

OPERATION OF THE **DIRC** AT THE HIGH LUMINOSITY PEP-II COLLIDER

Outline:

- **DIRC Concept and Design**
- **Operational Experience**
 - Performance Highlights
(see also other DIRC talk, Wed.)
 - Photon Yield, PMT Longevity
 - Sensitivity to Backgrounds
- **Detector Upgrade R&D**

Jochen Schwiening

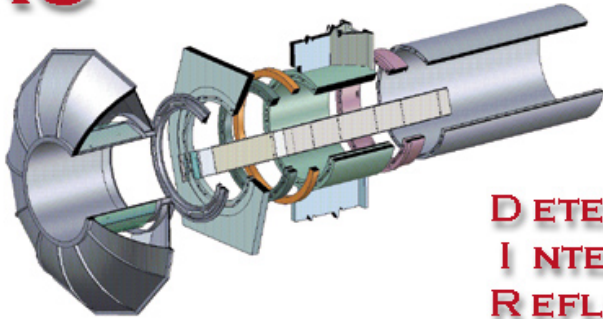


**Stanford
Linear
Accelerator
Center**

A national laboratory funded by the Department of Energy

BABAR-DIRC COLLABORATION

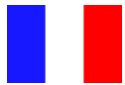
DIRC



DETECTION OF
INTERNALLY
REFLECTED
CHERENKOV LIGHT

Novel RICH detector used for the first time in BABAR

DIRC combines with dE/dx from drift chamber and vertex detector (mostly in the $1/\beta^2$ region) as hadronic particle identification system for BABAR.



The BABAR-DIRC Collaboration



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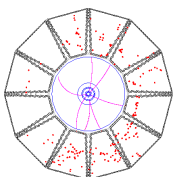
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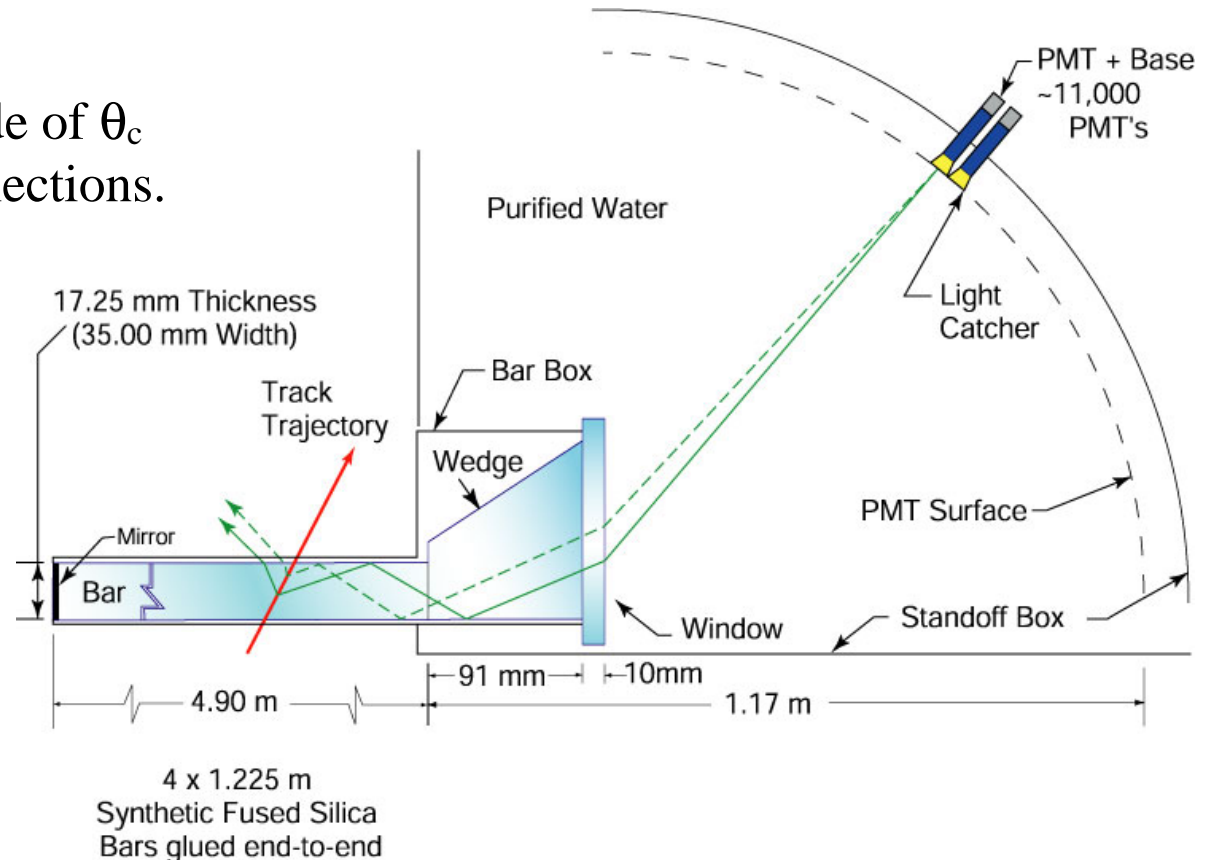
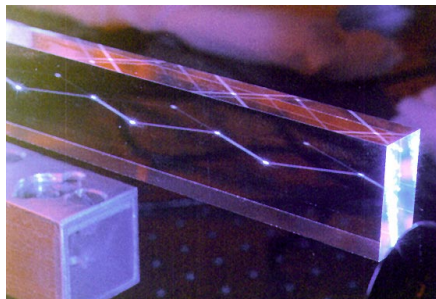
DIRC PRINCIPLE I

- A charged particle traversing a radiator with refractive index n with $\beta = v/c > 1/n$ emits Cherenkov photons on cone with half opening angle $\cos \theta_c = 1/n\beta$.
- If $n > \sqrt{2}$ some photons are always totally internally reflected for $\beta \approx 1$ tracks.
- **Radiator and light guide:** Long, rectangular **Synthetic Fused Silica** (“Quartz”) bars
(*Spectrosil*: average $\langle n(\lambda) \rangle \approx 1.473$, radiation hard, homogenous, low chromatic dispersion;
144 bars: $490 \times 1.7 \times 3.5 \text{ cm}^3$, polished to surface roughness $< 5 \text{ \AA}$ (*rms*); square to better than 0.3 mrad .)

- Square radiator bar \rightarrow magnitude of θ_c preserved during internal reflections.

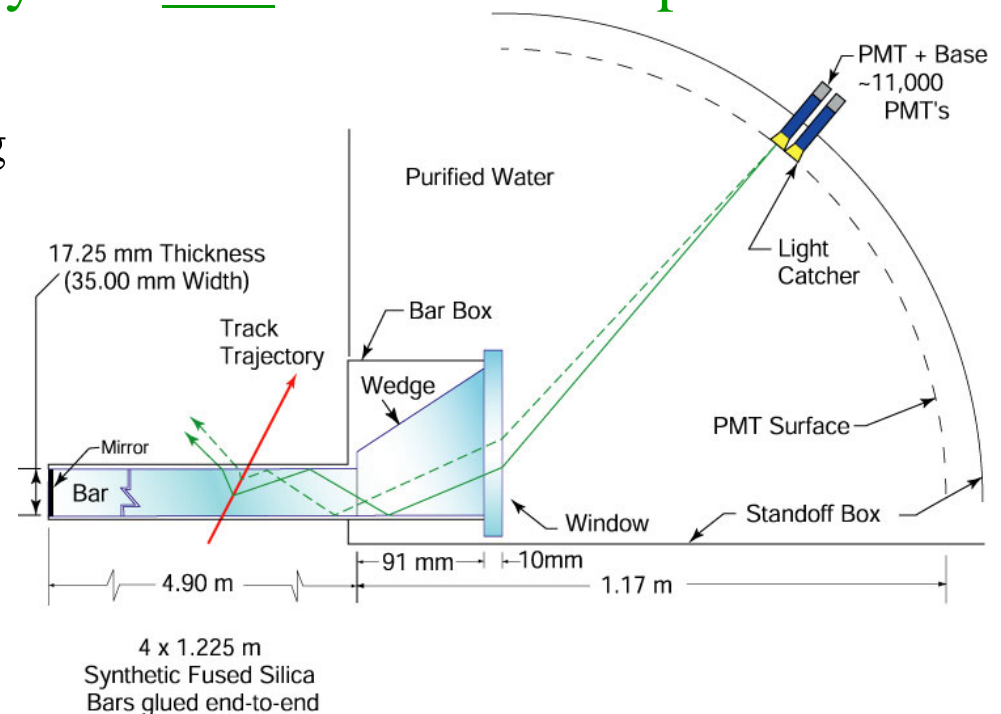
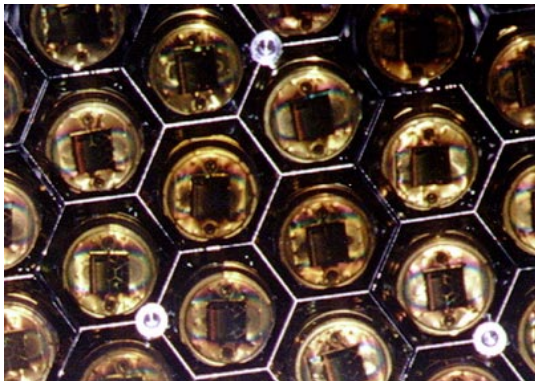
Typical DIRC photon:

- $\lambda \approx 400 \text{ nm}$,
- ~ 200 bounces,
- $\sim 10\text{-}60 \text{ ns}$ propagation time,
- $\sim 5 \text{ m}$ path in quartz.



