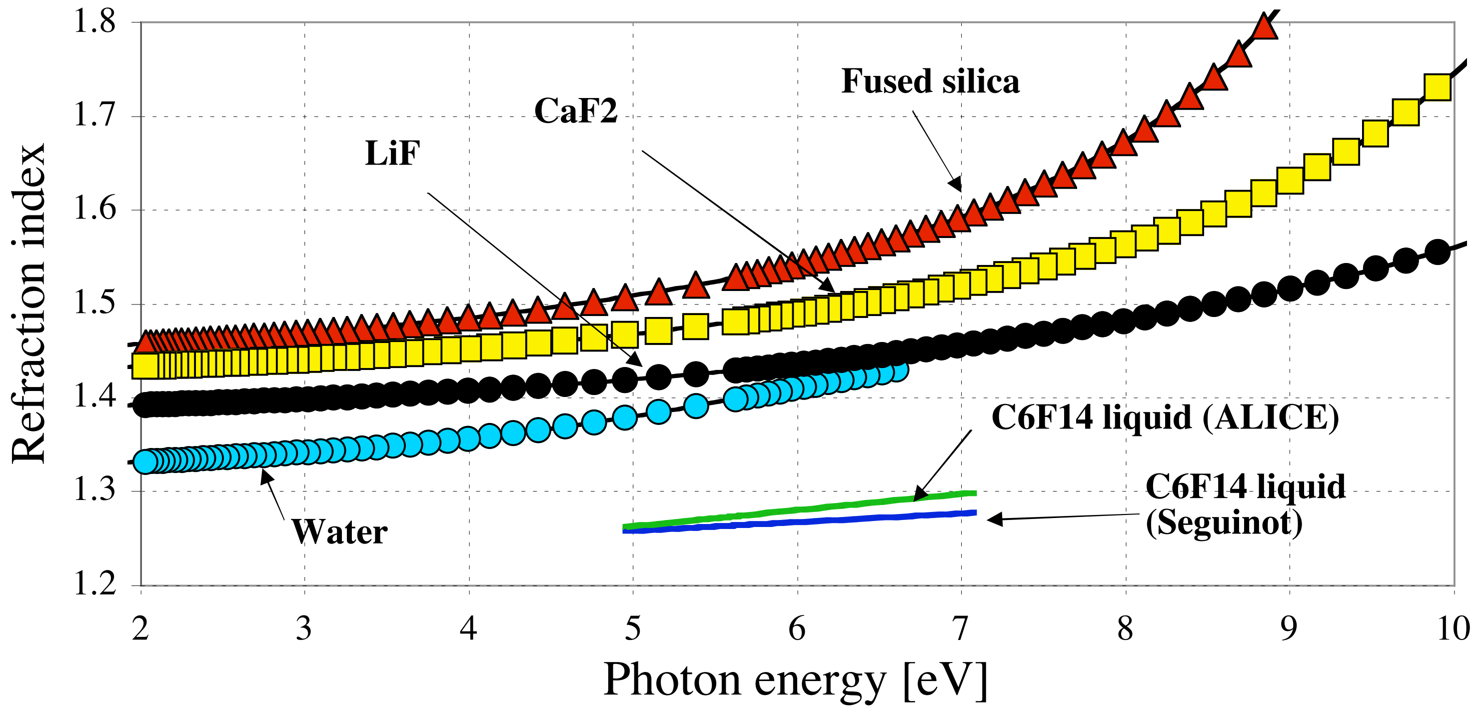
- **Up to ~1.5 GeV/c** (one does not need a RICH device)
  - TOF detector (Example: CDF at Fermilab, ALICE TOF)
- **Up to 3-4 GeV/c:**
  - DIRC (Fused Silica radiator)
  - ALICE (Liquid/solid radiator)
- **Up to 5-6 GeV/c:**
  - Focusing DIRC (Fused Silica radiator)
- **Above 5-10 GeV/c:**
  - One definitely needs a gaseous radiator, which takes away 50-80 cm at least from valuable detector space (Example: HERA-B)

Some basic parameters

- **Refraction index**
- **Photocathode material**
- **Transmission of some basic materials**

Chromaticity of various radiators

J. Va'vra, Nucl.Instr.&Meth., A453(2000)262



- Working in far UV region means large chromatic error.

Number of generated photons by 1cm-thick radiator

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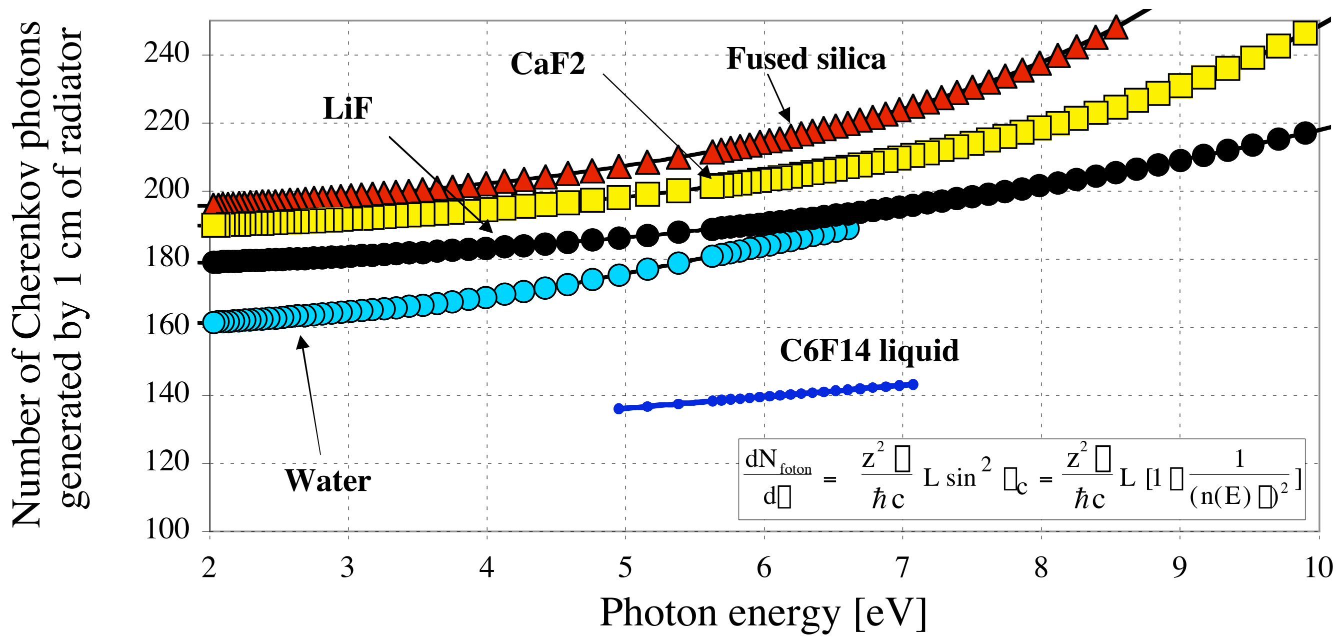
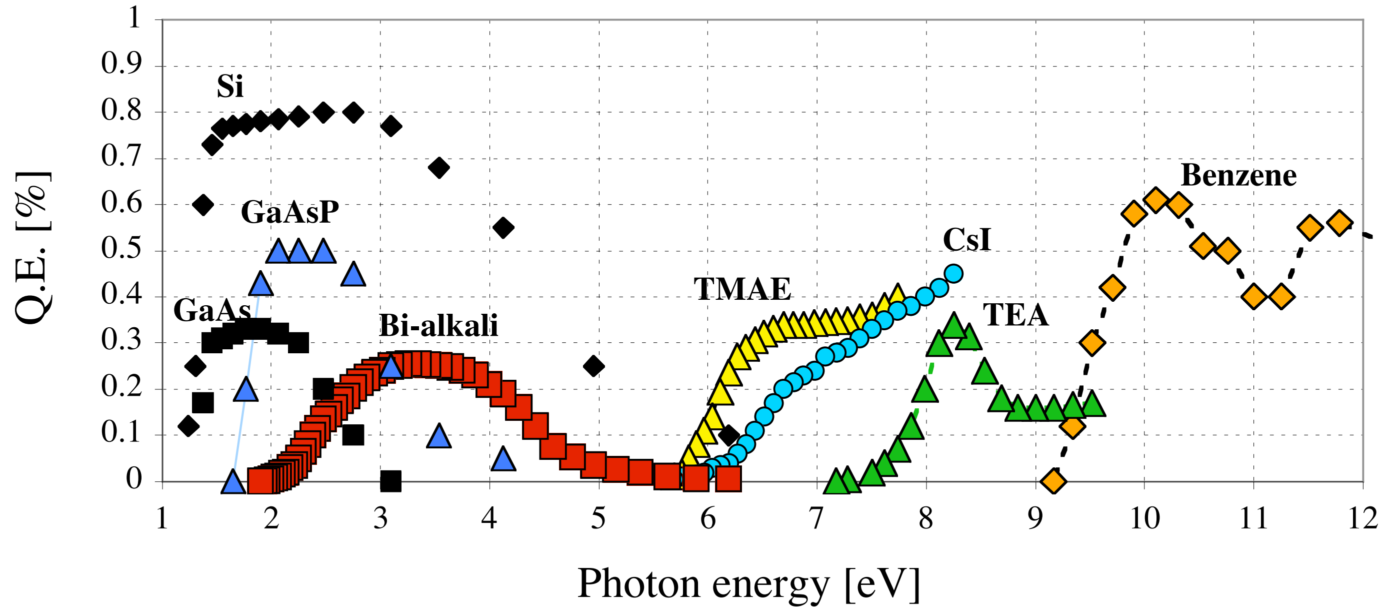


- If the chromatic error is not an issue, as in threshold detectors, the far-UV region yields larger number of photoelectrons.
- Number of photoelectrons in a certain bandwidth:

$$N_{pe} = L \frac{z^2 \alpha}{\hbar c} \int_{E_1}^{E_2} \prod_i \varepsilon_i(E) \sin^2 \theta_c(E)\, dE$$

Photocathodes

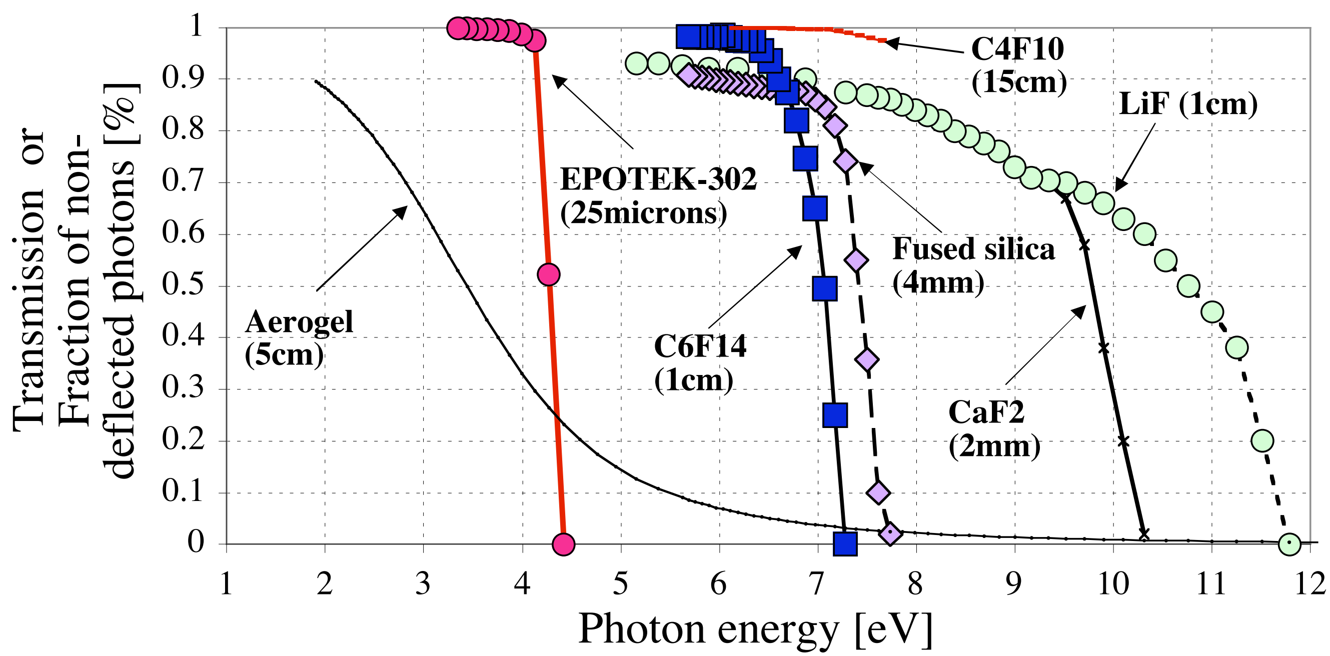
J. Va'vra, Nucl.Instr.&Meth., A453(2000)262
K. Arisaka, Nucl.Instr.&Meth., A442(2000)80



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

Transmission of various materials

J. Va'vra, Nucl.Instr.&Meth., A453(2000)262

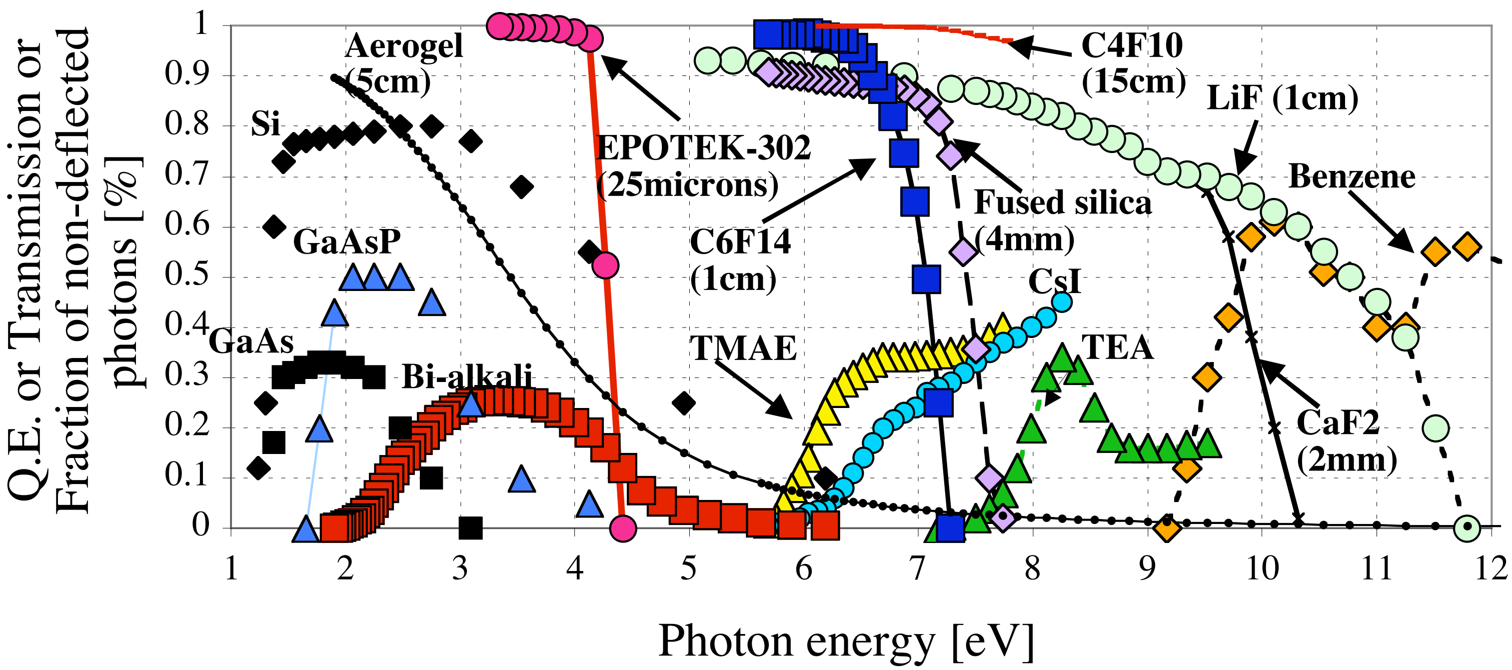


- **DIRC:** It is not the Fused silica radiator, which defines the wavelength bandwidth, but EPOTEK-302 glue used to glue bars together !
- **Aerogel:** Due to its granular structure, the light propagation is dominated by Rayleigh scattering. A fraction of non-deflected photons is calculated as follows: $N = A \lambda^4 (1-\exp(-CL/\lambda^4) / CL$, where $A = 0.96$ and $C = 0.010 \mu m^4 cm^{-1}$ and 5 cm thickness sample (LHC-b parameters). **The Reyleigh scattering limits usefulness of Aerogel to a visible wavelength region only.**

Choices depends on marriages of various materials

J. Va'vra, Nucl.Instr.&Meth., A453(2000)262

K. Arisaka, Nucl.Instr.&Meth., A442(2000)80



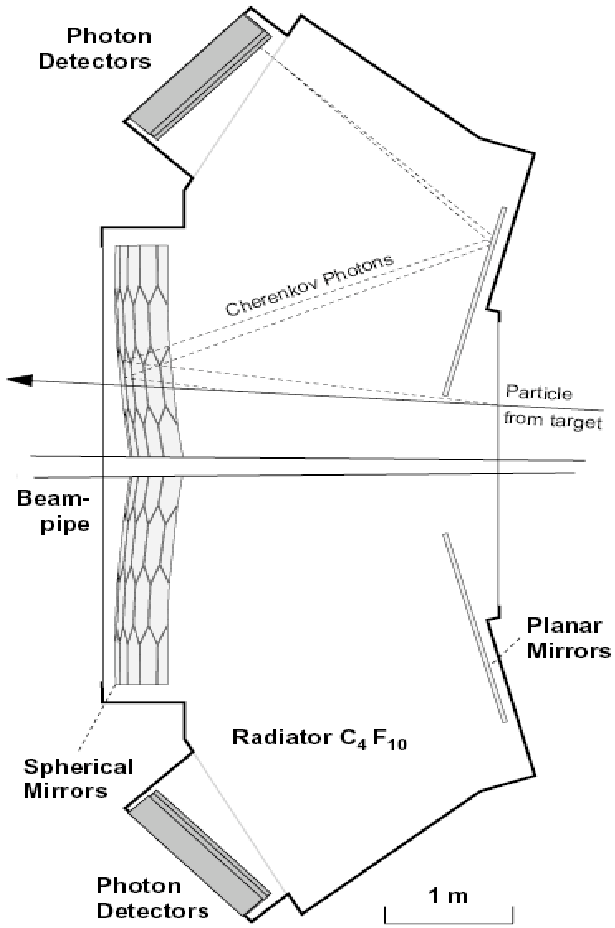
- **Aerogel**-based detectors would benefit tremendously if coupled to either Si, GaAsP of GaAs photocathodes.
- **TEA** requires expensive LiF windows.
- **TMAE** allows the fused silica (quartz) windows.