DIRC PRINCIPLE II

- Only one end of bar instrumented; **mirror** attached to other (forward) end.
- Spectrosil **wedge** glued to readout end reduces required number of PMTs by \sim factor 2 and improves exit angle efficiency for large angle photons .
- Photons exit from wedge into **expansion region** (filled with 6m^3 pure, de-ionized water).
($\langle n_{\text{water}}(\lambda) \rangle \approx 1.346$, Standoff distance ≈ 120 cm, outside main magnetic field; shielding: $B \lesssim 1$ Gauss)
- Pinhole imaging on **PMT array** (bar dimension small compared to standoff distance).
(10,752 traditional PMTs ETL 9125, immersed in water, surrounded by hexagonal “light-catcher”, transit time spread $\sim 1.5\text{nsec}$)
- **DIRC is a 3-D device, measuring: x, y and time of Cherenkov photons.**
- PMT / radiator bar combination plus track direction and location from tracking define θ_c , ϕ_c , $t_{\text{propagation}}$ of photon.



DIRC RECONSTRUCTION I

DIRC “Ring” images:

- limited acceptance for total internal reflection,
- reflection ambiguities (initial reflection up/down, left/right, reflection off mirror, wedge
→ up to 16 (θ_c , ϕ_c) ambiguities per PMT hit),
- toroidal detection surface,
→ Cherenkov ring images are distorted:

complex, disjoint images

Low energy photons from accelerator hit Standoff Box.

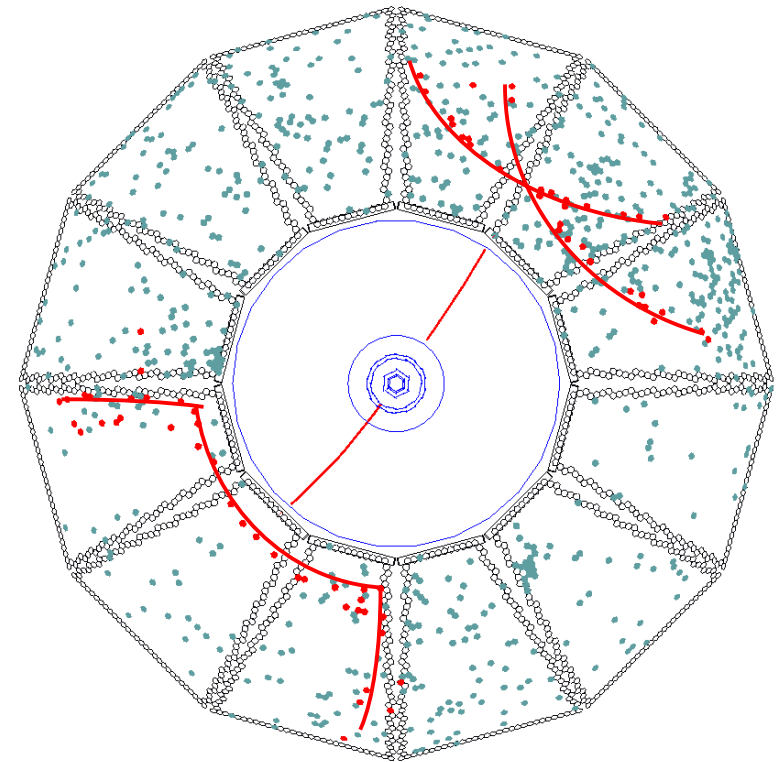
At current luminosity that causes rates of 80-200 kHz/tube.

80-200 kHz \otimes 10,752 PMTs \otimes \pm 300 nsec trigger window

→ 500-1300 background hits (~10% occupancy)

compared to

50-300 Cherenkov photons



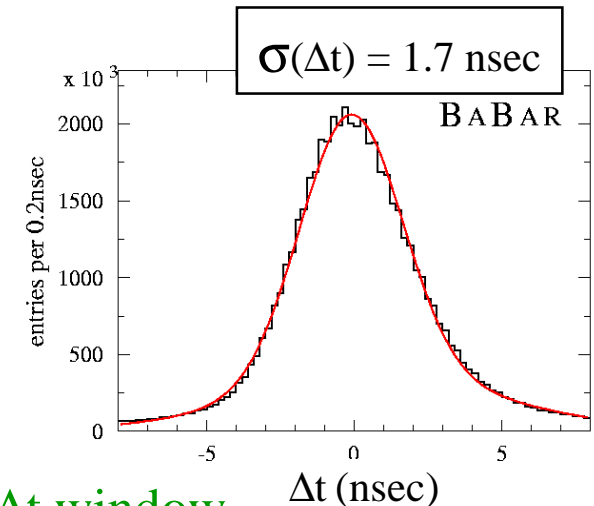
DIRC RECONSTRUCTION II

Time information provides powerful tool to reject accelerator and event related background.

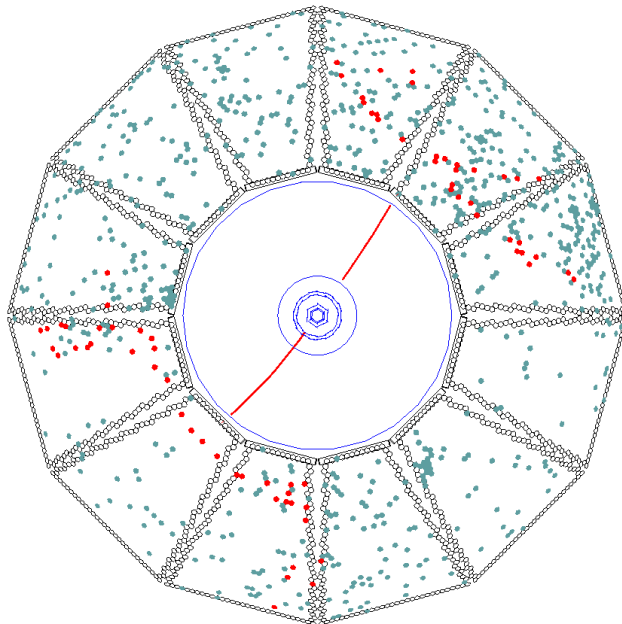
Calculate expected arrival time of Cherenkov photon based on

- track TOF
- photon propagation in radiator bar and in water

Δt : difference between measured and expected arrival time



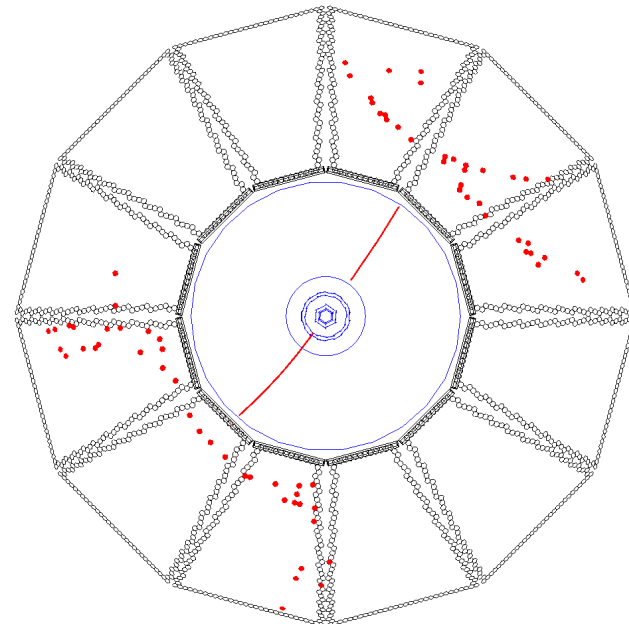
$\pm 300 \text{ nsec}$ trigger window
(~500-1300 background hits/event)



→

$\pm 8 \text{ nsec}$ Δt window
(1-2 background hits/sector/event)

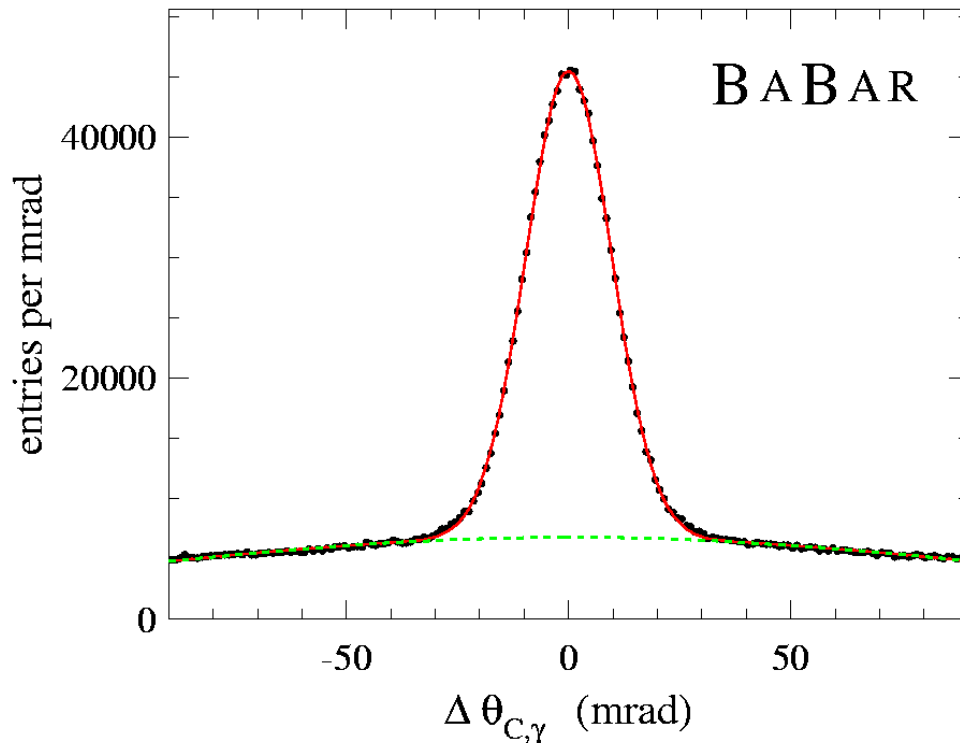
→



DIRC PERFORMANCE HIGHLIGHTS I

Single Photon Cherenkov angle resolution:

$\Delta\theta_{c,\gamma}$: difference measured $\theta_{c,\gamma}$ per photon solution and expected track θ_c (di-muons)



$$\sigma(\Delta\theta_{c,\gamma}) = 9.6 \text{ mrad}$$

Expectation: ~ 9.5 mrad

dominated by:

7mrad from PMT/bar size,

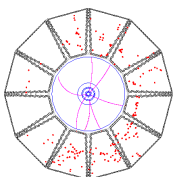
5.4mrad from chromatic term,

2-3mrad from bar imperfections.

$\sim 10\%$ **Background** under $\Delta\theta_{c,\gamma}$ peak:

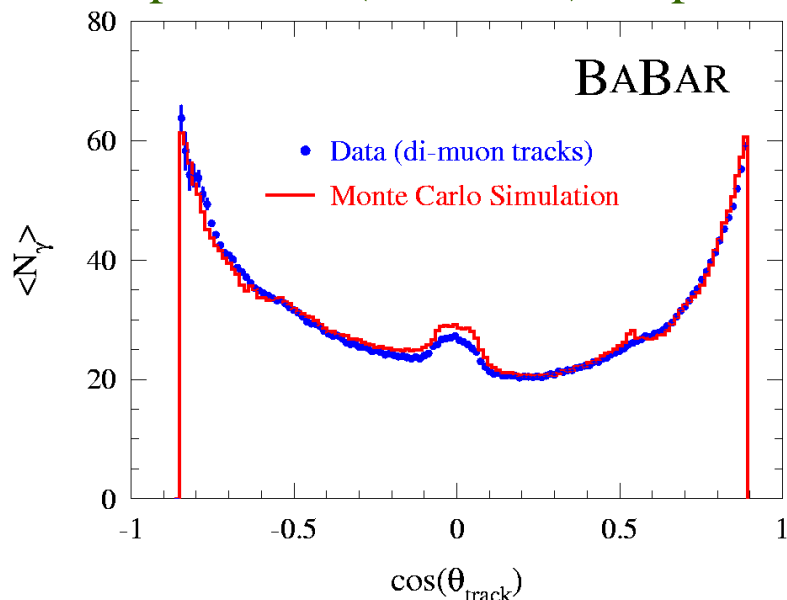
combinatoric background, track overlap, accelerator background,

δ electrons in radiator bar, reflections at fused silica/glue interface, ...



DIRC PERFORMANCE HIGHLIGHTS II

Number of Cherenkov photons
per track (di-muons) vs. polar angle:

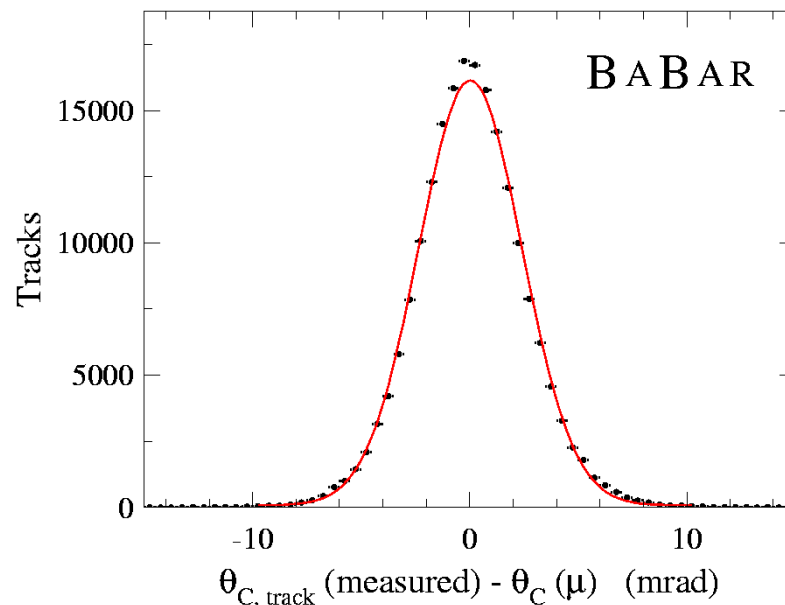


Between 20 and 60 signal photons per track.

Very useful feature in BABAR environment:
higher momentum correlated with
larger polar angle values

→ more signal photons,
better resolution ($\sim 1/\sqrt{N}$)

Resolution of Cherenkov angle fit
per track (di-muons):

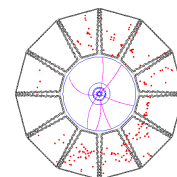


$$\sigma(\Delta\theta_c) = 2.4 \text{ mrad}$$

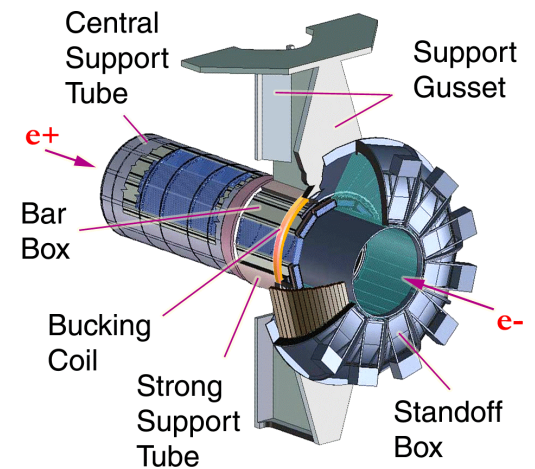
Track Cherenkov angle resolution is
within $\sim 10\%$ of design.

Should improve with advances in
track- and DIRC-internal alignment.

For more on DIRC performance, see DIRC talk in Wednesday session.



DIRC is Stable and Robust

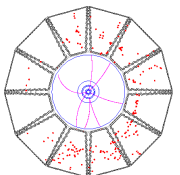
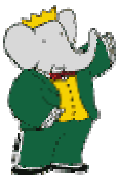


BABAR-DIRC Timeline:

- November 1998: installed SOB and one bar box, PMTs in water;
- April 1999: BABAR moves into beamline, added 4 more bar boxes;
- November 1999: all 12 bar boxes installed, start of first physics run.