Examples of large Cherenkov detectors

- **HERA-B**
- **HERMES**
- **DIRC**
- **ALICE**
- **COMPASS**
- **LHC-b**
- **BTeV**

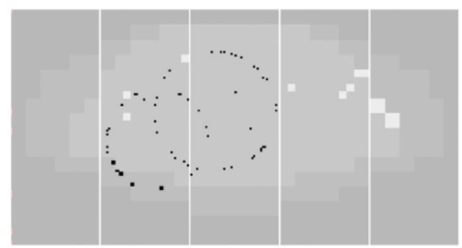
HERA-B

S. Korpar, Nucl.Instr.&Meth., A502(2003)41

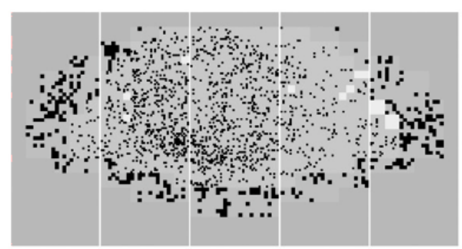


- Designed to study B and D physics in e-p interactions.
- Interaction rate: up to 20MHz

  Beam crossing time: 96ns
- Radiator: C_4F_{10} gas (Length ~270cm)
- Photon detector: R-5900-M16 or R5900-03-M4 Hamamatsu Multi-anode PMTs.
- RICH is not in the magnetic field.
- Fixed target experiment.



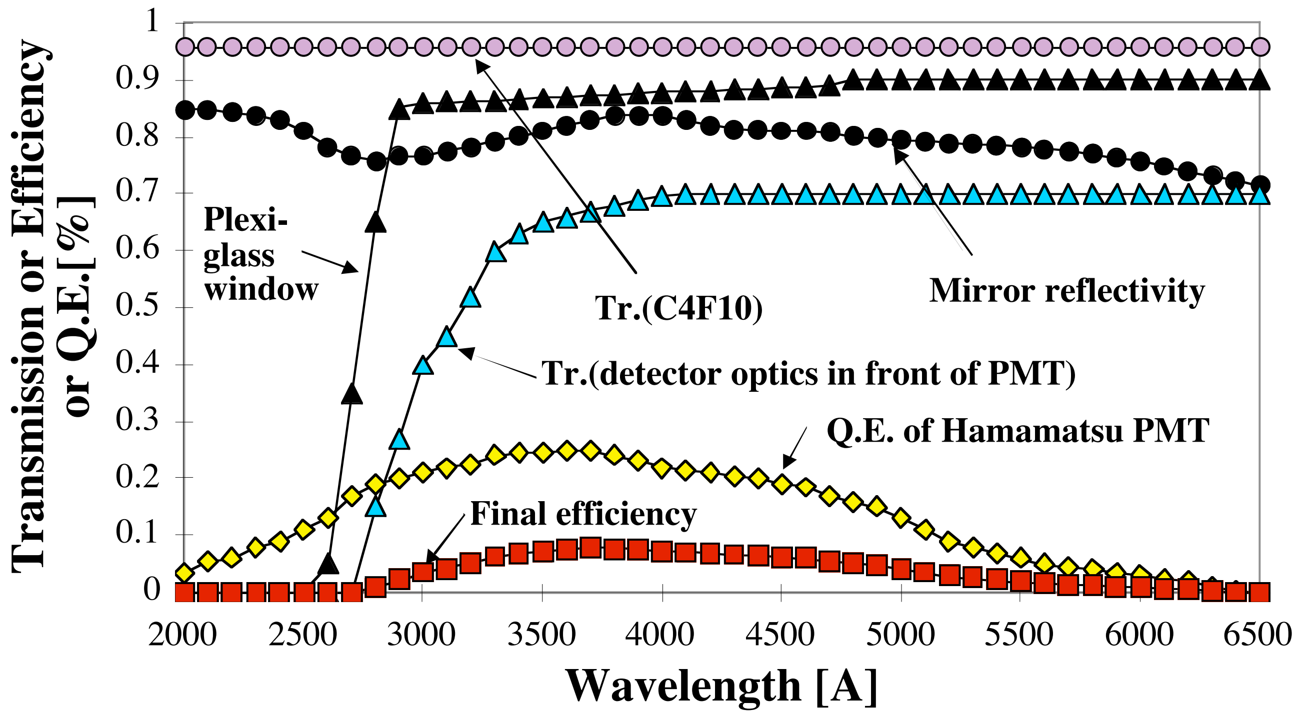
- Simple events



- Typical events

HERA-B performance

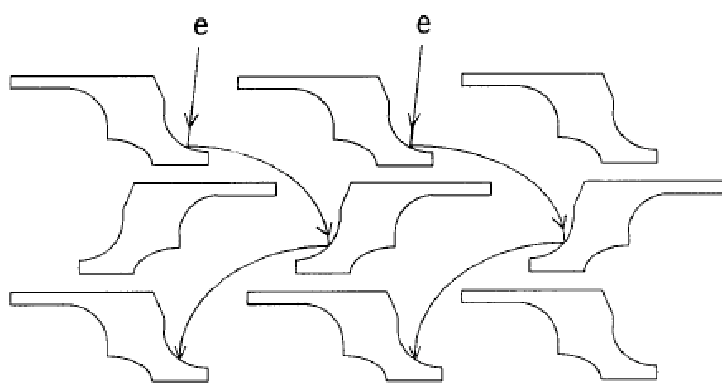
J. Va'vra, Nucl.Instr.&Meth., A453(2000)262

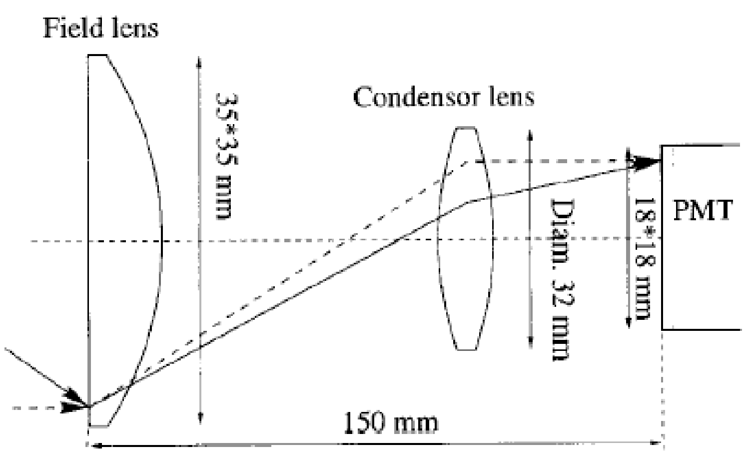


- **Type of detector:** R5900-00-M16 or R5900-03-M4
- **Average refraction index:** 1.0013 for E~ 3.2 eV
- **N_o :** 45 cm^{-1} (my estimate), 42 cm^{-1} (measured)
- **N_{pe}/ring :** 32 (my estimate), 30-35 (measured)

HERA-B photon detector

- Hamamatsu R-5900-M16 Multianode PMT

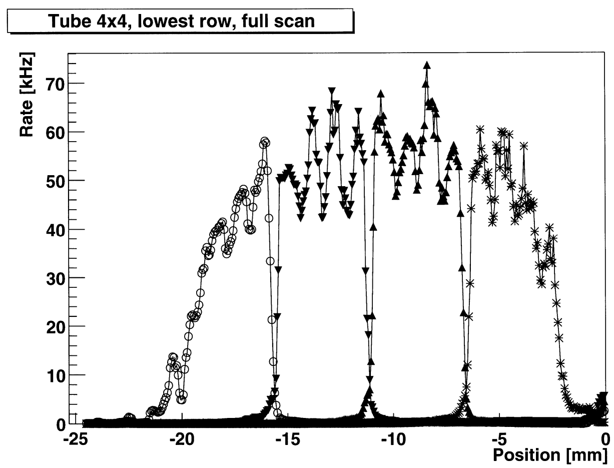


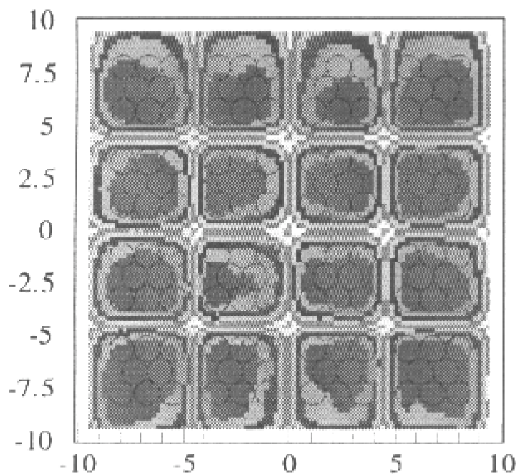


- 12 stages
- 4x4 = 16 pixels
- 4 mm x 4 mm anode size
- 4.6 mm anode-to-anode pitch
- Gain at 800 V ~ $2x10^6$
- Cross-talk ~1%
- Cannot work in the magnetic field
- Poor packing fraction (38%)
  --> needs corrective lenses
  (HERA-B used a plastic causing some losses in far UV)
- Additional losses of 20-30% due to inter-electrode boundaries - see next page

HERA-B photon detector

- Uniformity of a Hamamatsu R-5900-M16 Multianode PMT

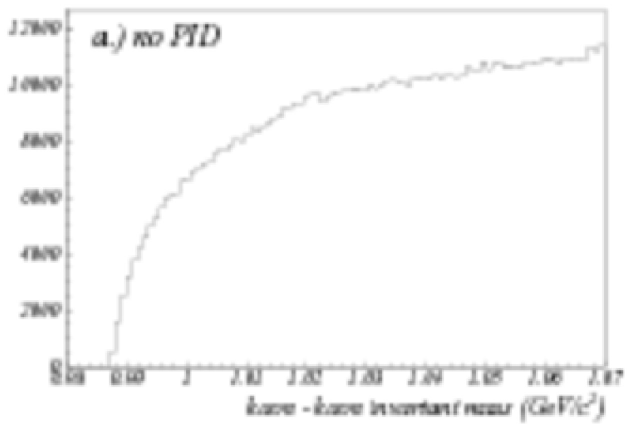


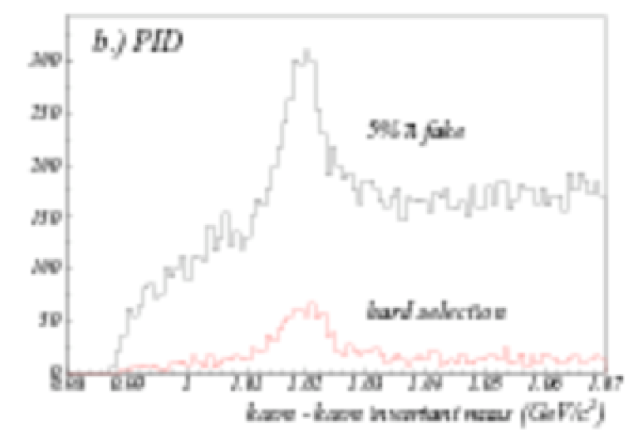


- Tests in our group at SLAC
- Losses near boundaries of the multi-anode structure

- Tests by Minos (P. Dervan, IEEE, Lyon)
- Mean charge distribution has clear edge effects

Example of HERA-B Physics: ϕ -> $K^+ K^-$



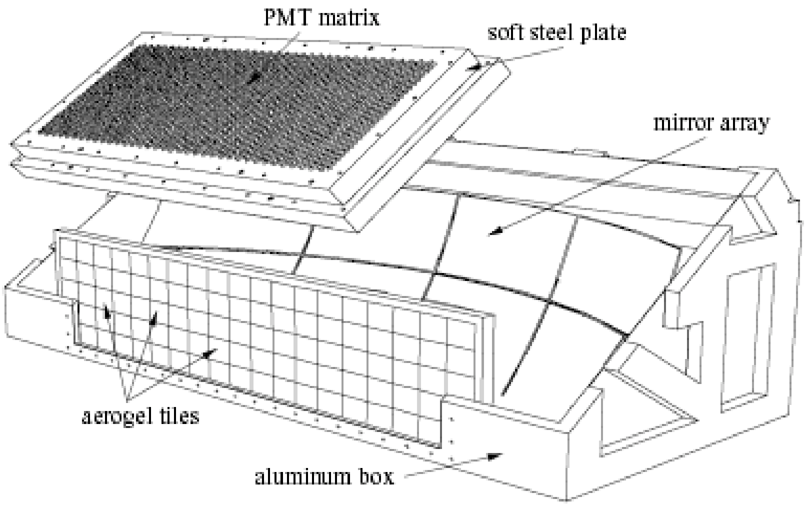


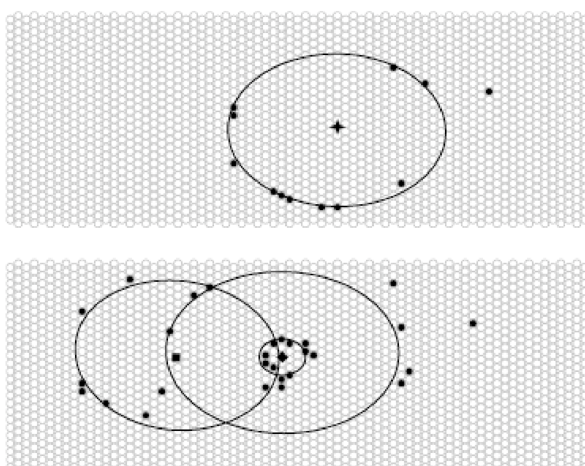
- **A definition of tough life:**
  - 96ns between proton bunches
  - ~80 rings/event on average !!!
  - ~15 reconstructed tracks/event above the Cherenkov threshold
  - ~80% of rings are from bckg tracks
  - N_o = 42 cm^{-1}
  - σ_θ = 1.2mrad/photon (average p)
    σ_θ = 0.8mrad/photon (p > 40GeV/c)

HERA-B RICH has demonstrated that its PMT-based detector works well even in a very tough environment !!

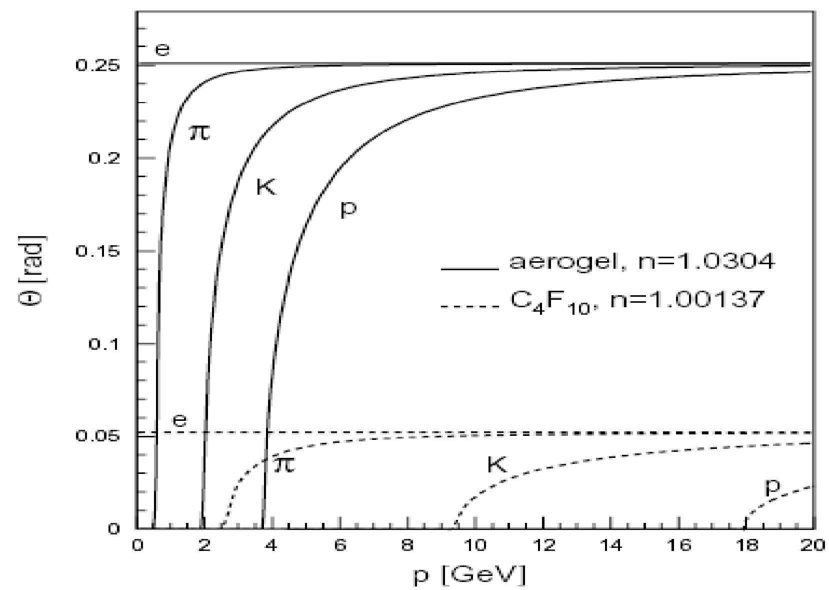
HERMES

H.E. Jackson, Nucl.Instr.&Meth., A502(2003)36



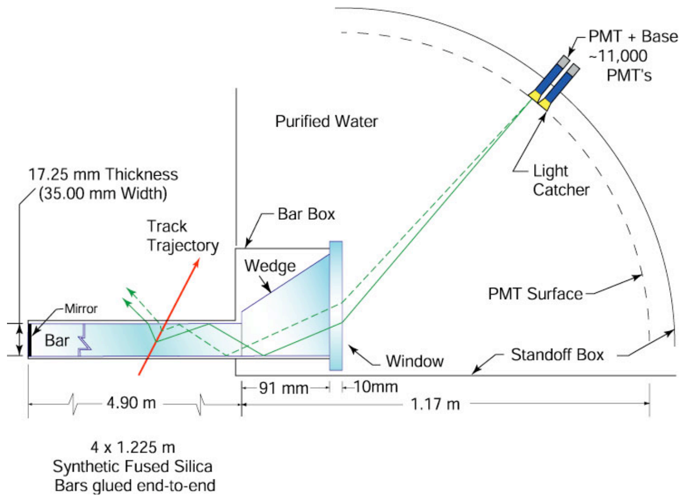


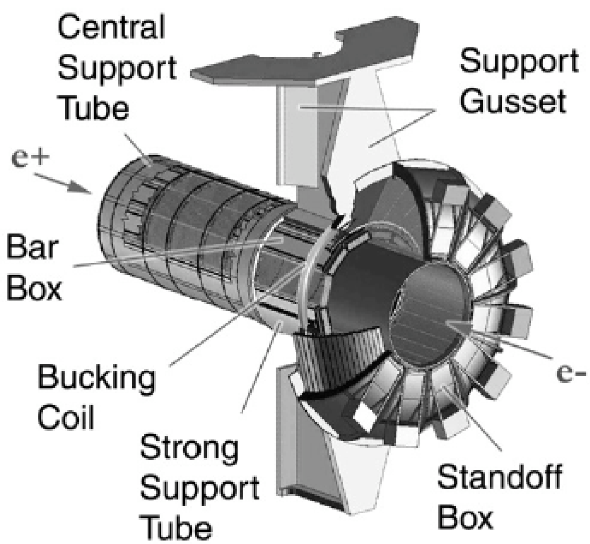
- Hadron identification over a momentum range 2-15 GeV/c.
- Photon detector: XP1911/UV enhanced Philips PMTs (~2000 tubes)
- Radiators: C_4F_{10} gas and Aerogel.
- RICH is not in the magnetic field.
- Fixed target experiment.