The two most significant operational issues that have emerged during three+ years of running:

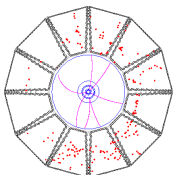
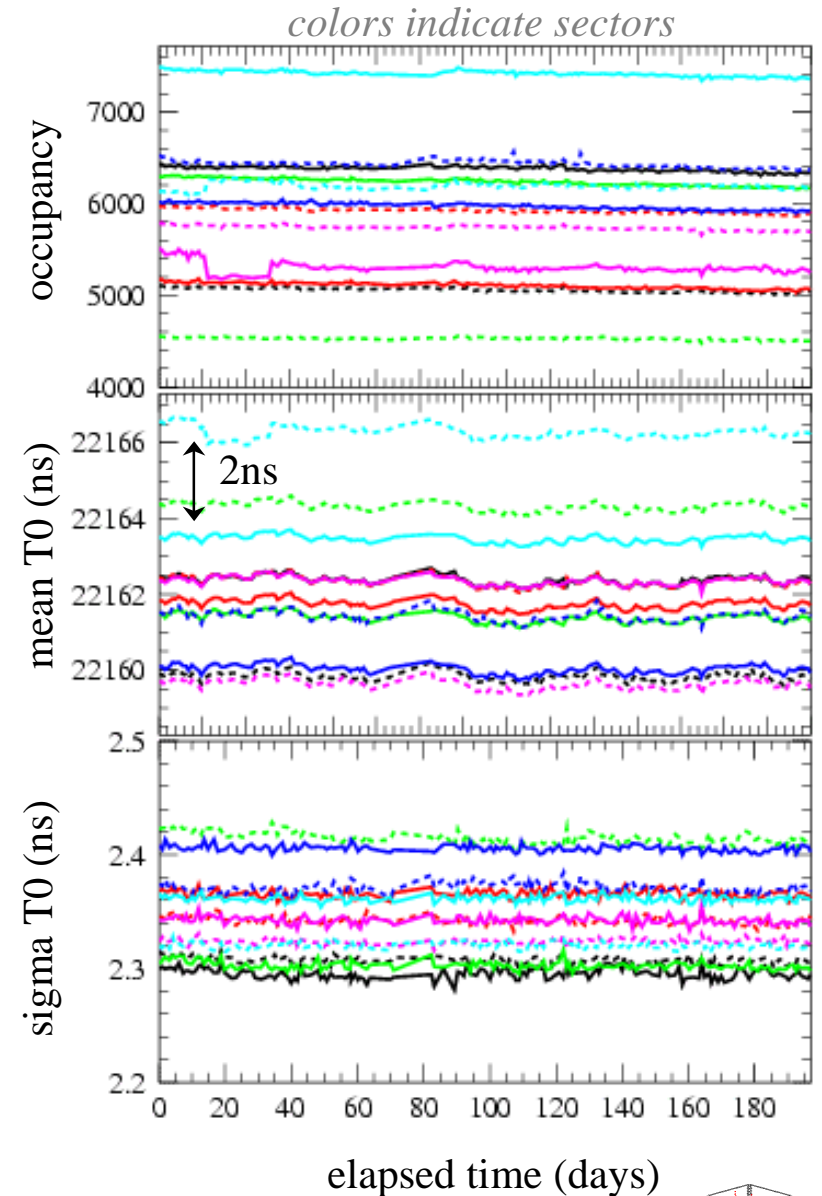
- Sensitivity of the DIRC to machine background interacting in the SOB (primarily DAQ issue)
- Concerns about PMT longevity due to PMT window degradation.



DIRC OPERATIONAL EXPERIENCE: STABILITY

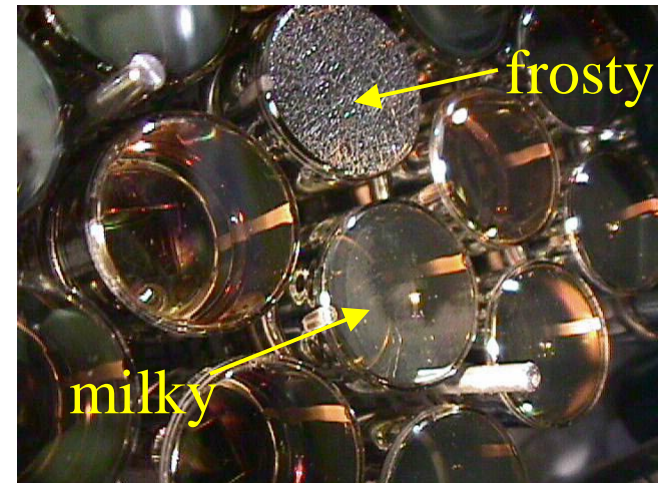
DIRC is Stable and Robust

- Calibration constants stable:
typical rms of T0 per channel ~ 0.1 ns
(light pulser and data stream).
- Monitor humidity of **nitrogen** return line from bar box: **dew points** constant at $-45\dots -55$ C, no leaks after installation.
- **Water** purification system keeps **resistivity** at $18.5\text{M}\Omega\text{cm}$ (input) and $9.5\text{M}\Omega\text{cm}$ (return).
- **Water transmission** in SOB remains stable at 98%/m (442nm, 325nm), 95%/m (266nm).



PMT front window corrosion

- Discovered after ~ 1 year immersion Oct. 99.
- Status Oct. 99: ~ 50 *frosty* tubes and ~ 2/3 visibly *milky*.
- Only front glass affected, side glass fine.

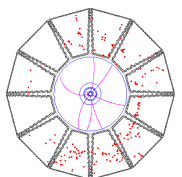
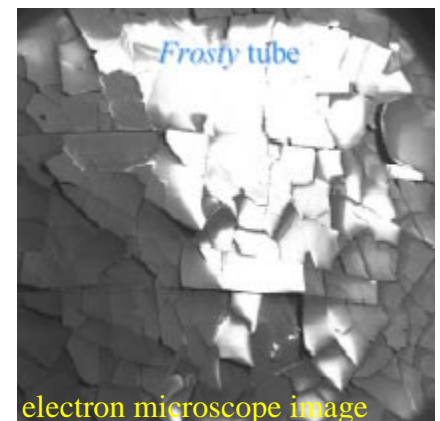


Studies →

- Strongly corroded (*frosty*) tubes are a **bad batch of PMT glass** (no zinc).
- *Milkeness* results from **sodium depletion** in near surface.

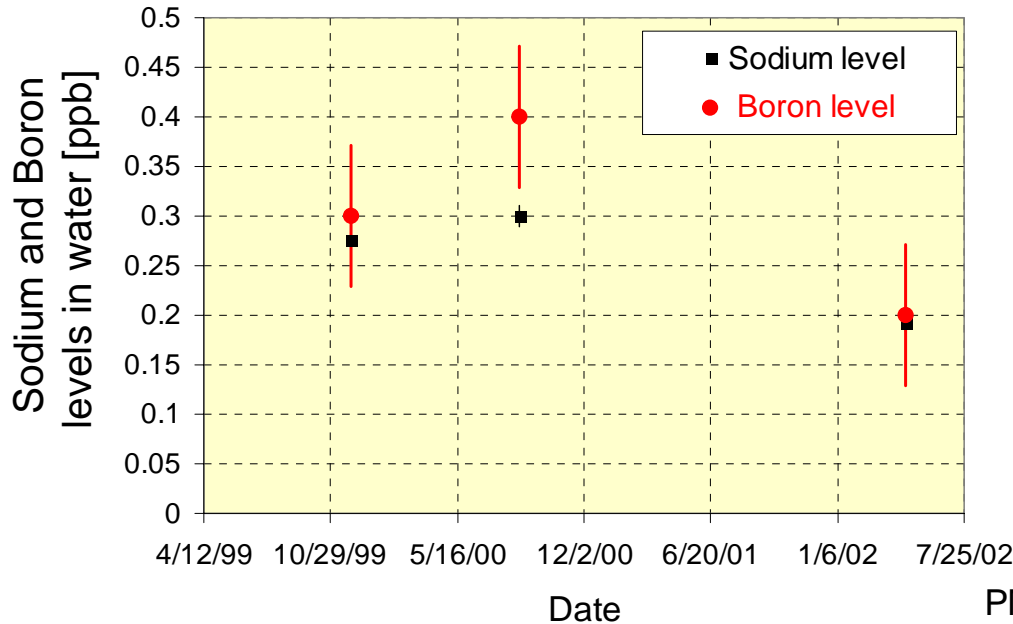
No obvious immediate effect (water provides good coupling) but ...

- ⇒ Might lose PMT efficiency with time.
- ⇒ Might lose vacuum in some of the ~ 50 *frosty* tubes on 10 year time scale (front window thickness: 1mm).



DIRC OPERATIONAL EXPERIENCE: PMT LONGEVITY II

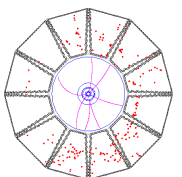
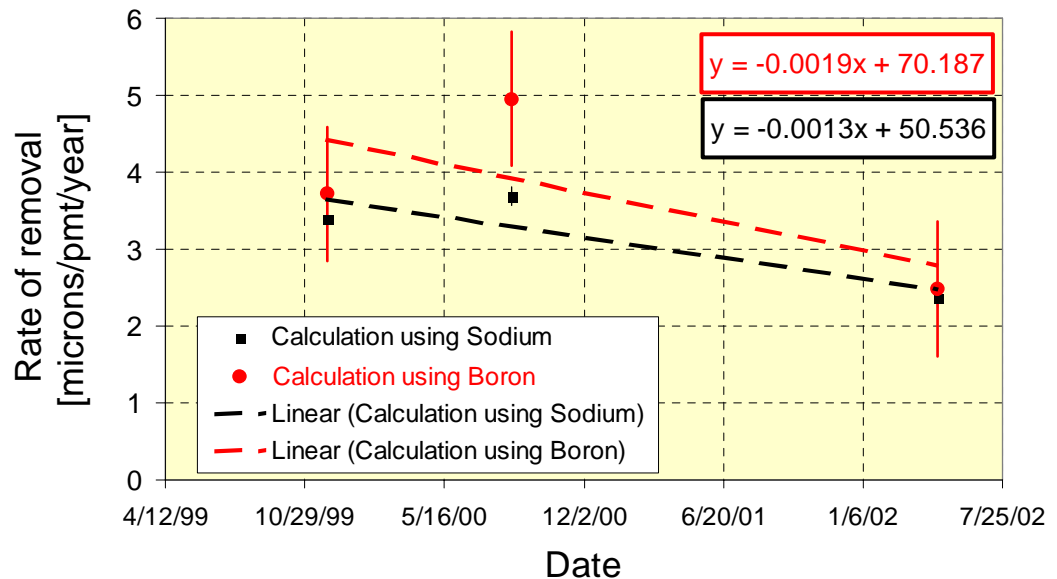
Sodium and Boron levels (return-supply)
in SOB water = f(time)



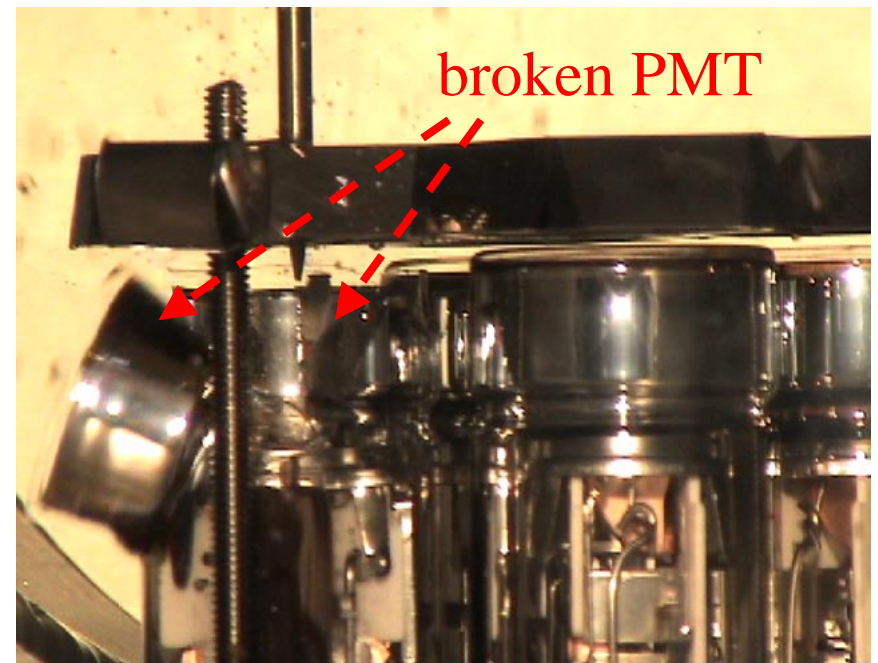
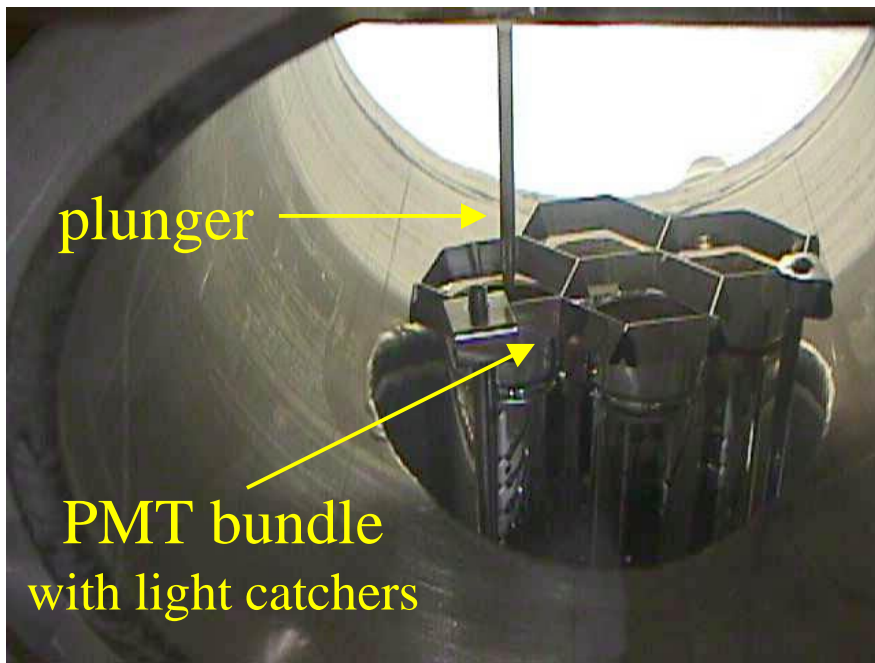
Chemical analysis of return water from standoff box:

- measure Sodium and Boron levels;
- three measurements since 1999;
- levels indicate loss of 2-3µm per year from PMT windows (1mm thick).

PMT front surface removal rate = f(time)

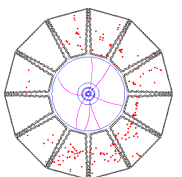


DIRC OPERATIONAL EXPERIENCE: PMT LONGEVITY III



Concern with **mechanical stability** of PMTs when front glass gets thinner (*Super-K...*)

- **breaking test** of PMT bundle at **4m and 8m** water column (DIRC max. < 4m);
- used sharp plunger to break PMT front glass;
- **no breaking of neighboring PMTs** observed at either depth.

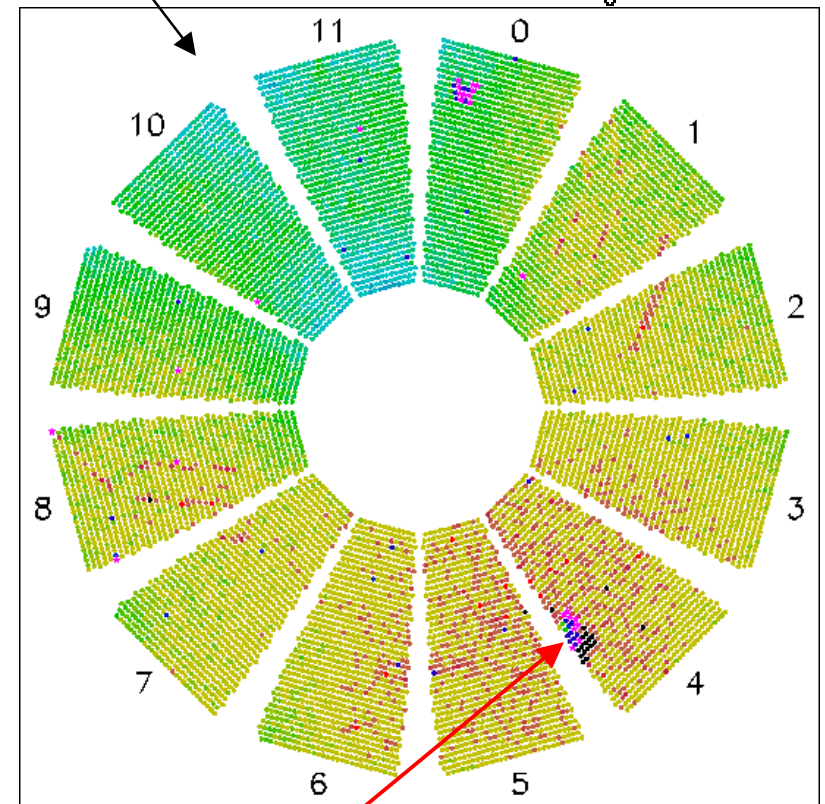
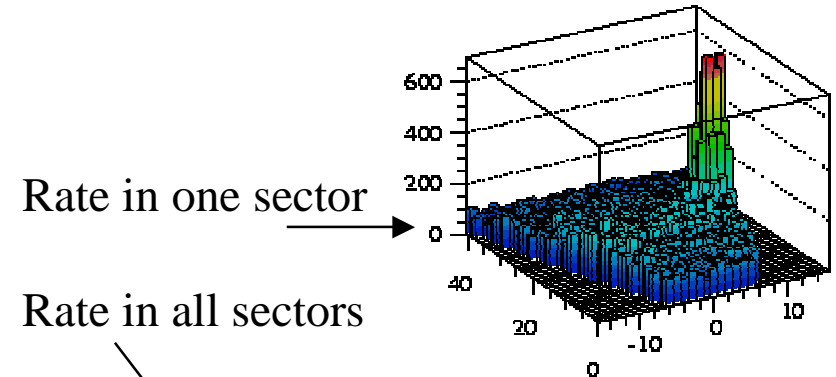


DIRC OPERATIONAL EXPERIENCE: PMT LONGEVITY IV

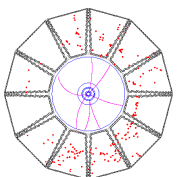
Most spectacular failure mode of PMTs:

“Christmas Tree”

- loss of vacuum in PMT at base;
- discharge in PMT creates many photons, emitted via front or clear side glass;
- extra photons are detected by neighbors (sometimes scatter through entire SOB);
- rates in affected PMT in MHz range, several 100kHz in neighbors;
- PMT dies after few hours – days;
- HV of affected PMT immediately (automatically) lowered to preserve data quality;
- observed rate: 5-6 per year.