DIRC

J. Schwiening et al., Nucl.Instr.&Meth., A502(2003)67

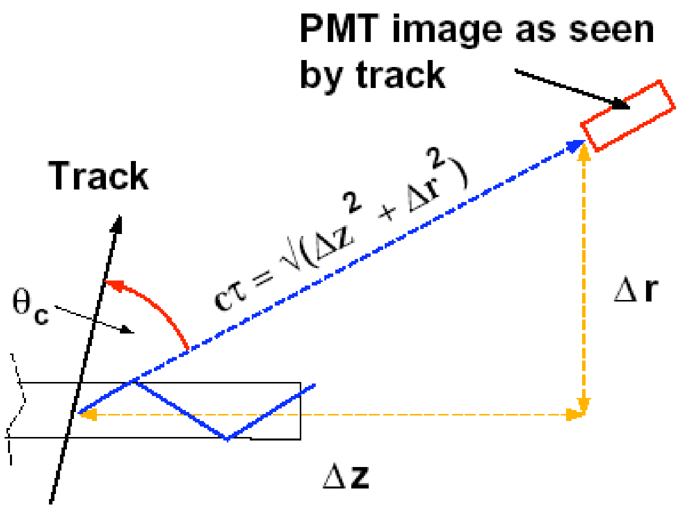




- BaBar experiment
- e^+e^- colliding beam experiment
- Photon detector: ETL 9125 PMTs (~11000 tubes), 1 inch dia., PMTs are outside of magnetic field.
- Radiator: Fused silica
- Typical rates: 150-300kHz/PMT (during injection up to 1MHz/PMT).
- PMTs are not in the magnetic field.
- Achieved a π/K separation of ~2.7σ at 4 GeV/c.

DIRC RICH has demonstrated that its PMT-based detector works well at high luminosity B-Factory experiment !!

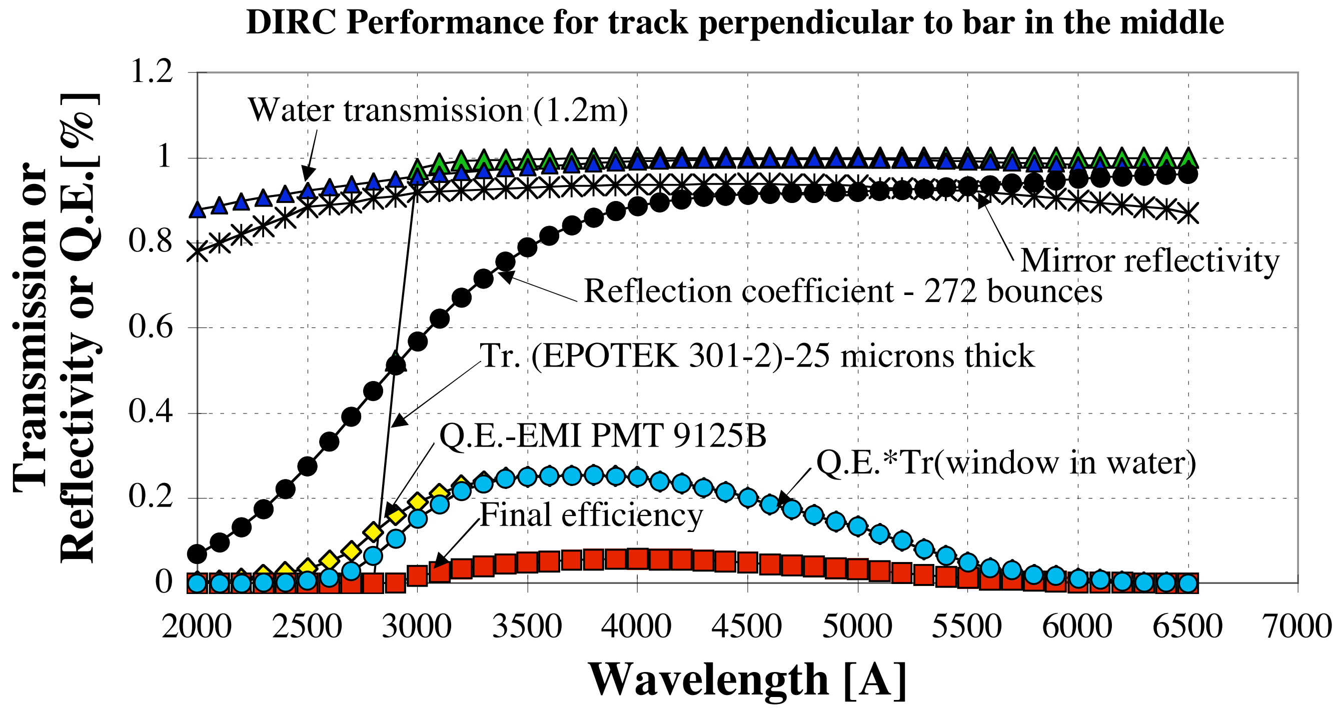
DIRC principle is rather simple



- A concept invented by B. Ratcliff
- To determine the Cherenkov angle θ_c, one measures (a) a track position, (b) a photon flight time (τ), and Δz and Δr ($\equiv \Delta y$). This <u>over-determines</u> the triangle.
- In the present BaBar DIRC, the time measurement is not good enough to determine the Cherenkov angle $\Delta\theta_c$. The time is, however, used to reduce the background.
- The concept utilizes a 3D imaging. It uses a “pinhole” geometry, where the bar’s exit area, together with a PMT position, define the photon exit angles in 2D. The time and the track position defines the third coordinate.

DIRC performance

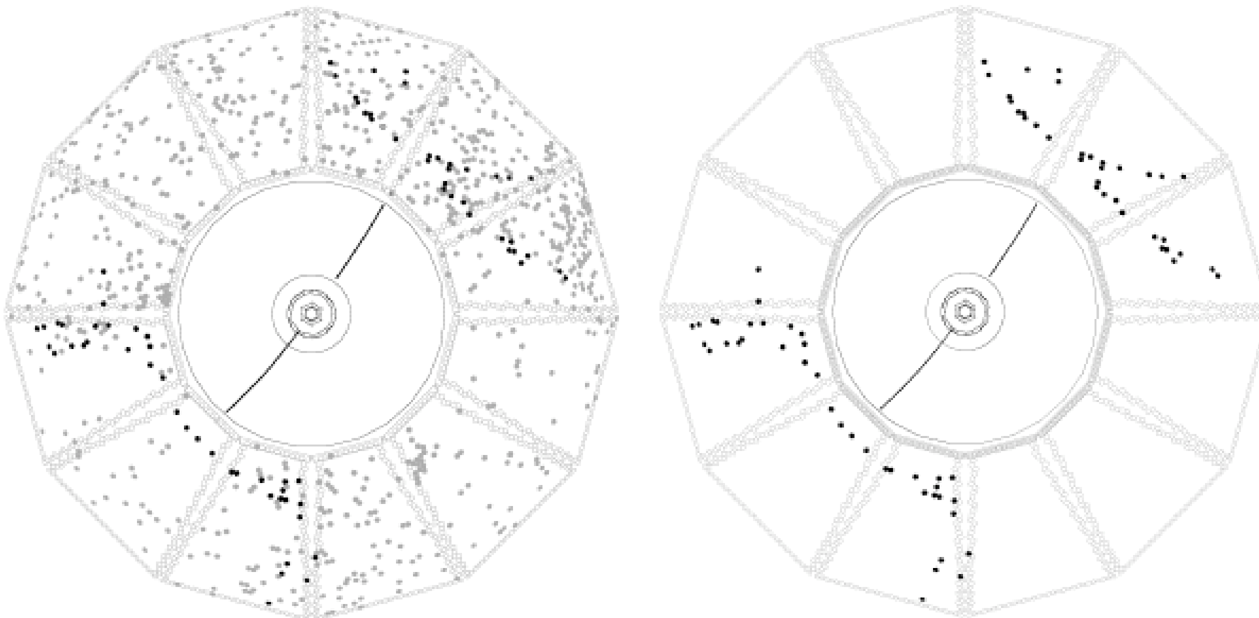
J. Va'vra, Nucl.Instr.&Meth., A453(2000)262



- **Type of detector:** ETL PMT 9125B with a Bialkali photocathode
- **Average refraction index:** 1.47011 for E$_{\gamma}$~3.1 eV
- **N$_o$:** 12 cm^{-1} (my estimate)
- **N$_{pe}$/ring :** 11 (my estimate) for 1.7cm thickness and θ_{track} = 90^o, (gets rapidly much better at larger angles).

DIRC - role of timing is to remove unwanted background

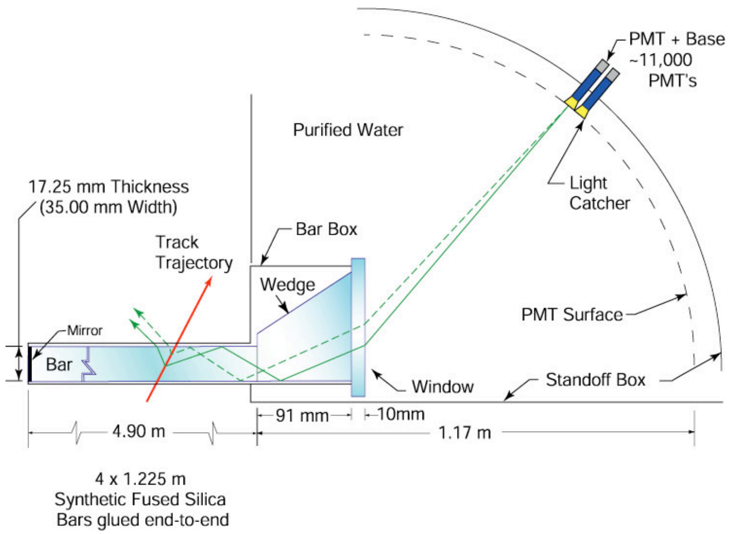
J. Schwiening, Nucl.Instr.&Meth., A502(2003)67



- e^+e^- -> $\mu^+\mu^-$ for a timing window of ± 300ns
- The same for a tight timing window of ± 8ns
- Timing resolution to detect a single photon: σ ~ 1.9ns

Present BaBar DIRC : Error in θ_c

J. Schwiening et al., Nucl.Instr.&Meth., A502(2003)67



- **Per photon:**

- $\sigma\theta_{track}$ ~1 mrad
- $\sigma\theta_{chromatic}$ ~5.4 mrad
- $\sigma\theta_{transport\ along\ the\ bar}$ ~2-3 mrad
- $\sigma\theta_{bar\ thickness}$ ~4.1 mrad
- $\sigma\theta_{PMT\ pixel\ size}$ ~5.5 mrad

- Total: $\sigma\theta_c^{photon}$ ~ 9.6 mrad

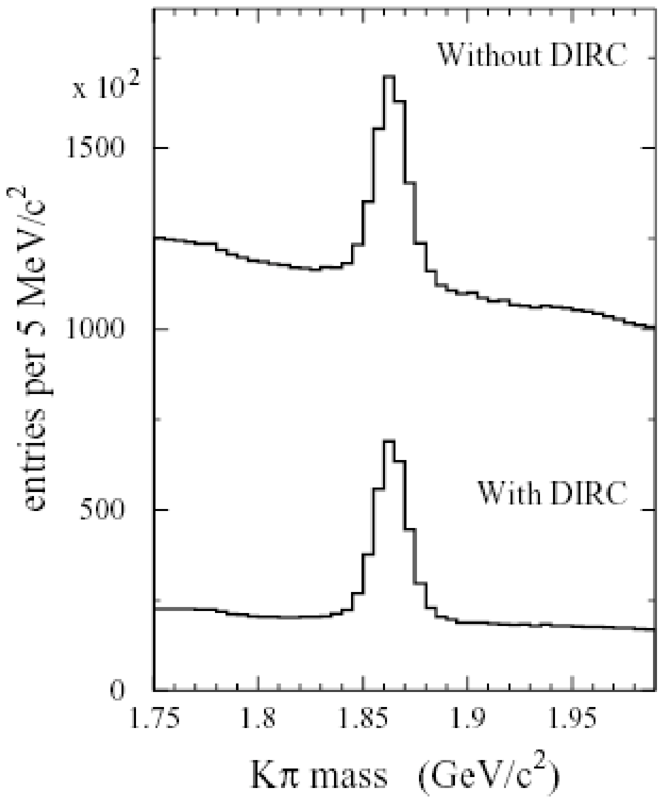
- **Per track (N_{photon}~20-60/track):**

$$\sigma\theta_c^{track} = \sigma\theta_c^{photon} / \; N_{photon} \quad \sigma\theta_{track}$$

~ 2.4 mrad on average

Example of physics with DIRC at BaBar - Dº -> K

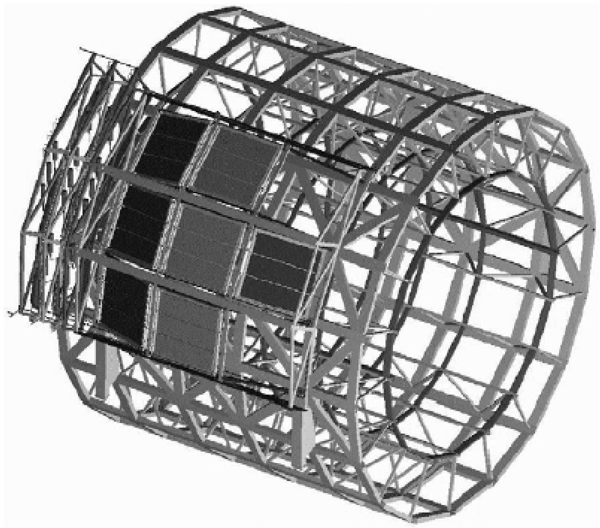
J. Schwiening, Nucl.Instr.&Meth., A502(2003)67



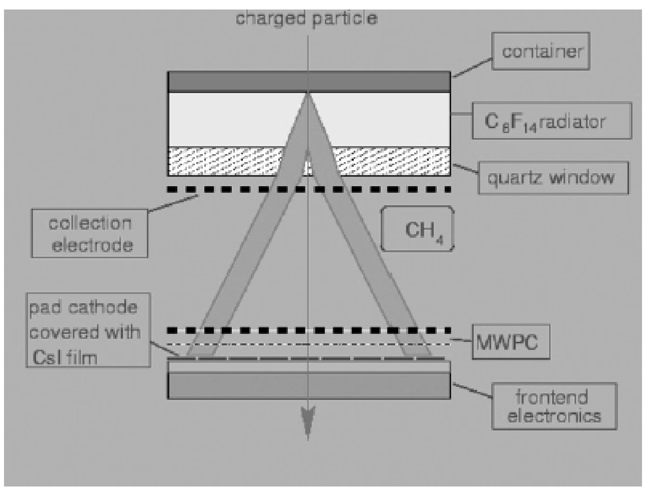
- Dº particle in a K inclusive spectrum with and without DIRC

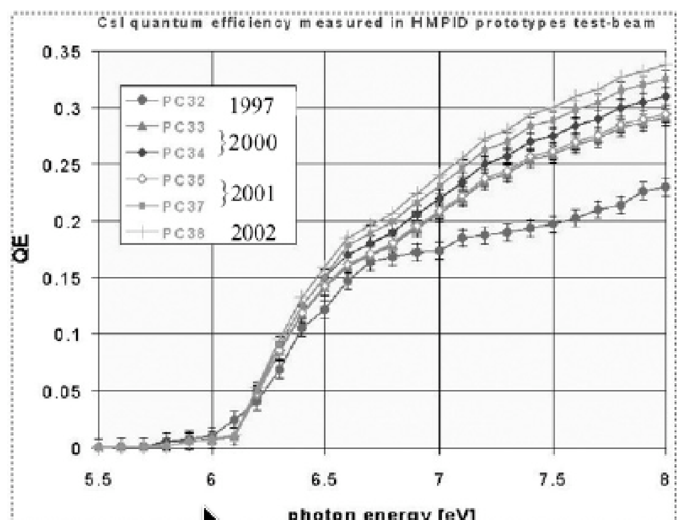
ALICE

D. Coza et al., Nucl.Instr.&Meth., A502(2003)101



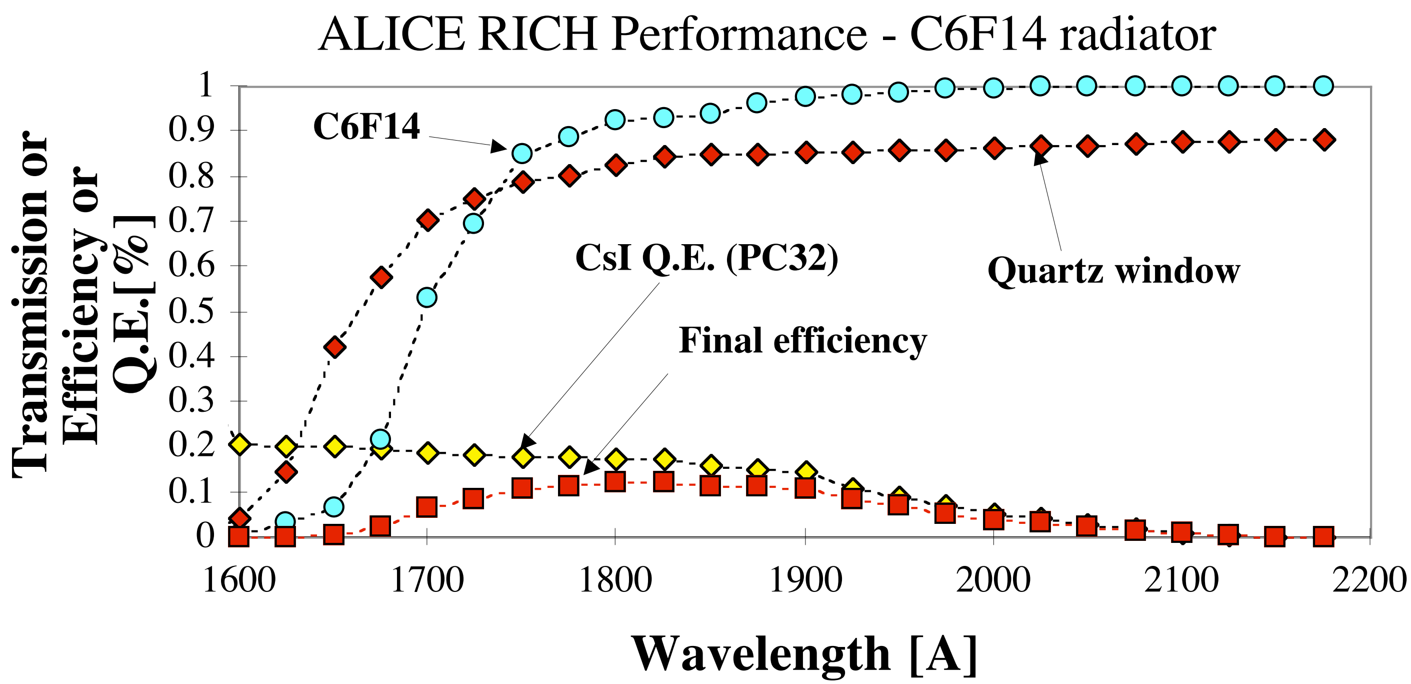
- LHC heavy ion colliding beam experiment with home-made CsI-based gaseous photon detectors.
- CsI photocathode, developed during past 10 years of R&D
- Radiator: Liquid C_6F_{14}
- Proximity focusing
- Can operate in the magnetic field
- /K PID for $1 < p < 2.7$ GeV/c





ALICE expected performance

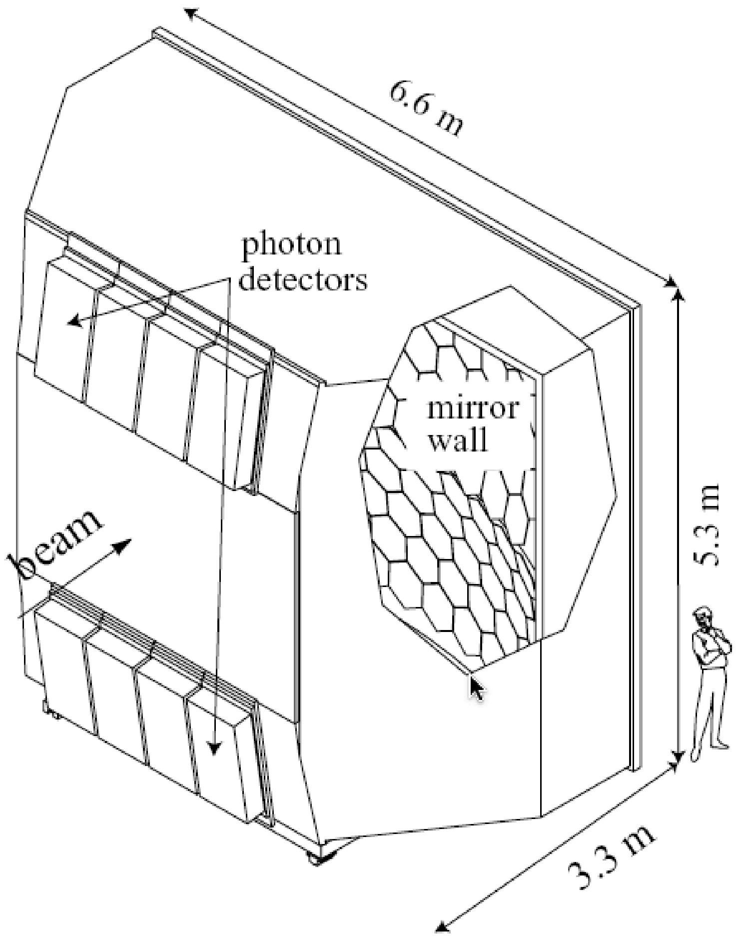
J. Va'vra, Nucl.Instr.&Meth., A453(2000)262



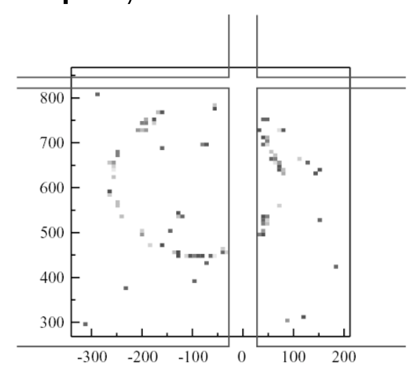
- **Type of detector:** MWPC with a CsI photocathode
- **Average refraction index:** 1.27441 for E_{γ}~6.8 eV
- $\mathbf{N_o}$ **:** 44 cm^{-1} (my estimate)
- $\mathbf{N_{pe}}$**/ring :** 17 (my estimate)

COMPASS

E. Albrecht et al., Nucl.Instr.&Meth., A502(2003)112



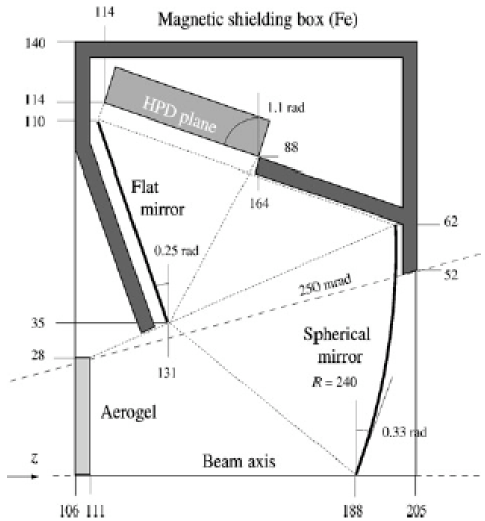
- Presently running high rate experiment studying spin structure of nucleon.
- CsI photocathodes a'la ALICE.
- Radiator: C_4F_{10} gas.
- Some starting difficulties with some detectors (problems are rate and voltage dependent).
- π/K PID up to 60 GeV/c.
- Fixed target experiment.
- RICH is not in the magnetic field.
- On-line display:



LHC-b RICH

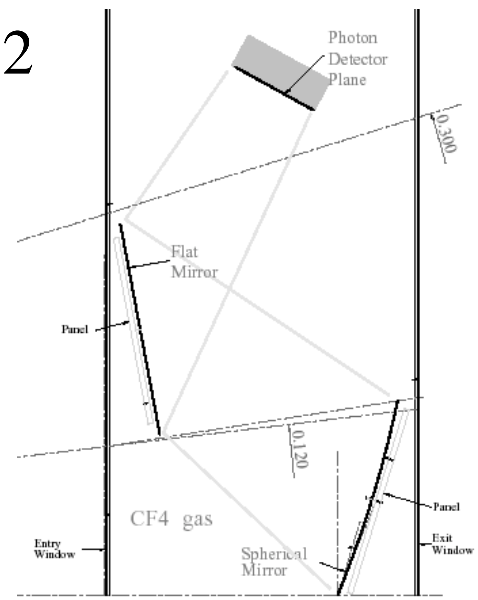
S.Easo, Nucl.Instr.&Meth., A502(2003)46

RICH 1

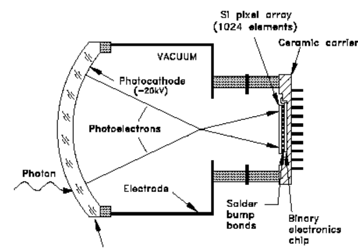


- **LHC experiment planning to study CP assymetry in B decays.**
- **Photon detector: HPD or MAPMT&Lenses.**
- **Expected rate: ~40MHz/HPD**
- **Radiators: Aerogel, CF_4 and C_4F_{10} gas**
- **Hadron PID 1- 65 GeV/c (RICH 1) and up to 150 GeV/c (RICH 2).**
- **Fixed target experiment.**
- **RICH is not in the magnetic field.**

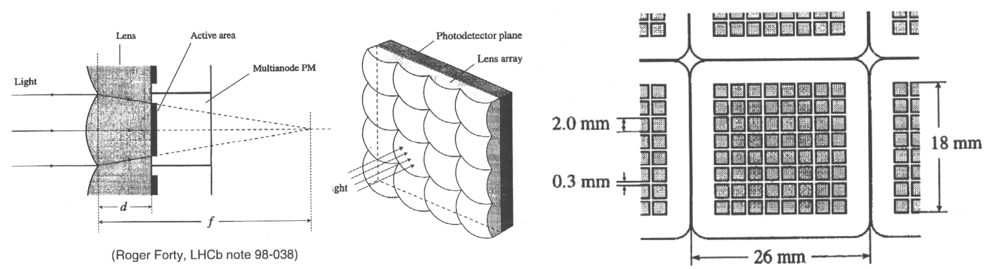
RICH 2



HPD:

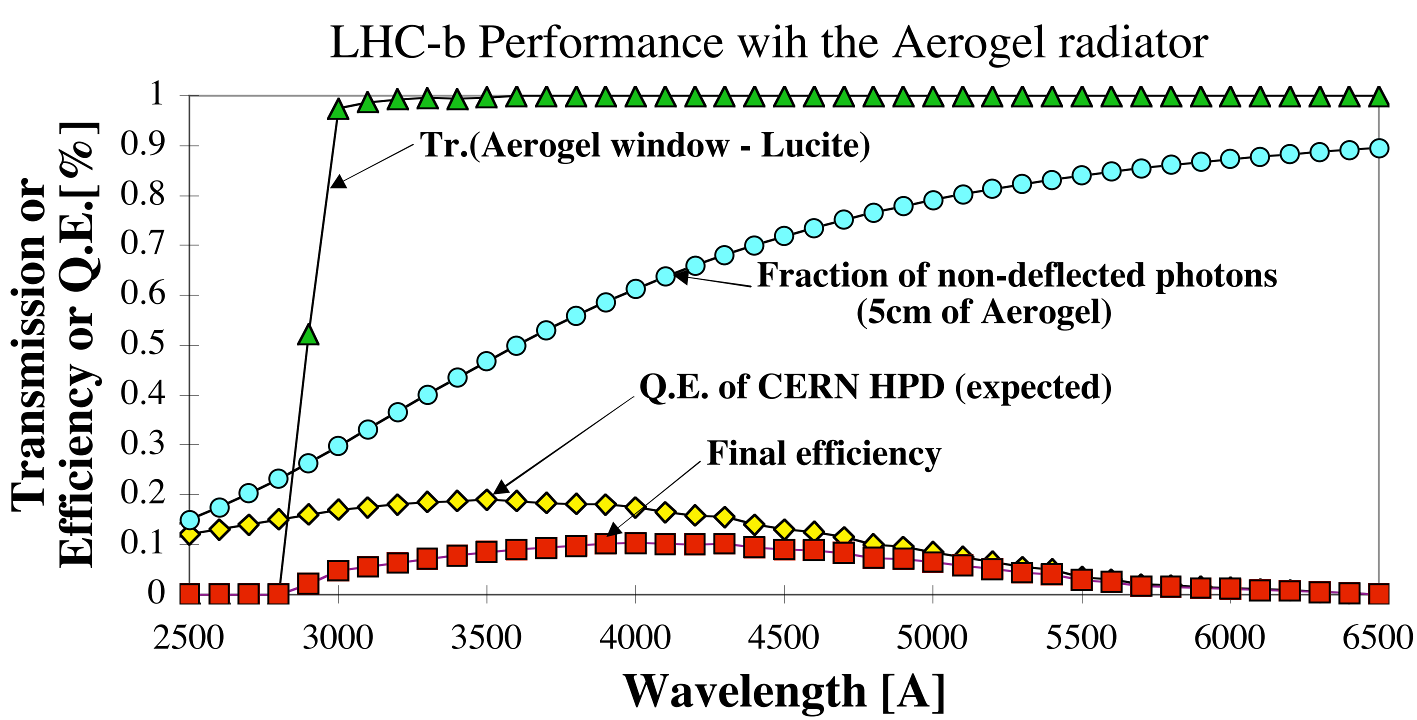


MAPMT R5900-M64+Lens:



LHC-b expected performance

J. Va'vra, Nucl.Instr.&Meth., A453(2000)262

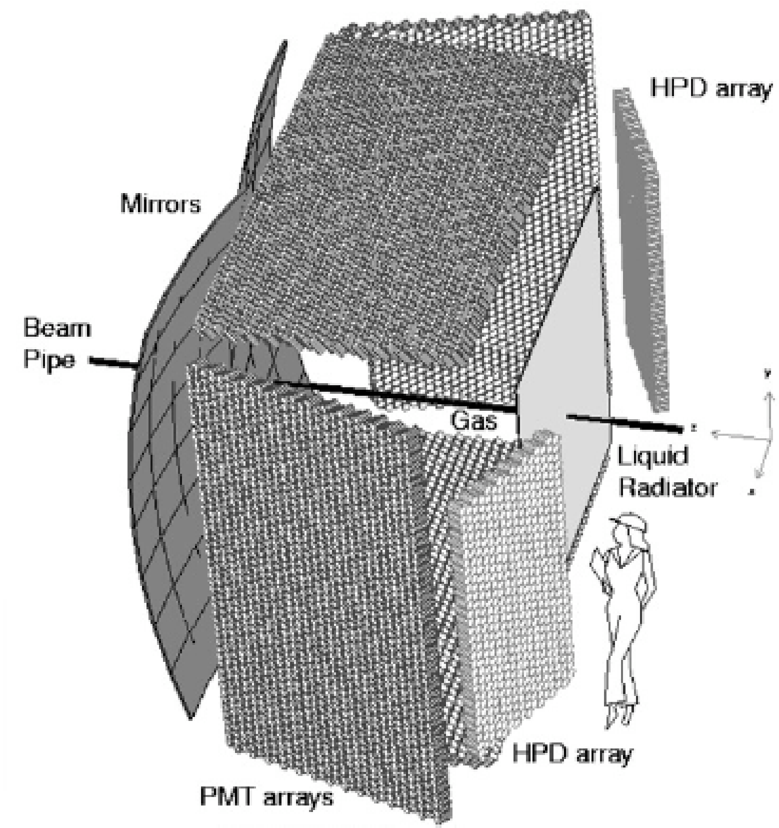


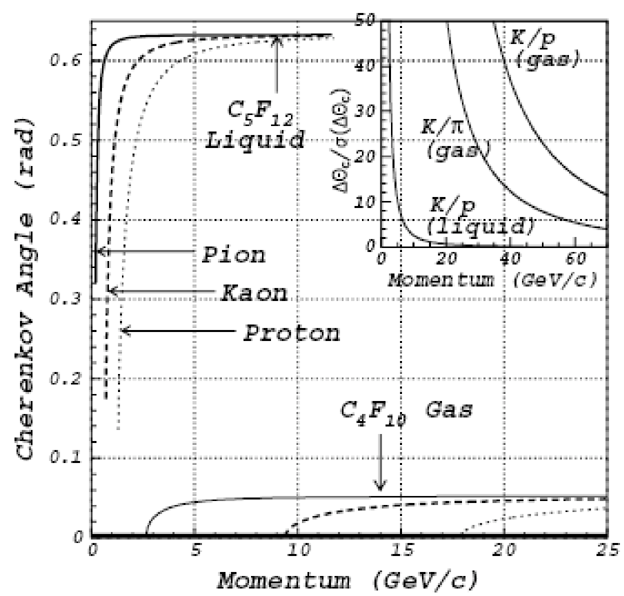
- **Type of detector:** HPD made by DEP
- **Average refraction index:** 1.029 fro E_{γ}~3 eV
- **N_o :** 58 cm^{-1} (my estimate)
- **N_{pe}/ring :** 16 (my estimate) for a 5 cm thickness

BTeV

S.R. Blusk, Nucl.Instr.&Meth., A502(2003)57

- Proposed experiment planning to study CP assymetry in B decays.
- Photon detector: HPD made by DEP
- Radiators: Liquid C_5F_{12} and C_4F_{10} gas.
- Fixed target experiment
- RICH is not in the magnetic field.