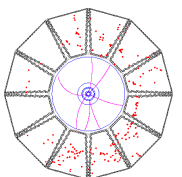
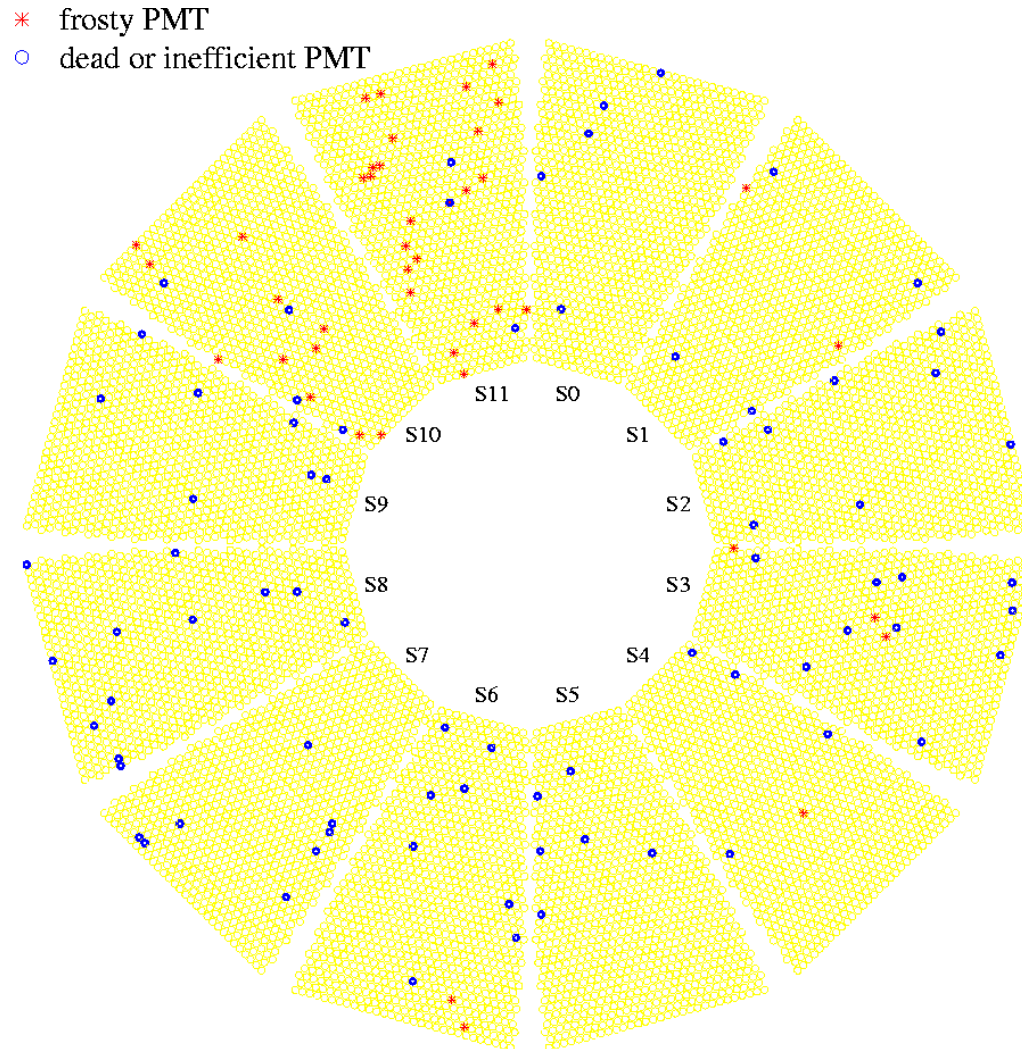


Christmas Tree PMT



DIRC OPERATIONAL EXPERIENCE: PMT LONGEVITY V

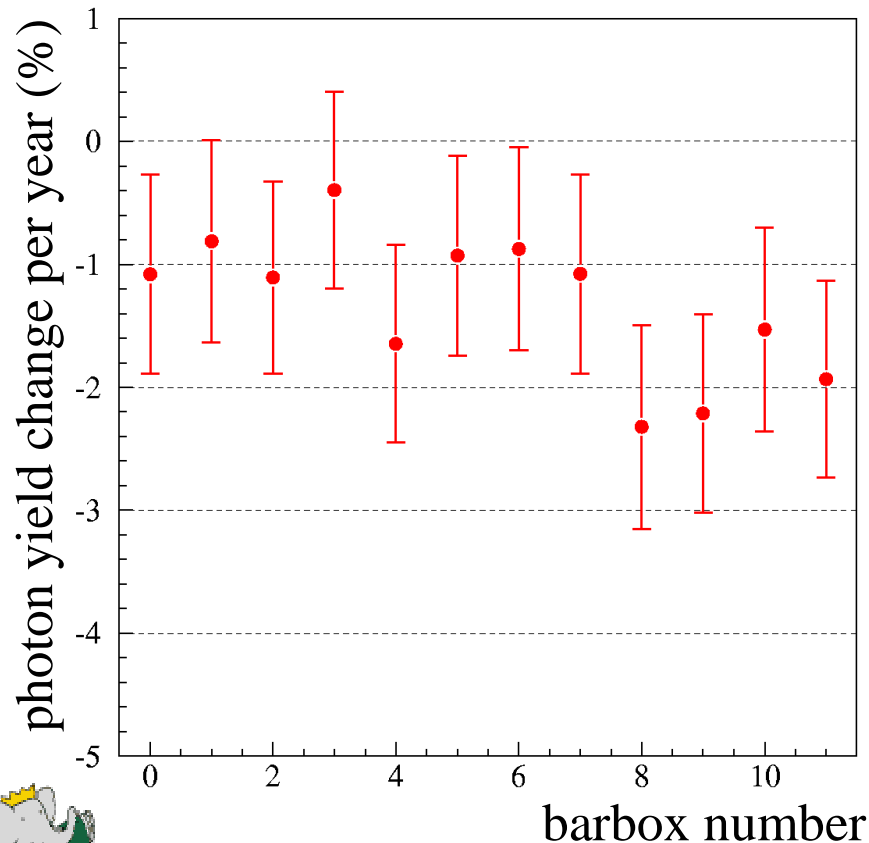
After over three years, 82 PMTs out of 10,752 are dead or inefficient
→ 99.2% fully functional



DIRC OPERATIONAL EXPERIENCE: PHOTON YIELD

Concern: stability of photon yield

- PMT directly immersed in purified water since 1998;
- observed front glass corrosion in October 1999;
- no direct experience with maintaining high (>0.999) radiator reflection coefficient for 10 years.



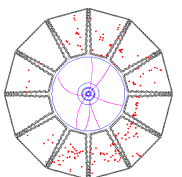
Detailed study of photon yield using:

- LED pulser calibration,
- PMT aging tests,
- comparison of photon yield in real Bhabha and **di-muon events** separately for every radiator bar (box).

Consistent result:

1-2% photon yield loss per year.

→ very minor impact on PID performance over 10 year lifetime of DIRC.



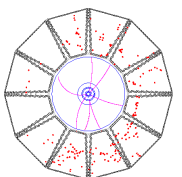
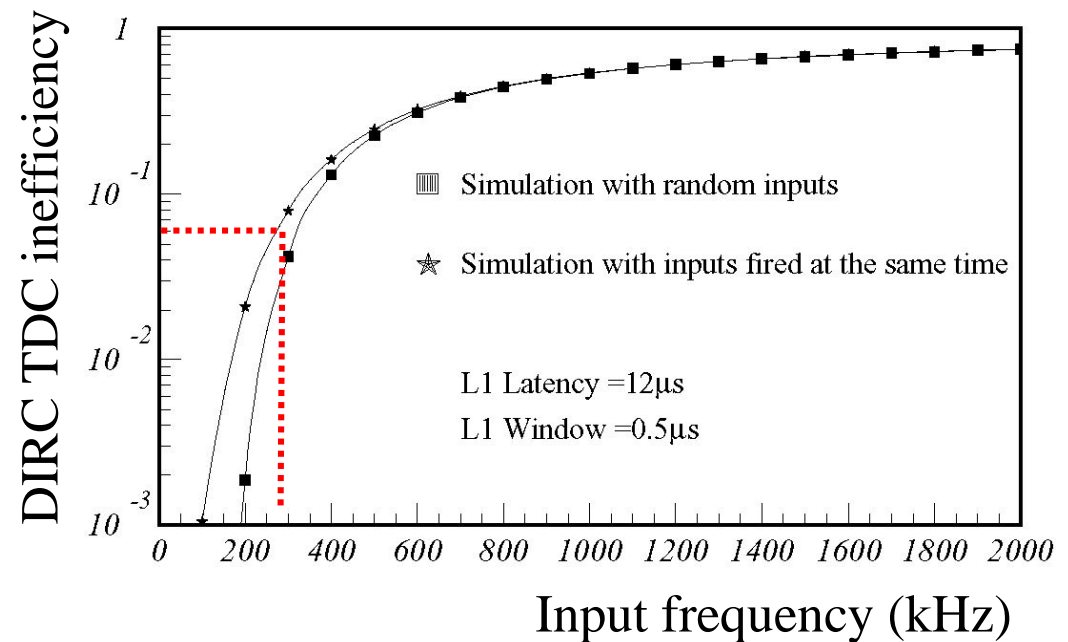
DIRC OPERATIONAL EXPERIENCE: BACKGROUNDS I

PEP-II Luminosity and currents are rapidly increasing

- $4 \cdot 10^{33} / \text{cm}^2 \cdot \text{s}$ now,
- expect $> 5 \cdot 10^{33} / \text{cm}^2 \cdot \text{s}$ at the end of the 2001/2002 run,
- $1-2 \cdot 10^{34} / \text{cm}^2 \cdot \text{s}$ in 2004/5;
- $10^{35} - 10^{36} / \text{cm}^2 \cdot \text{s}$ discussed (“SuperBABAR”).