New developments

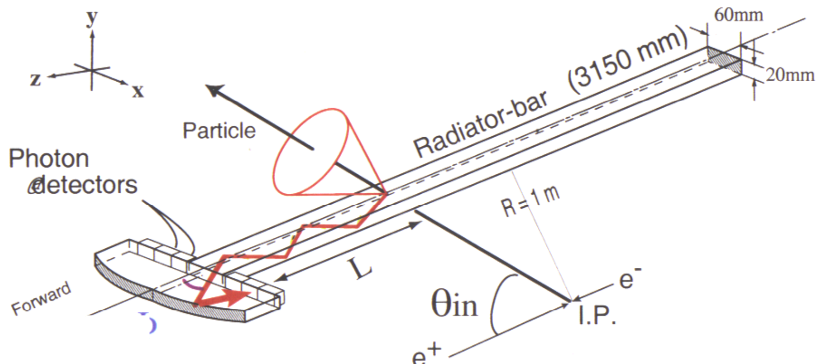
- **New generation of DIRC-style detectors**

  a) Focusing DIRC prototype at SLAC

  b) TOP counter prototype at Belle
- **Search for new photon detectors**
- **A few comments how to test a timing resolution**

Concepts of “DIRC-like” detectors

TOP counter with a mirror (Nagoya):



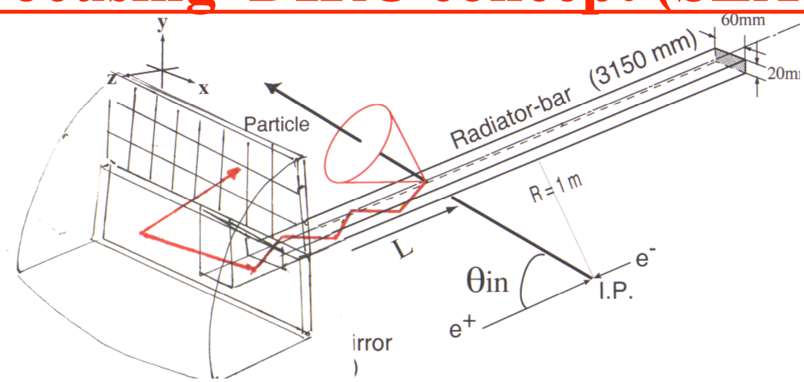
□, Time

- Measure:

  a) time (□ < 80ps), and

  b) photon □ angle.

Focusing DIRC concept (SLAC):



x, y, Time

- Measure:

  a) time (□ < 100ps), and

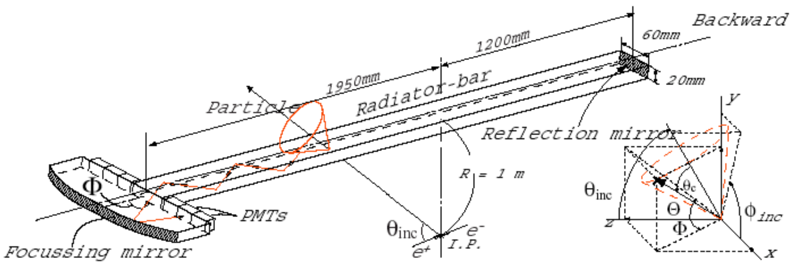
  b) photon position in

  both x & y.

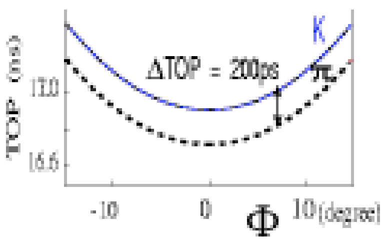
TOP Counter

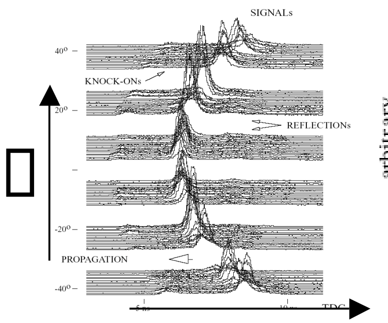
T. Ohshima, RICH 2002, Pylos, Greece

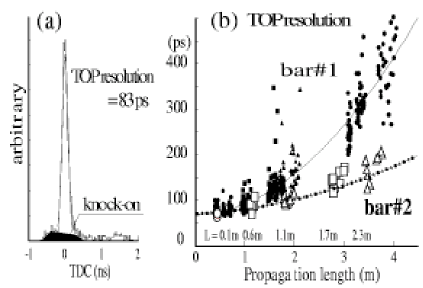
With a mirror:



3 GeV/c, L=2m, $□_{in}$ = 90°







- □ - horizontal emission angle
- **TOP(□,$□_c$) = [L/v_g(□)] / q_z(□,$□_c$)**

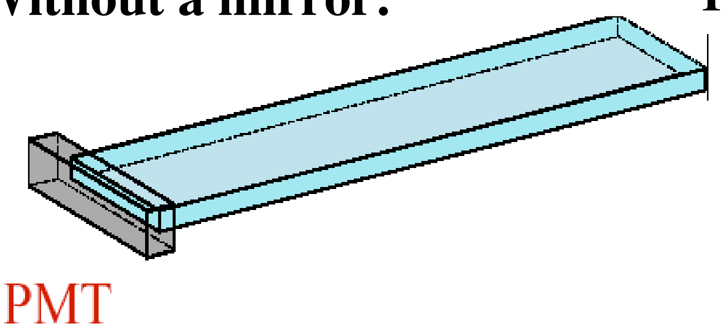
L - distance of light travel in bar

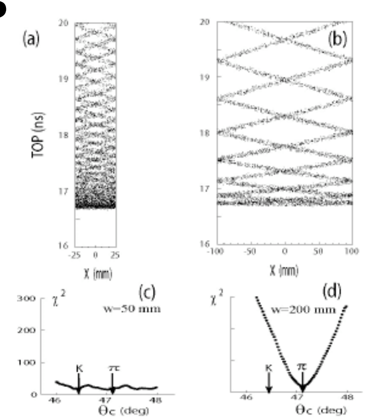
v_g(□) - group velocity

q_z(□,$□_c$) - unit velocity vector (x-comp.)

Excellent results obtained only with well-polished bar

Without a mirror:





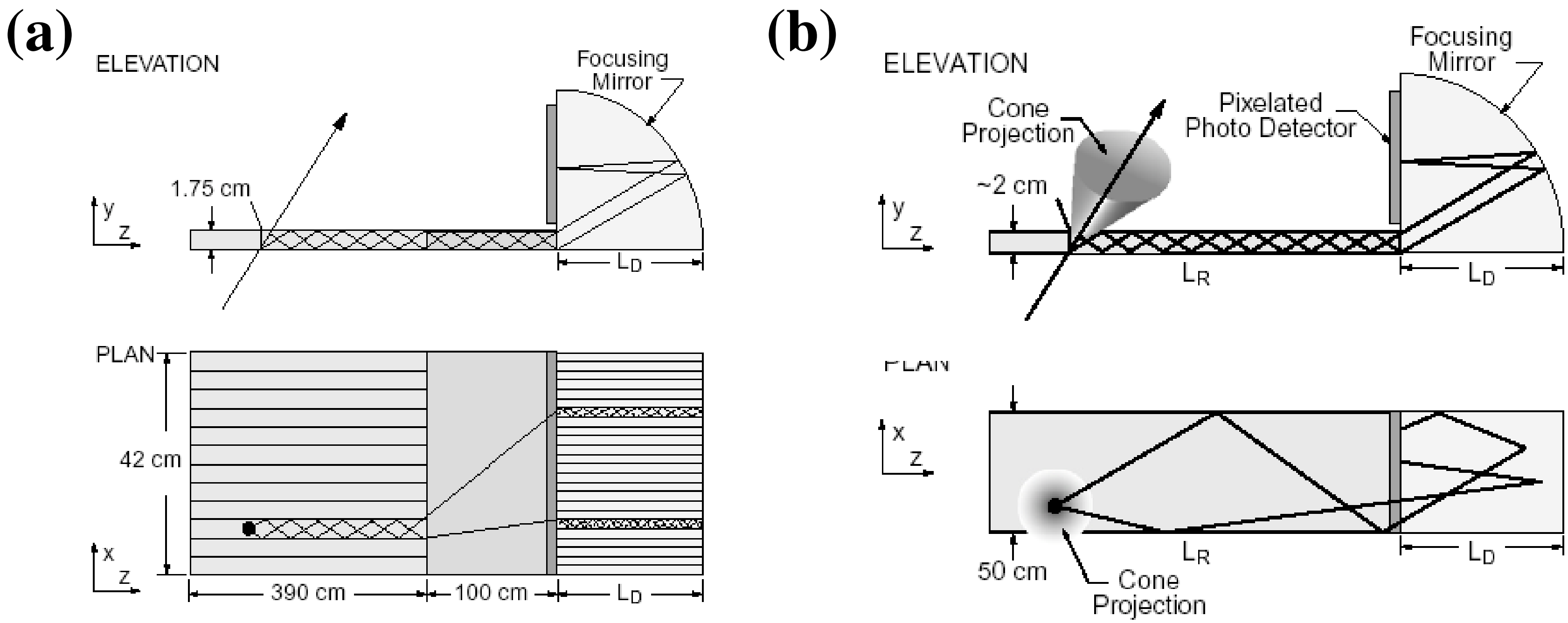
When the mirror is not used, the ambiguities arise. However, widening the bar width solved the problem.

The question is what happens in a high background condition !

Focusing DIRC detector - a future plan

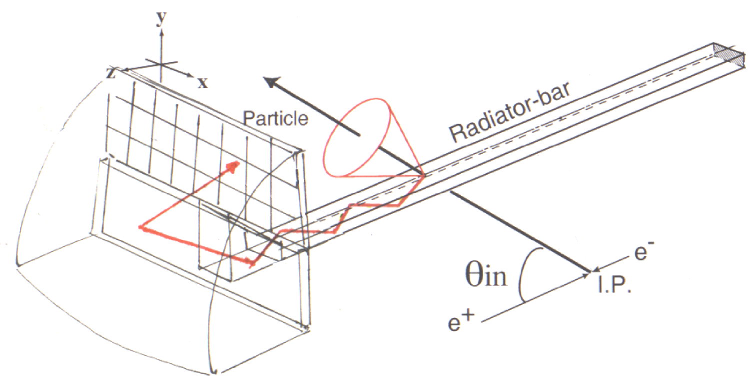
B. Ratcliff, Nucl.Instr.&Meth., A502(2003)211

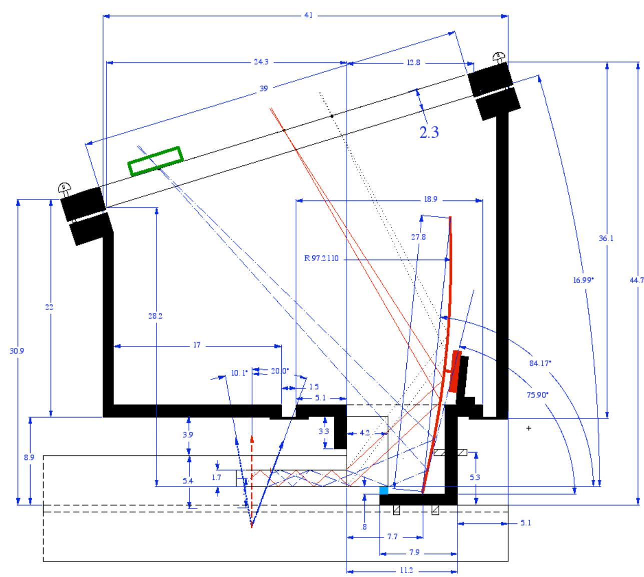
Two versions of the Focusing DIRC detectors:



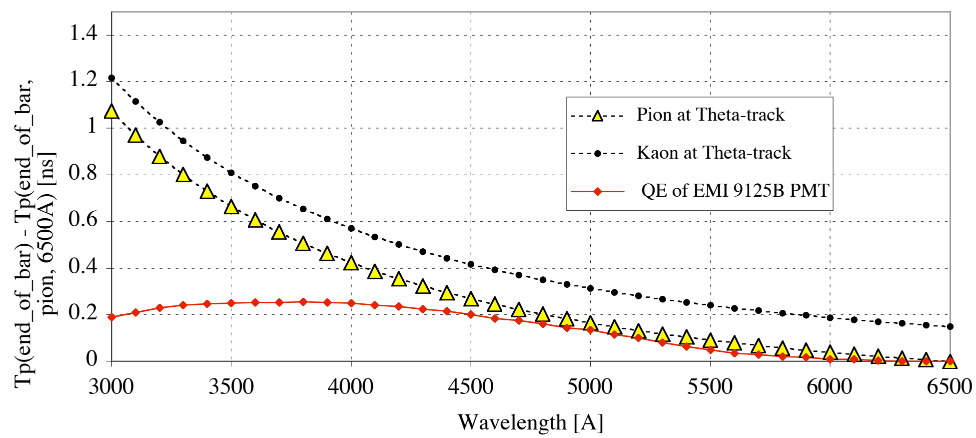
- The reason why we want to preserve more complex imaging (x,y and time) is a fear of degradation due to a large background.
- One would prefer that the photon detector is in the magnetic field
- The real question is what would be a photon detector !!

Focusing DIRC prototype - present activity

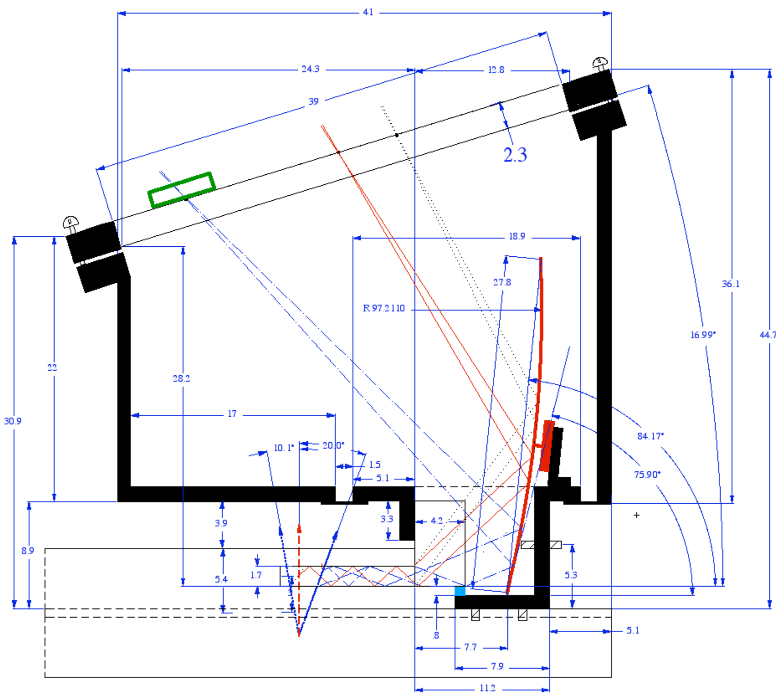




- Measure time to <100ps to remove the chromatic error contribution to the Cherenkov angular error.
- 3.66m-long single bar.
- Spherical mirror removes the contributions due to the bar thickness.
- Ten 64-channel multi-pad detectors.
- Chromatic effect on timing for 4 GeV/c, ~3.5m long bar; θ_{track} = 90°, photons propagate in y-z plane (A ~1ns overall effect for a Bialkali photocathode):



Focusing DIRC prototype: Error in $\square_c$



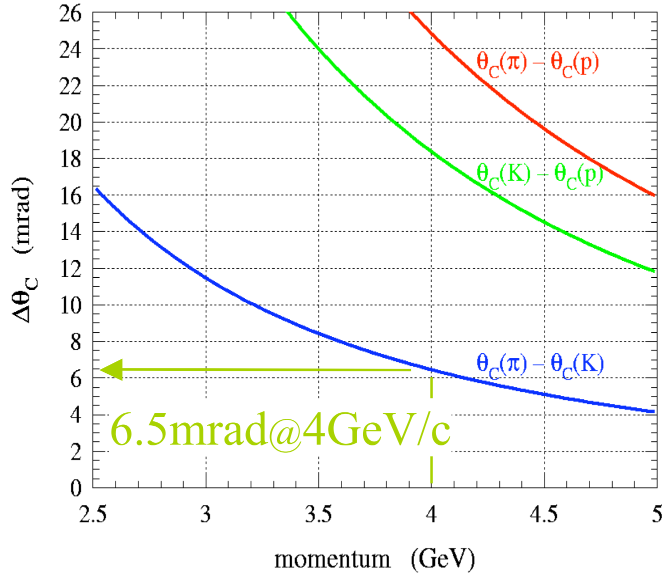
- <u>Per photon:</u>
  - $\square\square_{track}$ ~1 mrad
  - $\square\square_{chromatic}$ **~1 mrad**
  - $\square\square_{transport\ along\ the\ bar}$ ~2-3 mrad
  - $\square\square_{bar\ thickness}$ **~1 mrad**
  - $\square\square_{PMT\ pixel\ size}$ ~4.0 mrad → **4.1 mrad**
  - **Total: $\square\square_c^{photon}$ ~4.8 mrad**

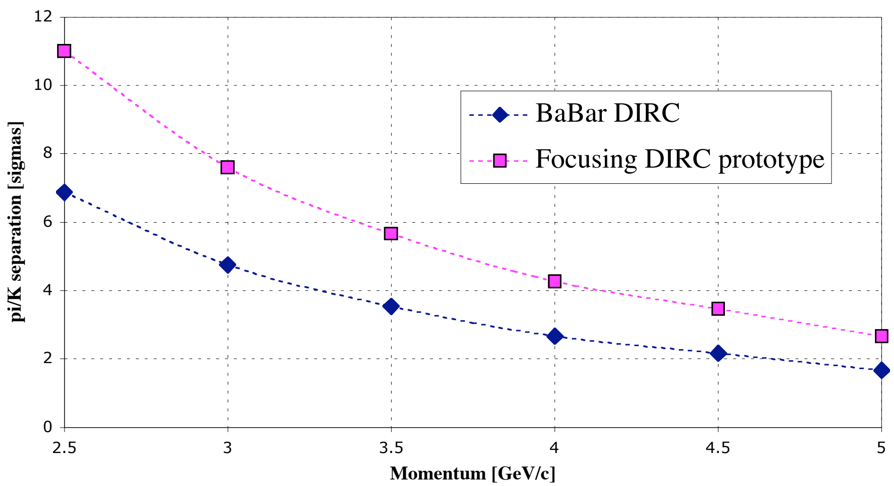
- **<u>Per track</u> (N_{photon}~20-60/track):**

$\square\square_c^{track} = \square\square_c^{photon} / \sqrt{N_{photon}} \quad \square\square_{track}$

<u>~ 1.5 mrad is possible !!!</u>

Expected performance of the prototype

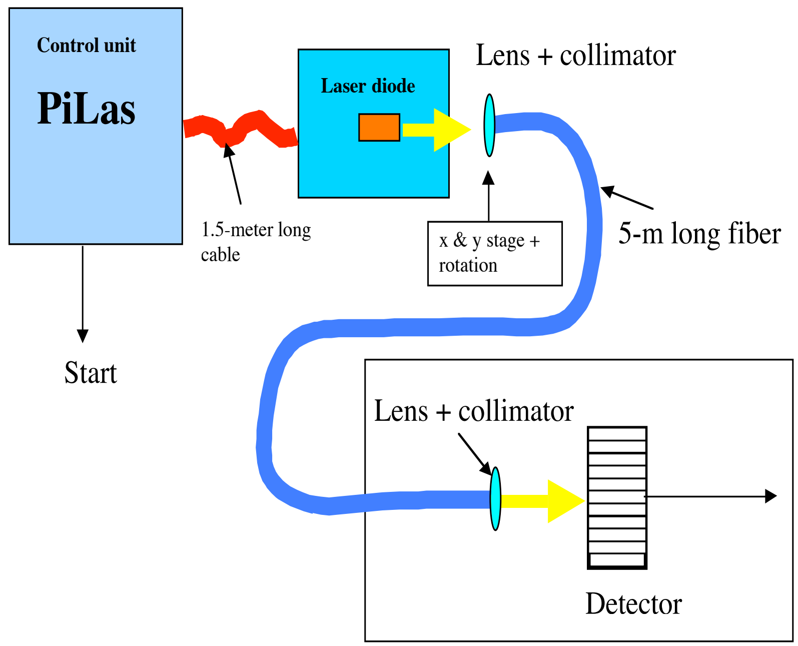




- We assume that the mirror corrects out the bar thickness effect, and that we are successful to correct the chromatic error by the timing measurement (50-100ps timing resolution is needed).
- **<u>Present BaBar DIRC:</u>**
  - 2.7σ π/K separation at 4GeV/c
- **<u>Focusing DIRC prototype:</u>**
  - 4.3σ π/K separation at 4GeV/c
  or
  - 2.7σ π/K separation at 5GeV/c
- **<u>Possible future improvement:</u>**
  - Change a pixel size from the present 6x6mm to 3x12mm, which would reduce the pixel resolution by a factor two

How to test a fast detector ?

J.Va'vra, log book

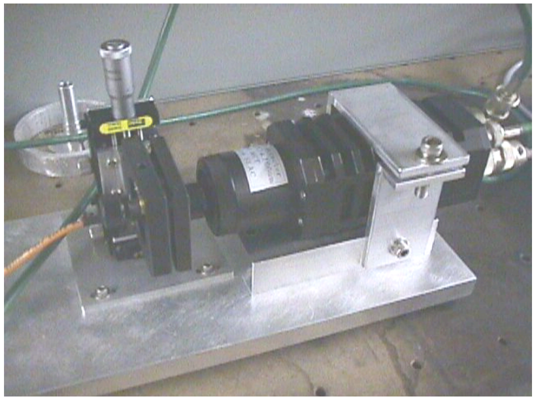


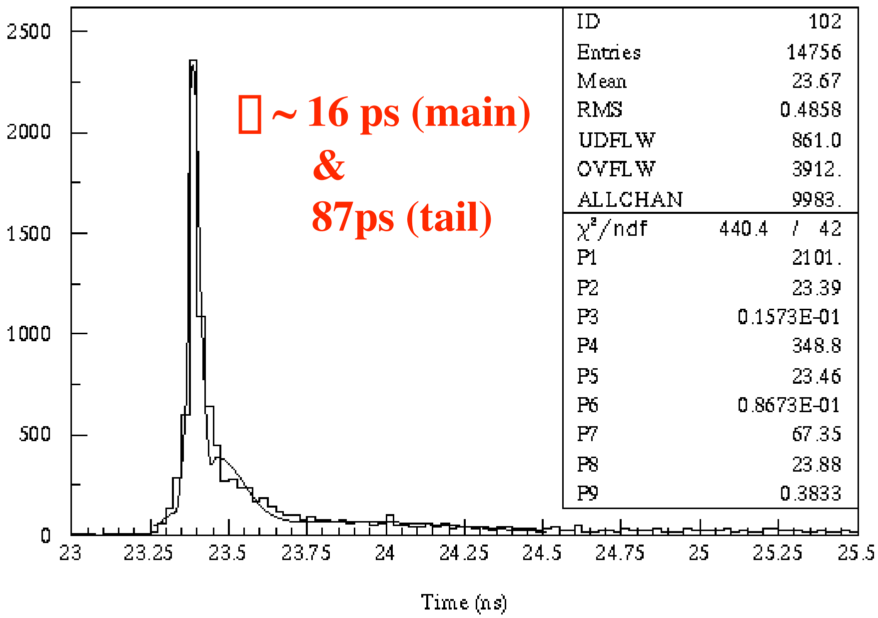
Parameter	SLAC tests	Nagoya tests
Laser diode source	**PiLas**	**Hamamatsu**
Wavelength	535 nm	394 nm
FWHM of light pulse spread	~35 ps	34 ps
Light pulse jitter relative to trigger	~2 ps*	±10 ps
Fiber size	62.5 μm dia.	2 mm dia.
Fiber length	5 m	2 m
Diffuser	No	Yes

* Not yet directly confirmed directly by tests at SLAC.

Verification of the light pulser timing resolution

J.Va'vra, log book

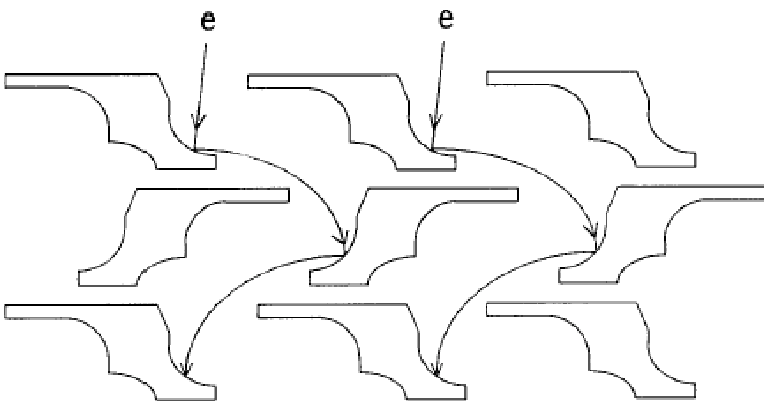


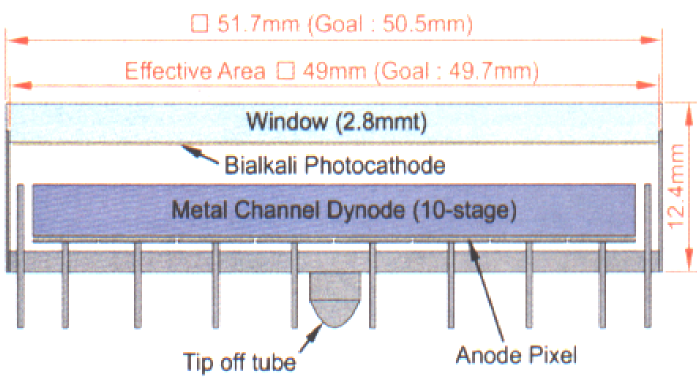


- 100 □m dia. GaP APD operating in a Geiger mode with active quenching. The APD designed by Sopko, quenching electronics by Prochazka, CVUT, Prague.
- I feed the APD signal into our Constant Fraction Discriminator.
- Systematic errors at this level of timing resolution are non-trivial.
- A true result is somewhere between 16-25ps.

Hamamatsu H-8500 Flat panel PMT

Hamamatsu Co. data sheet





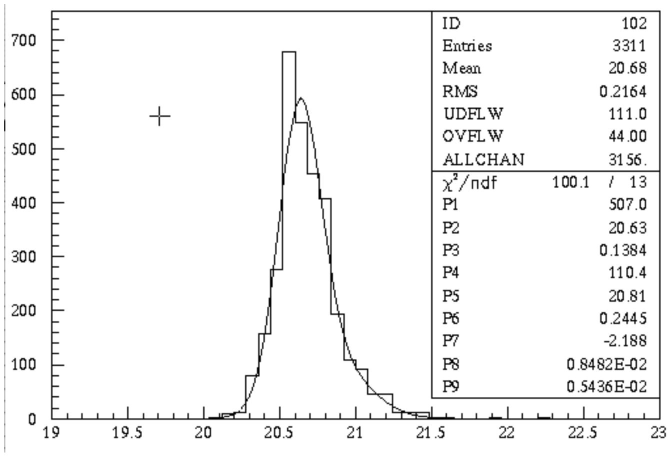
Photocathode	Bi-alkali (visible & UV)
Accelerating medium	vacuum
Geometrical packing efficiency	~97%
Collection efficiency of the dynode structure	~70-80%
Operating voltage (max.)	-1 kV
Pixel size	5mm x 5mm
Matrix	8 x 8
Number of pixels	64
Gain (Hamamatsu claim)	~10^6 @ –1 kV
Type of amplifier (SLAC)	Elantec EL2075C
Amplifier BW (SLAC test)	2 GHz @ gain 1
Number of stages	12
Resistor chain (K - D1 - D2 - -> A)	1-1-1-....-1-0.9-0.1
Transit time distribution (Hamamatsu claim)	□~80 ps + tail
Timing resolution per single photon (SLAC)	□~125 ps

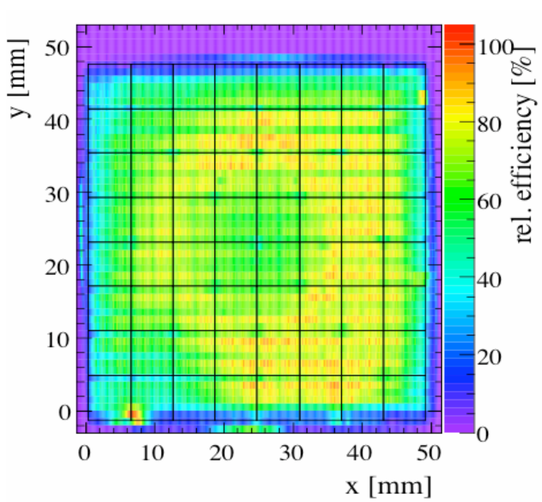
Low

- The tube has a low gain at present -> <u>need an amplifier</u> !!
- Good timing resolution, and an excellent packing efficiency.

Hamamatsu H-8500 Flat panel PMT

C. Field et al., Nucl.Instr.&Meth., Elba 2003

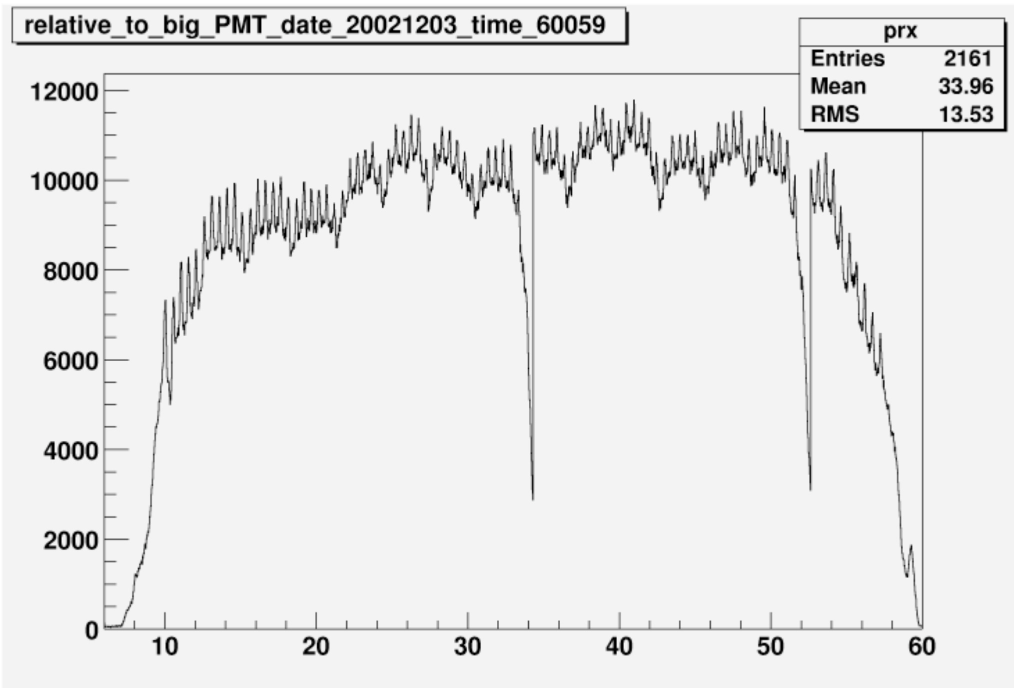




- **Fit:** G1+G2+a+bx+cx^2
- σ_{Major} **~138 ps** (σ_{Minor} **~244 ps)**
- **This resolution is an upper limit the Focusing DIRC would still tolerate**
- x-step: 0.1mm, y-step: 1mm.
- **Scan performed in the single photon counting regime**
- Efficiency losses caused by a lower gain along edges of slots and the boundaries (up to 20-30% !!).
- Elantek amplifier: G_V~130x
- Constant-Fraction-Discriminator
- **SLAC measurement**

Hamamatsu H-8500 Flat panel PMT

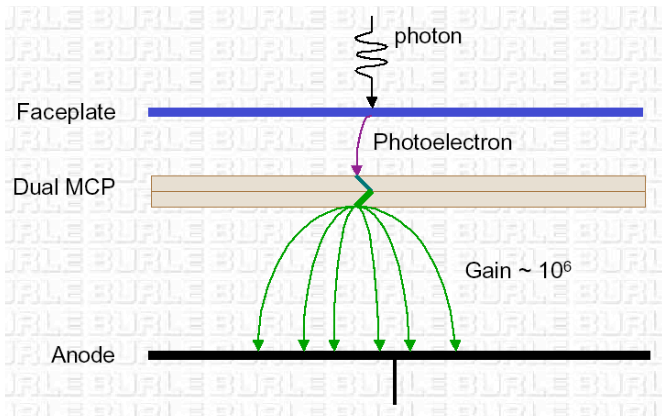
SLAC measurement

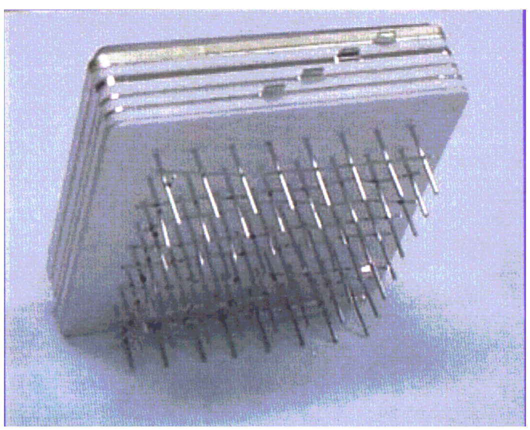


- Relative response
- Use PiLas laser diode operating in the single photon mode
- Step size: 25 um
- Scan over one raw
- See a micro-structure of slots in the multi-anode structure

Burle MCP-PMT

Burle Electron tube info.





- **Two MCPs**
- **8x8 pads**
- **50 x 50mm overall size**
- **Holes inclined by ~12^o angle to limit the ionic damage of the photocathode**
- **25μm dia. holes in MCP (at present)**
- **Not suitable for a large magnetic field of 1.5 Tesla**
- **Gain ~5x10^5 at B = 0**
- **σ_{TTS} ~ 50-60 ps at B = 0**
- **Losses (Burle Co. info):**

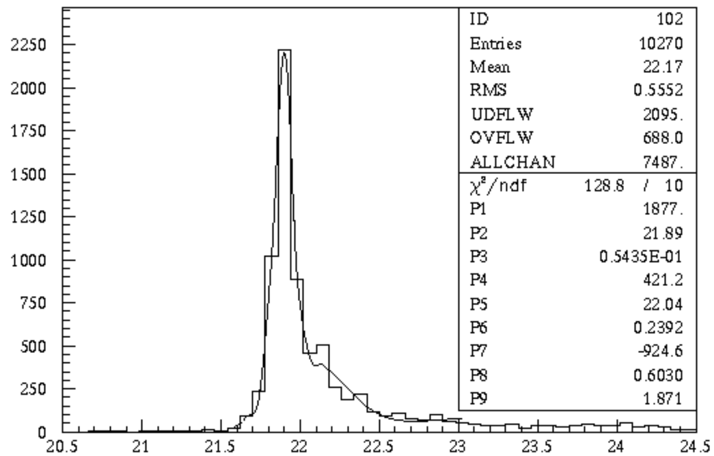
a) Q.E.