Δt cut very effective in removing accelerator induced background from reconstruction.

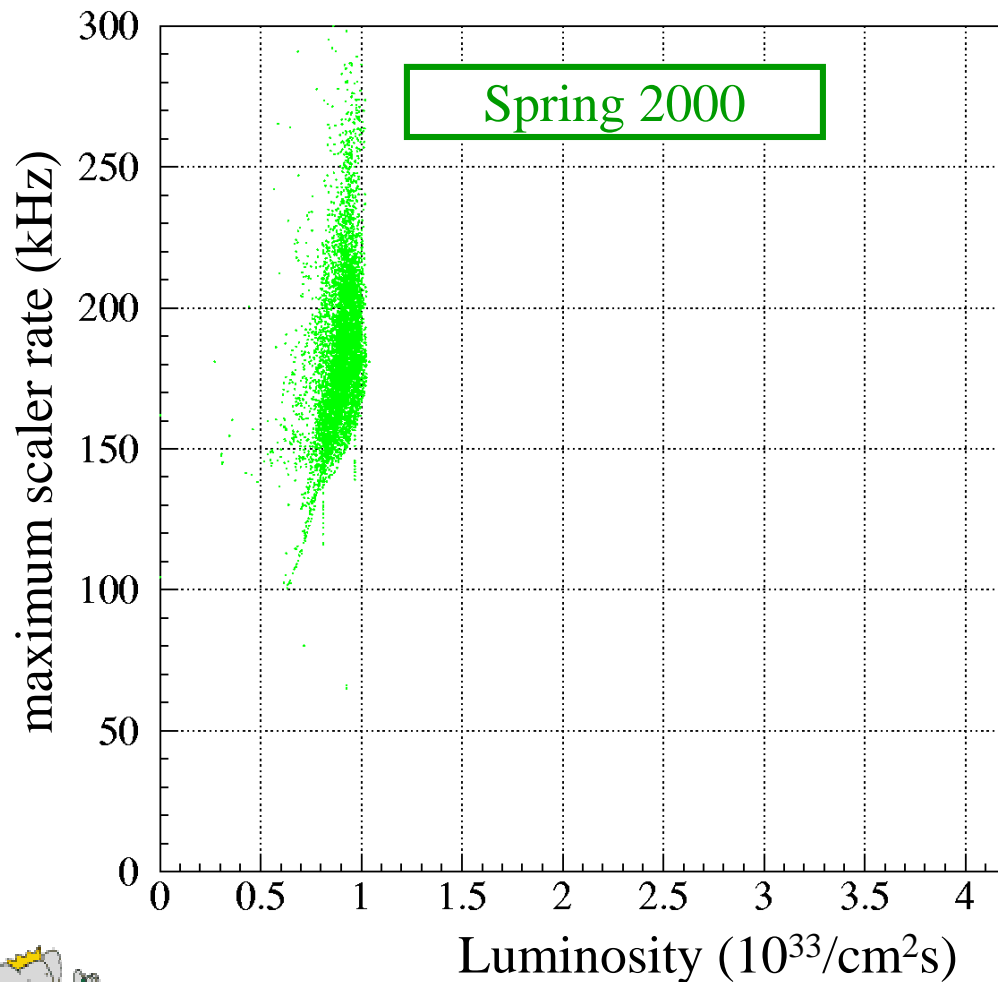
But high counting rates cause inefficiency of present DIRC TDC:
~5% inefficiency at 250 kHz



DIRC OPERATIONAL EXPERIENCE: BACKGROUNDS II

Monitor background rates:

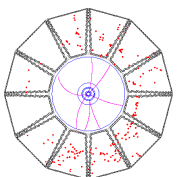
one PMT/sector is read out via scaler, available online,
used in slow control (current operational limit 400kHz).



Status during early BABAR running:

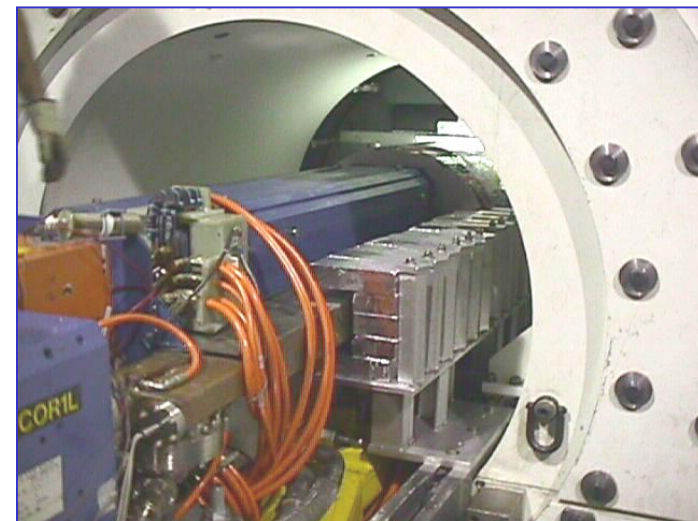
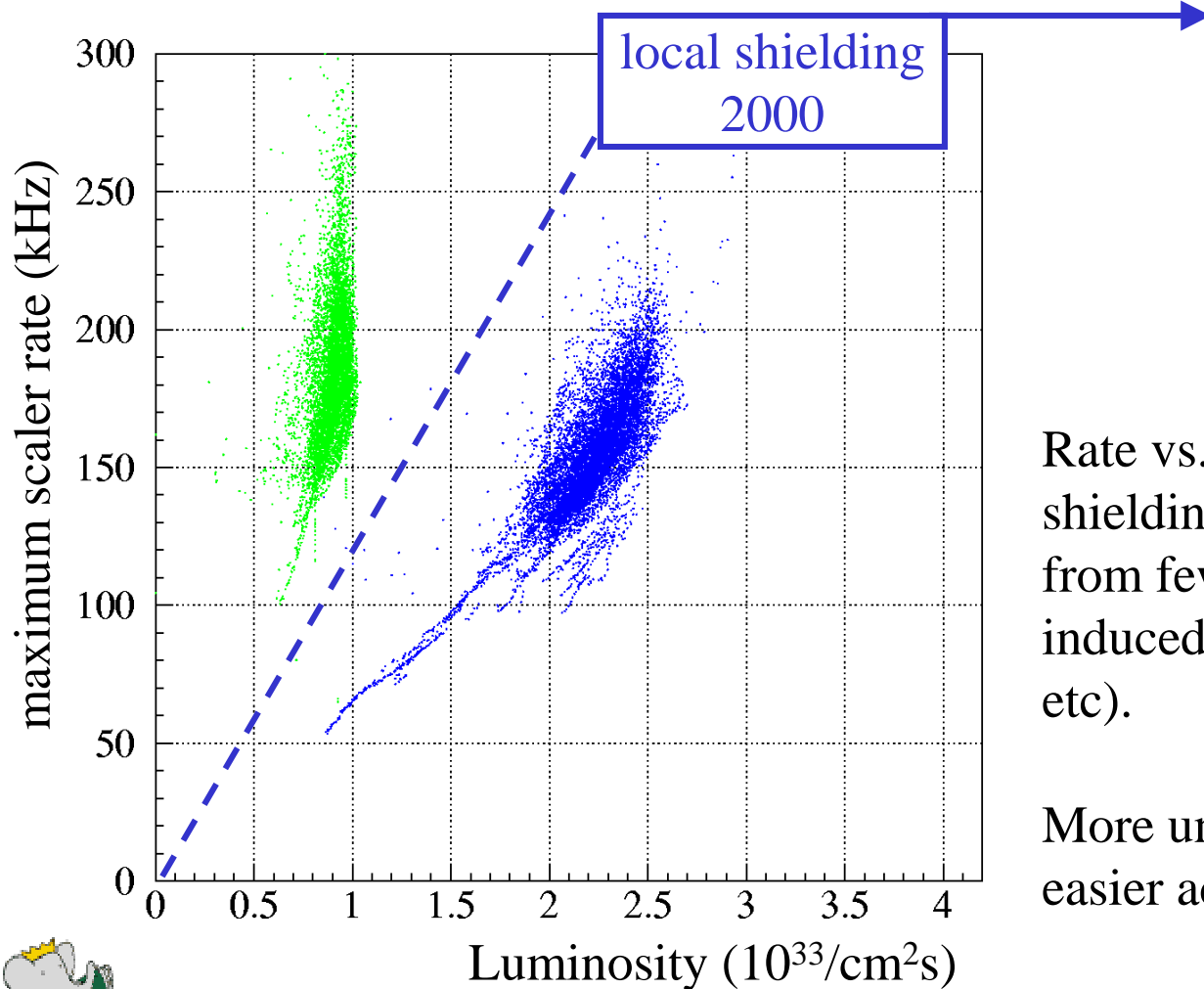
rates of $>250\text{kHz}$ causing
noticeable TDC deadtimes
at 1/3 of design luminosity

Started to install localized lead
brick shielding to block potential
background sources.



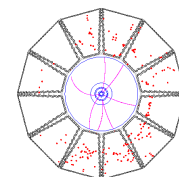
DIRC OPERATIONAL EXPERIENCE: BACKGROUNDS III

Summer 2000 - 2000/2001 shutdown:
localized lead brick shielding around
beampipe and quadrupoles in BABAR



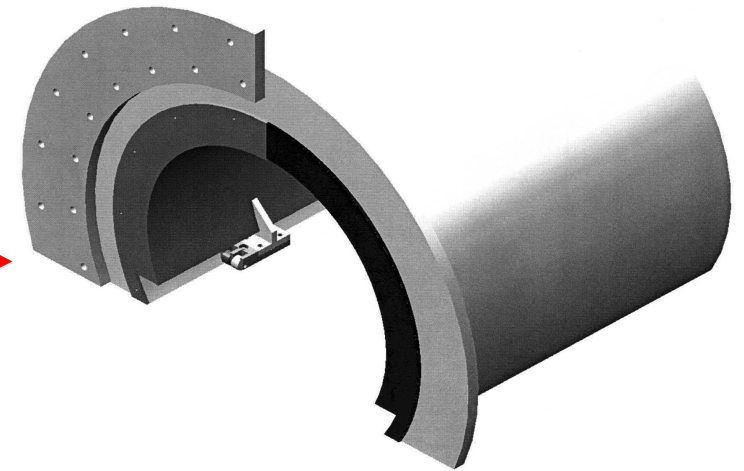
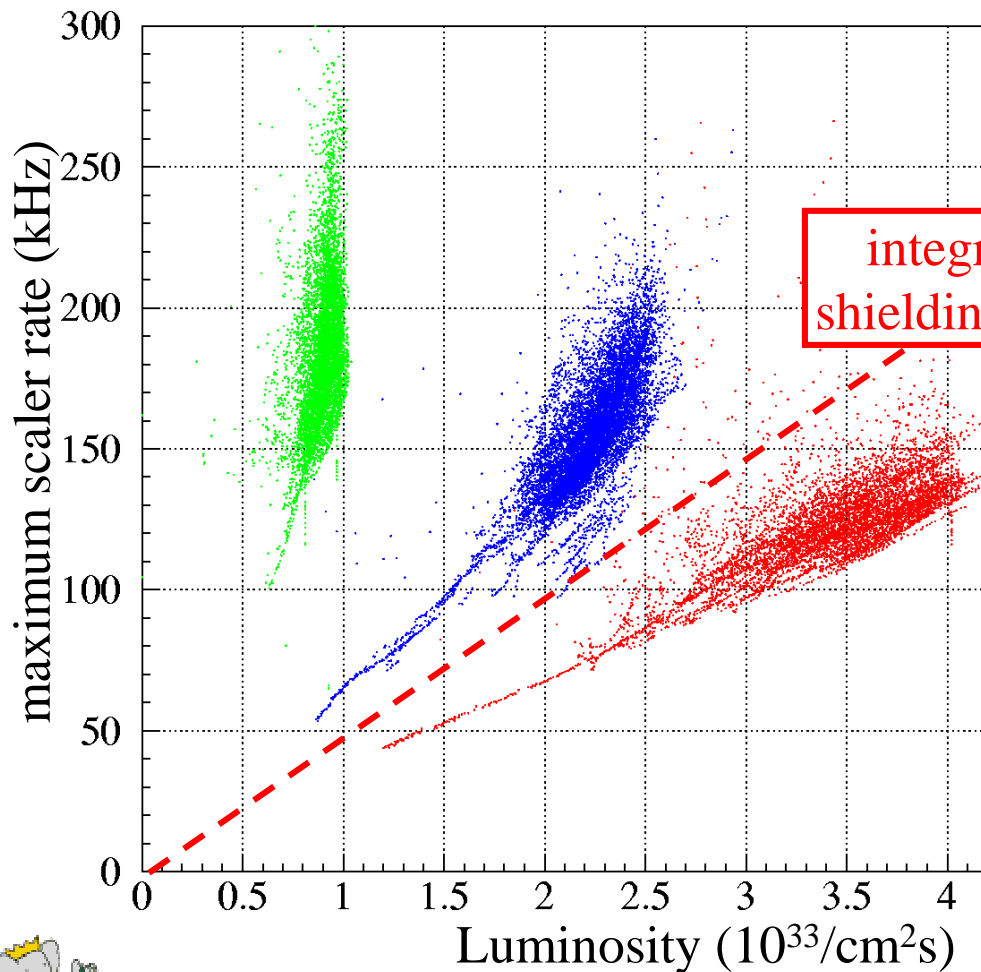
Rate vs. Luminosity showed that lead shielding essential in protecting DIRC from few MeV photon accelerator induced background (radiative Bhabhas etc).

More uniform, complete shielding and easier access to detector required.

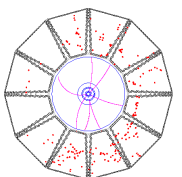


DIRC OPERATIONAL EXPERIENCE: BACKGROUNDS IV

In January 2001, installed new, more homogenous lead shielding (5-7cm of lead in upper 2/3, 2-3cm in lower 1/3 of shield).



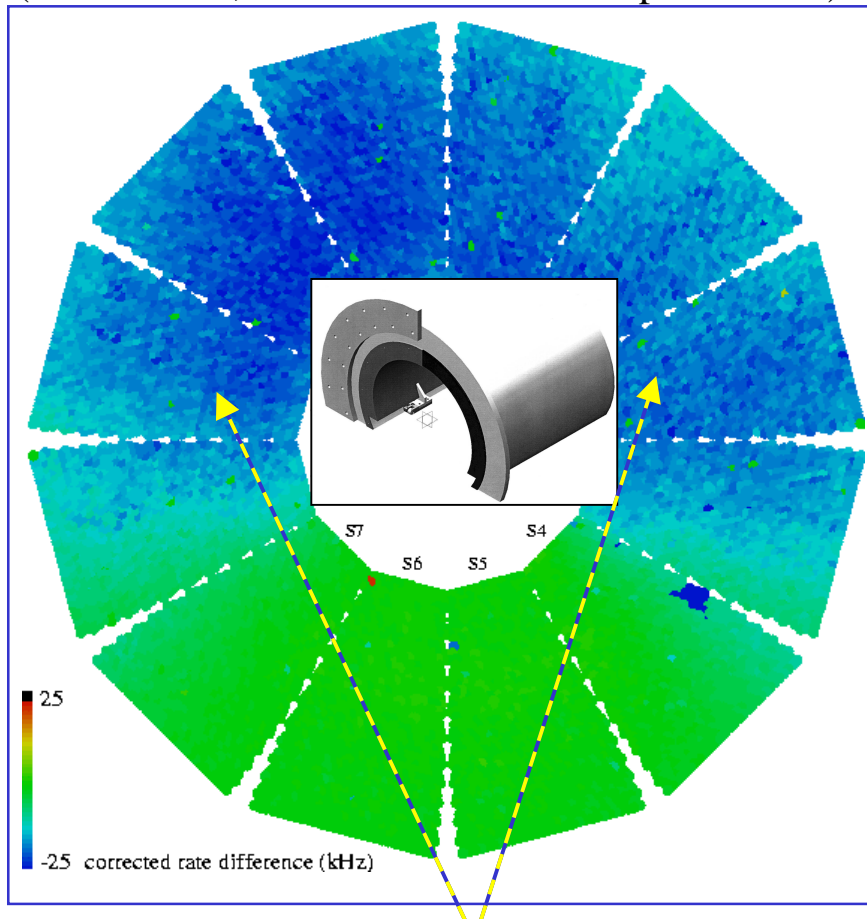
PMT rates acceptable even above design lumi.



DIRC OPERATIONAL EXPERIENCE: BACKGROUNDS V