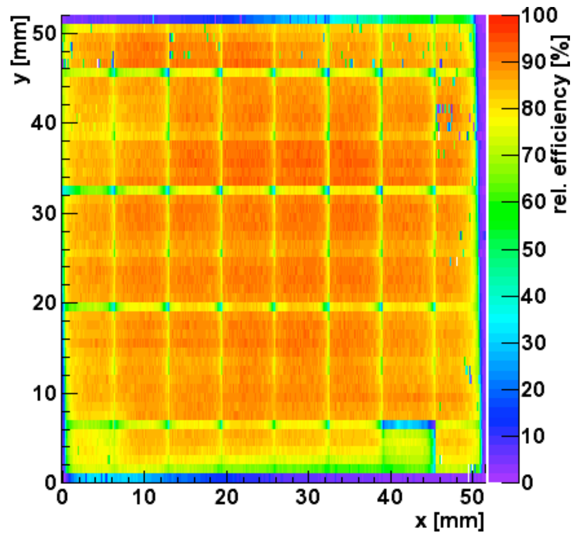
b) <u>Photoelectron collection efficiency</u>: ~60-65% for 25μm dia. hole, and approaching ~70% for 12μm dia. hole design.

c) <u>Packing fraction</u>: ~67% for the <u>raw tube</u>, <50% for the tube with a housing, aim for 85% raw tube.

Burle MCP-PMT

C. Field et al., Nucl.Instr.&Meth., A???(2003)???



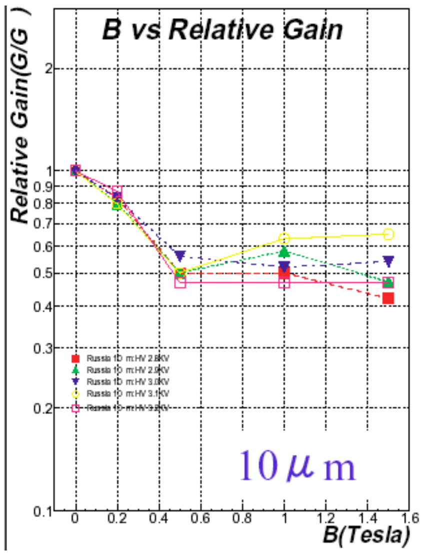


- **Fit:** G1+G2+a+bx+cx^2
- □$_{Major}$ **~53 ps** (□$_{Minor}$ **~240 ps)**
- A long tail is due to recoiled electrons from top MCP surface.
- x-step: 0.1mm, y-step: 1 mm.
- **Scan performed in the single photon counting regime**
- Elantek amplifier: G_V~130x (~300 MHz BW at this gain)
- Constant-Fraction-Discriminator
- 25ps/count TDC
- **SLAC measurement**

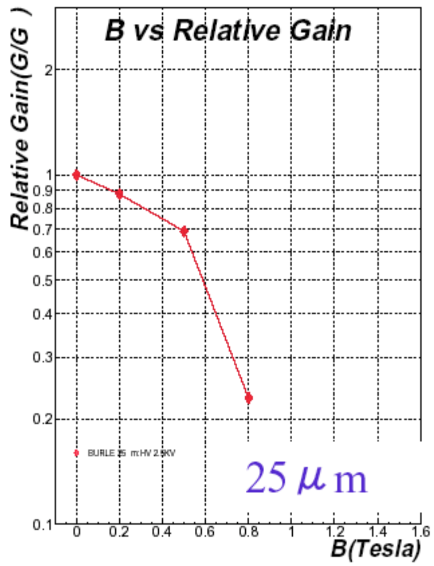
MCP peration in the magnetic field

Measurements by M.Akatsu et al., Nagoya, Japan - preliminary

Russia MCP:



Burle MCP:



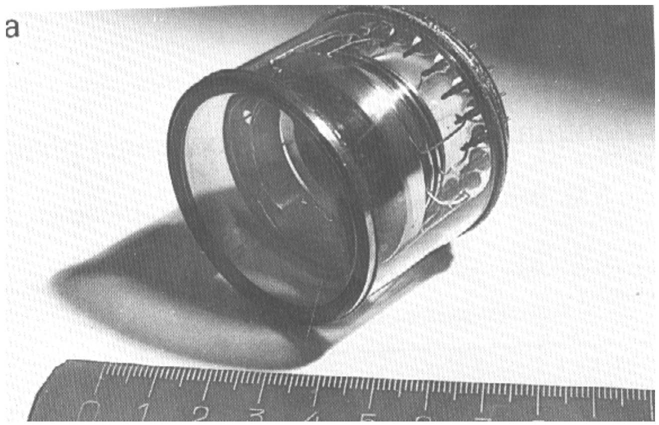
- **Gain in MCP:**
  $G \sim e^{(A*\text{MCP thickness/MCP dia})}$

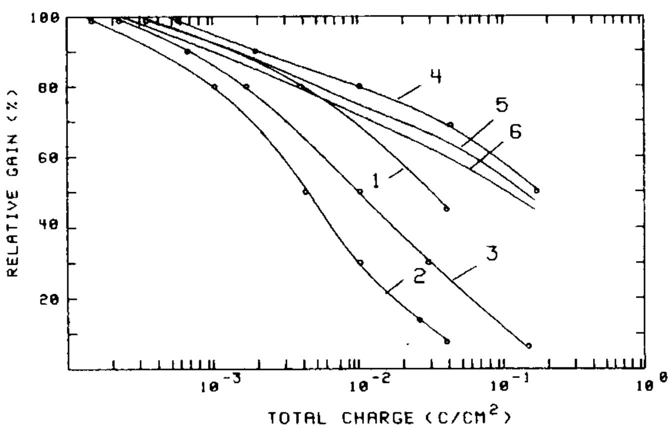
  gets severely reduced in a large magnetic field of 1.5 Tesla.

  The 25□m dia. holes are too large. One needs to reduce their size to ~10□m dia., or even less. This is our next step.
- In addition, one needs to increase the electric field between anode and cathode.

Aging of the MCP Bialkali photocathode by ions

V.V. Anashin et al., Nucl.Instr.&Meth., A357(1995)103



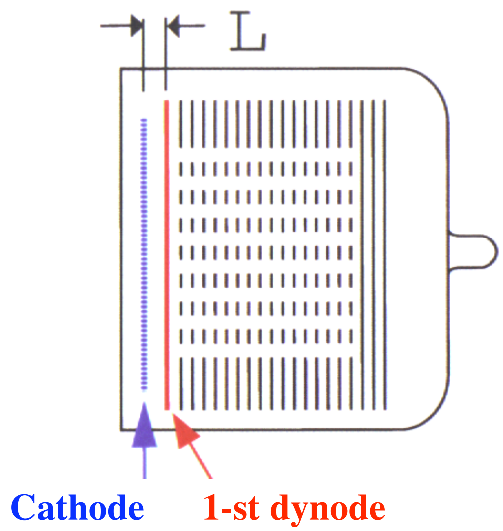


- Early work of V.V. Anashin et al. indicated real problem after an anode charge of **10-20mC/cm^2** (operated at a gain of 10^7!!!).
- DIRC, if equipped with such a MCP, would last a year only.
- That is why all manufacturers now incline holes (~12^o)., plus apply various tricks.
- Burle Co.'s measurement:

  a 50% response loss after ~200mC/cm^2, i.e., a factor of ~10 improvement. This was not yet verified by us !!

Hamamatsu Multi-anode Fine-mesh PMT R-6135-L24 □, □, □

M. Hirose et al., NIM A460(2001)326



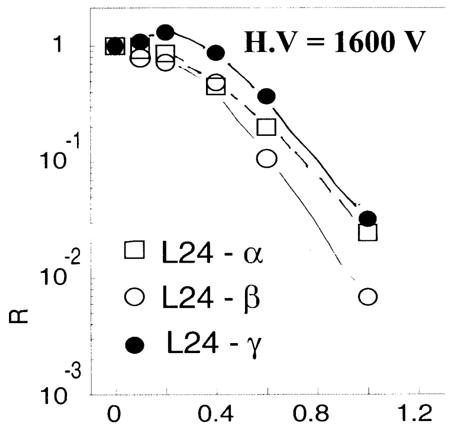
Photocathode	Bi-alkali (visible & UV)
Maximum magnetic field	1.5 Tesla
Geometrical packing efficiency	**~90%**
Collection efficiency of the dynode structure	**52%(□) & 63%(□) & 85% (□)**
Cathode-the 1-st dynode distance = L	2.5-3 (□) and 1 (□,□) mm
Mesh design (lines/inch)	2000 (□,□) 2500 (□) lines/inch
Mesh design (pitch)	9 (□) &12.5 (□) □m
Operating voltage (B=1.5 Tesla)	**-3.4 kV (□)**
Pixel size	26.5 mm x 0.8 mm
Number of pixels	24
Gain in 1.5 Tesla	**~5x10^{6} @ –3.4 kV (□)**
Number of stages	24 (□) 19 (□,□)
Resistor chain (K - D1 - D2 - -> A)	**1-1-….-1 (□) & 2-1-….-1 (□,□)**
PMT rise-time	**~1.0 ns**
Timing resolution per single photon (Nagoya)	**□ ~100 ps at B < 1Tesla**
Timing resolution per single photon (Nagoya)	**□ ~150 ps at B ~ 1.5Tesla**

- This PMT has a good single photon pulse height distribution.
- It can operate at 1.5 Tesla magnetic field.

Behavior of the Fine-mesh PMT R-6135-L24 □, □, □in the magnetic field

M. Hirose et al., NIM A460(2001)326

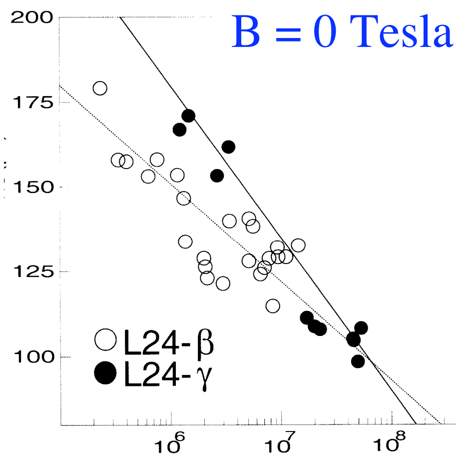
Relative Gain [G/G_0]



B [Tesla]

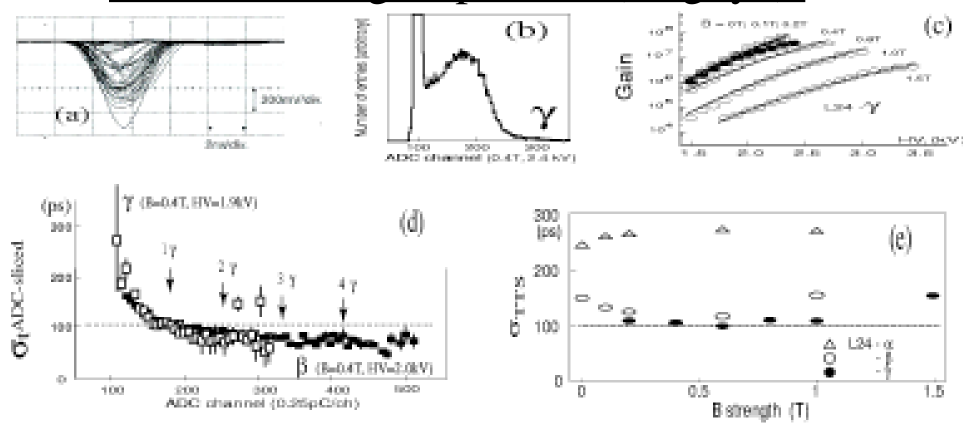
- The gain reduces by a factor of more than 100 at 1.5 Tesla.
- As a result, the timing resolution gets worse also
- It is necessary to choose a very fine mesh
- To reach a timing resolution of □~100ps, one needs to reach a gain of 3-5x10^7 at 0 Tesla.

□$_{TTD}$ [ps]



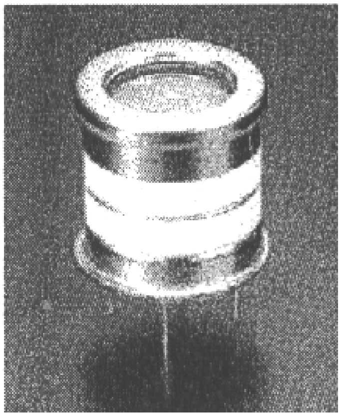
Gain

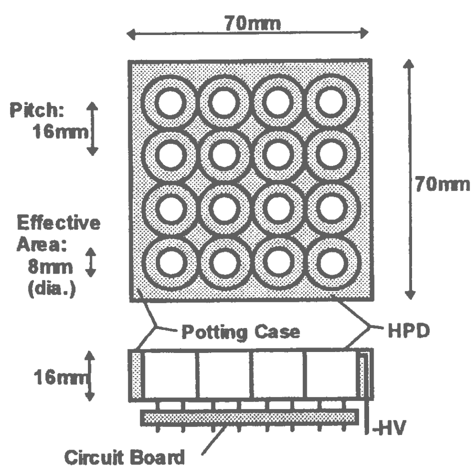
TOP counter group effort (Nagoya):



Hamamatsu HAPD R7110U-07

S. Matsui et al., NIM A463(2001)220, Belle Detector R&D in Nagoya



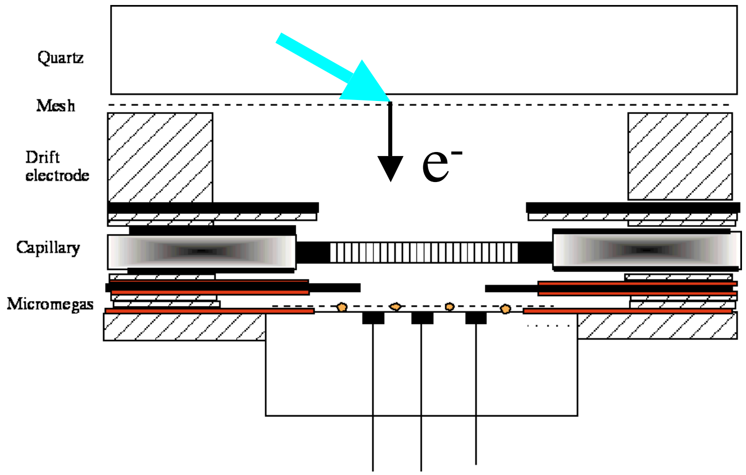


Photocathode	Multi-alkali
Accelerating medium	vacuum
Max. recommended value of $V_{photocathode}$	-8.5 kV
APD diode bias voltage V_{APD}	~155 Volts
Avalanche Photodiode Detector diameter	3mm dia.
Sensitive area	8 mm dia.
Pixel capacitance	120 pF
Geometrical packing efficiency	16 %
Gain @ $V_{photocathode}$ = -9 kV and V_{APD} ~160 V	~1.5×10^5
Type of amplifier	MITEQ, 60dB,300MHz BW
Rise time	~1.1 ns
Fall time	~14.8 ns
Pulse width	~4.9 ns
Timing resolution per single photon	□ ~ 150 ps
Planned operating magnetic field	1.5 Tesla

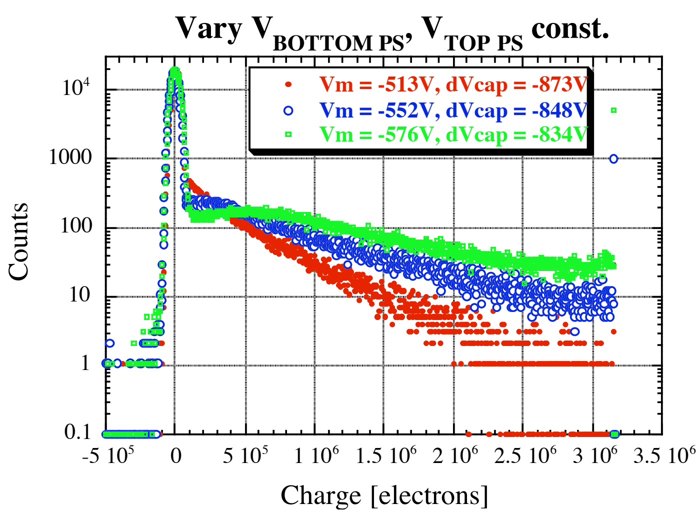
- They reached □~150ps at a total HAPD gain of ~1.5×10^5, by correcting the time walk with an ADC.
- To reach □~100ps, they conclude that they would need a total HAPD gain of ~4×10^5.

Capillary+Micromegas+pads

J.Va'vra,T. Sumiyioshi, to be presented at IEEE, Portland, Oregon, Oct. 2003



89.1%He+10.9%iC$_4$H$_{10}$ gas at 1 bar:



- **Works like a charm in the single electron mode!!**
- **Supports a very high gain (even though one would want to run at much lower gain in the final application).**
- **Would work at 1.5 Tesla.**
- **Timing resolution ? Based on the C. Williams results, one may reach a timing resolution of <100ps per single photon.**
- **How to add a Bialkali photocathode ? Talking to Burle Co.**
- **Can a gaseous device compete with the vacuum MCP-PMT ?!**

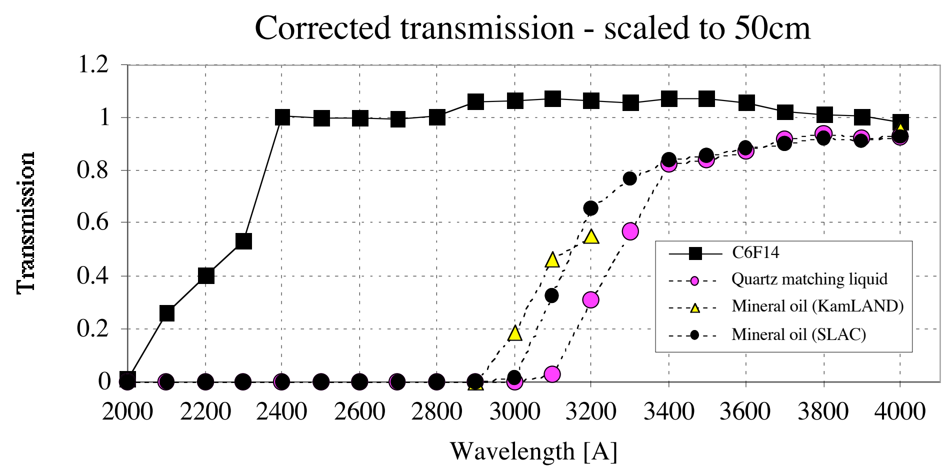
Conclusions

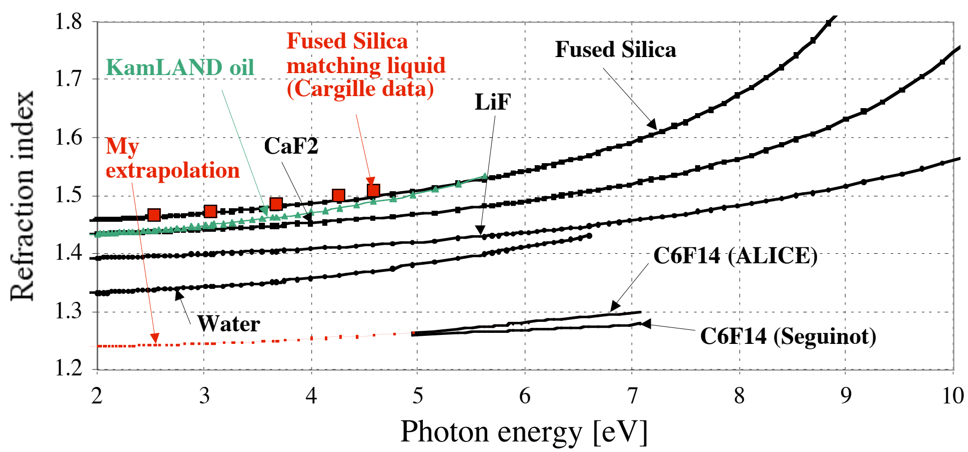
- It has been a long road for the Cherenkov detectors since I started. From a "Cinderella status," they now often excel over the tracking devices, especially in experiments with fixed target geometries. The colliding experiments are still hard.
- **DIRC-based PID detectors might be useful for the hadron machines if they can be perfected to work inside the magnetic field and succeed to correct the chromatic error by timing, and thus reach pi/K separation up to 6-8 GeV/c. I would guess that CDF would take it…**
- There is a progress in photon detectors in the area of resolutions down to 50-100 ps per single photon working in no magnetic field. However, there is still a need for a further development so that they work in large magnetic fields of 1.5 Tesla.
- Until this point, the chromatic error was considered as an uncorrectable quantity. Now, either the TOP counter (Belle) or the Focusing DIRC (BaBar) are aiming to prove that this contribution to the Cherenkov angle error can be eliminated. This is clearly the new frontier.
- Can gaseous detectors compete in the new game of fast timing resolution ?

Back up slides

What matching liquid to use in the box ?

J.Va'vra, log book





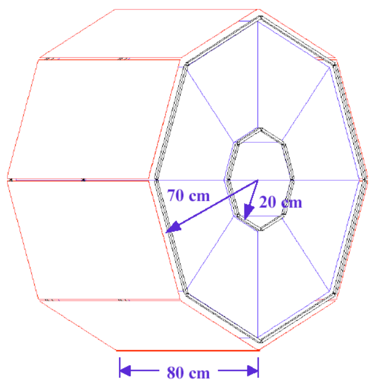
- C_6F_{14} is very transparent, but a poor match to the fused silica refraction index.
- Fused silica matching liquid is not very transparent.
- KamLAND oil seems to be a good solution.
- **SLAC measurement**

What are the candidates for a photon detector ?

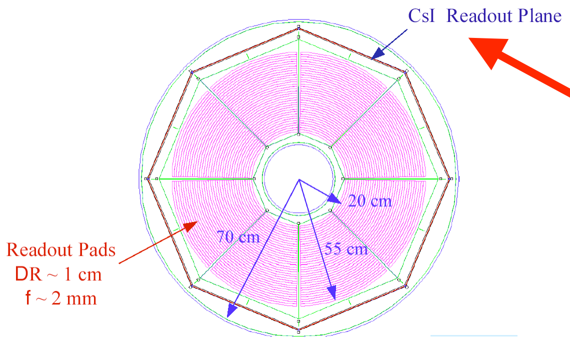
Manufacturer	**Name**	**PMT**	**σ_{TTS} [ps]**
Photonis	Quantacon	XP2020	250
Photonis	PMT	XP2020/UR	150
ETL	DIRC PMT	9125B	1500
Hamamatsu	Flat-panel	H-8500	~120
Hamamatsu	Multi-mesh	R-6135	~80
Burle	MCP-PMT		<50
Dolgoshein	Silicone PM	SiPM	~60

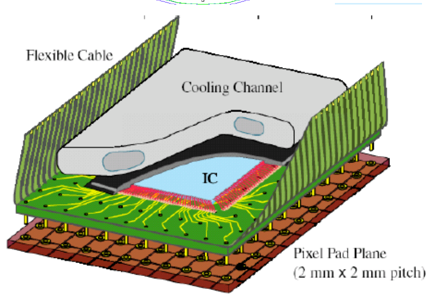
PHENIX TPC with HBD

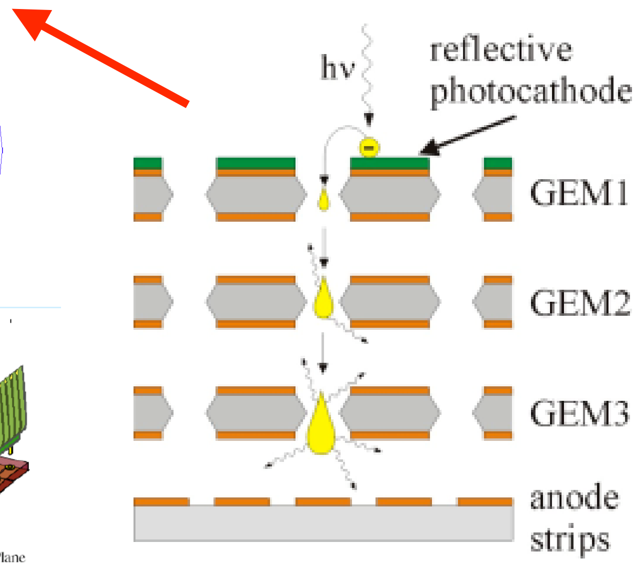
C. Woody, I. Tserruya, Phenix upgrade proposals, RHIC, BNL
D. Mormann et al., Nucl. Instr. & Meth., A478 (2002) 230



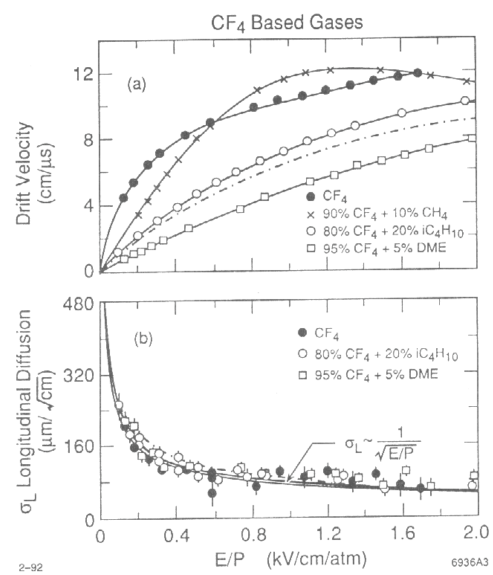
- Colliding heavy ion beam experiment at RHIC
- GEM-based detector for both the TPC readout and a Hadron Blind Detector (HBD), used to detect electrons.
- CF_4-based gas is a TPC gas and also a Cherenkov radiator
- RICH is in the magnetic field.







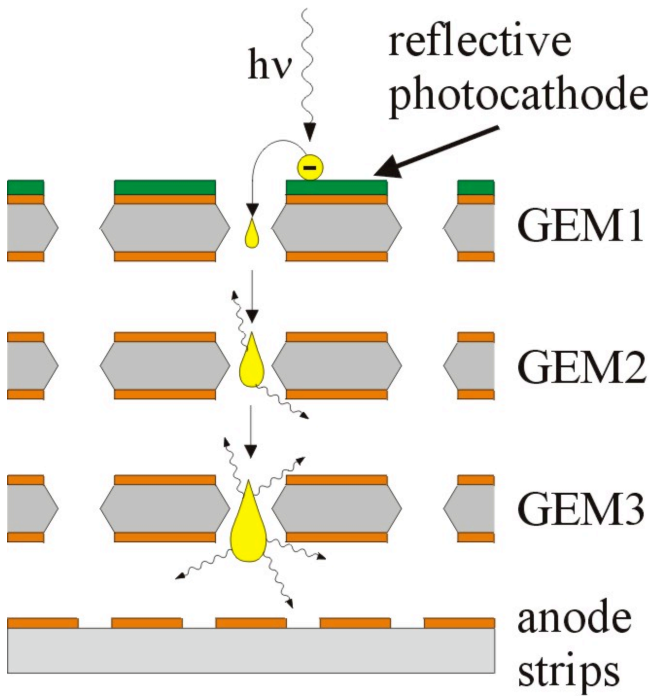
J. Va'vra et al., Nucl. Instr. & Meth., A324 (1993)113



Hadron-blind GEM-based Detector

I. Tserruya et al., Phenix proposal, RHIC, BNL.
Based on work D. Mormann et al., Nucl. Instr. & Meth., A478 (2002) 230

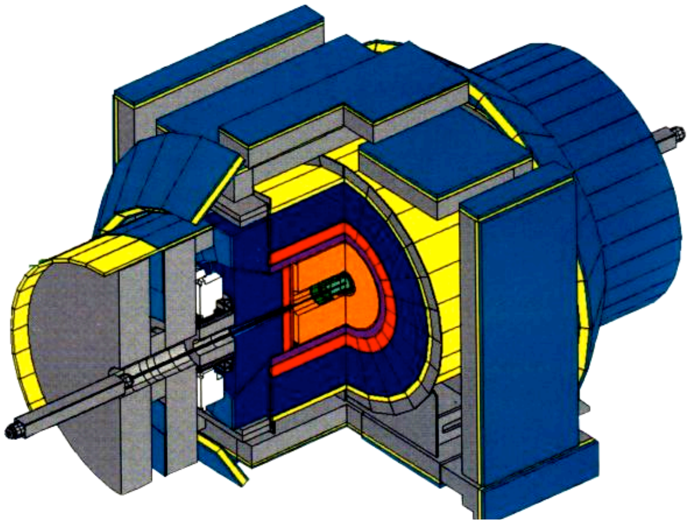
CsI evaporated on top of the GEM foil:

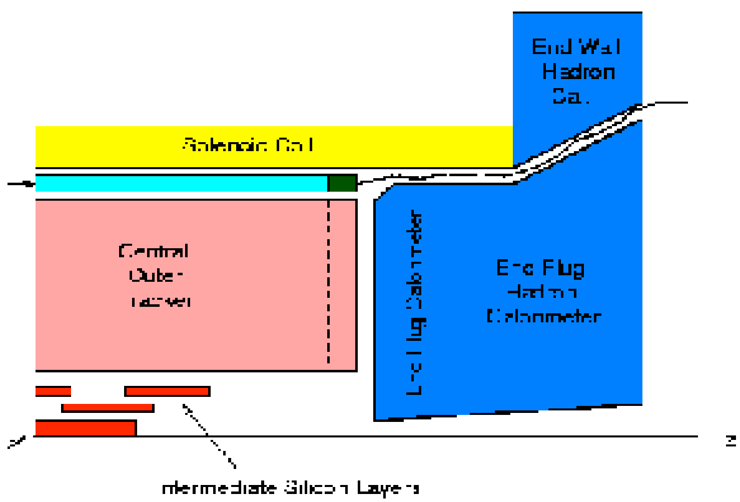


- **Advantages:**
  - Thick reflective photocathodes have superior QE
  - The detectors are almost free of the photon feedback
  - Detectors are fast (time resolution σ~2.1ns in CF_4).
  - High gain operation demonstrated (>10^5).
  - Good 2D resolution (σ ~100μm).
- **Possible problems:**
  - CF_4 gas can be corrosive.

Example of a TOF system - CDF

E. Vataga, 9-th Pisa metting, Elba, Italy, 2003

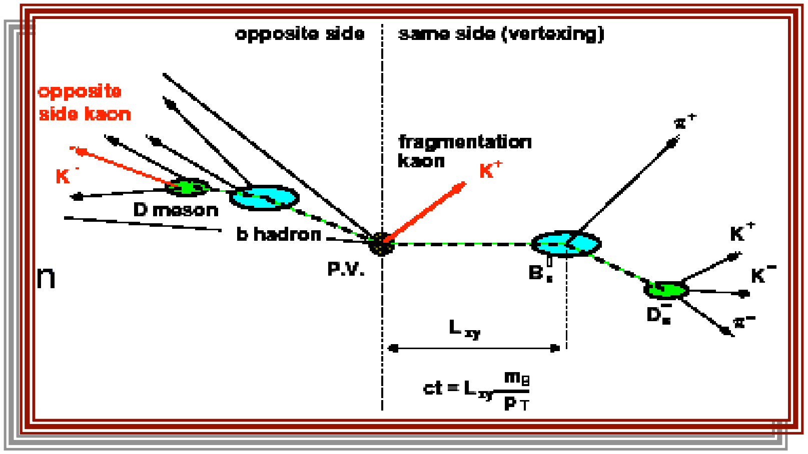




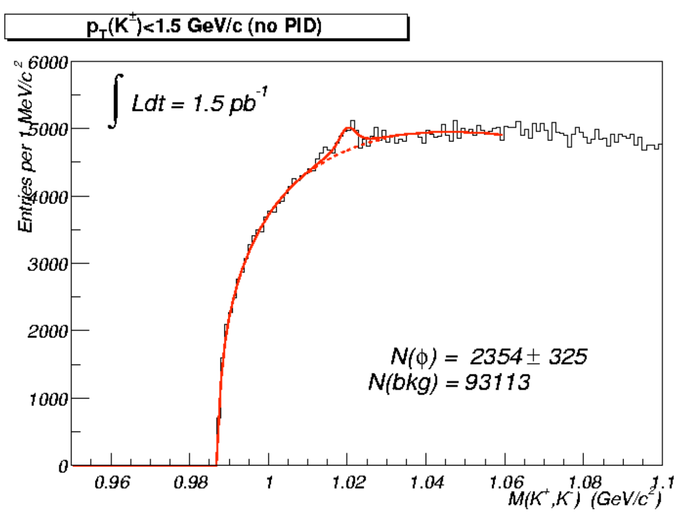
- 216 TOF counters, 4 x 4 x 280 cm long, Bicron BC-408 scintillator
- Hamamatsu R7761 fine mesh PMT, gain reduction at 1.4 T: 500x !!
- Distance to the beam pipe ~1.4m (fastest particle ~5ns)
- Design timing resolution: 100ps (presently reached: ~125ps)
- **Achieved a π/K separation of ~3σ at 1.5 GeV/c.**
- **Even this modest improvement in PID performance helps the B-meson physics in certain channels**

CDF TOF performance

E. Vataga, 9-th Pisa metting, Elba, Italy, 2003



- □ -> K^+ K^-
- Background is reduced by a factor of 20; signal is reduced by a factor of 17



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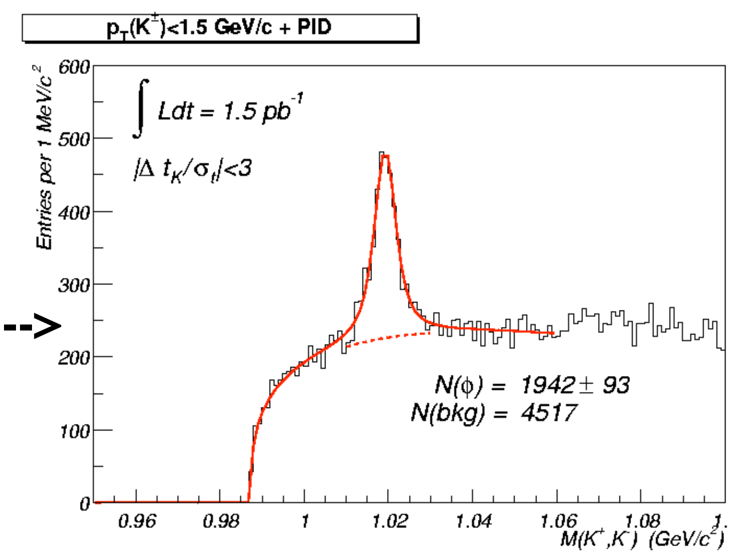
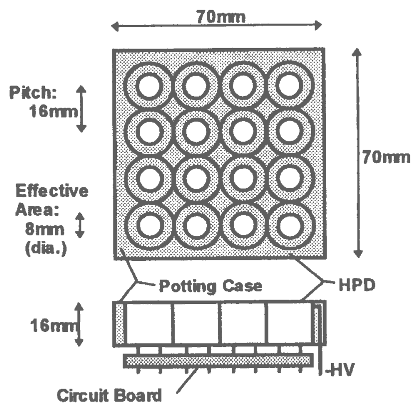


Hamamatsu offers "multi-pixel" 4x4 array R7110U-01 HPDs



- Multi-alkali photocathode
- 3mm dia. APD
- 7mm dia. sensitive area
- Planned operation: 1.5 Tesla
- 300MHz BW amplifier: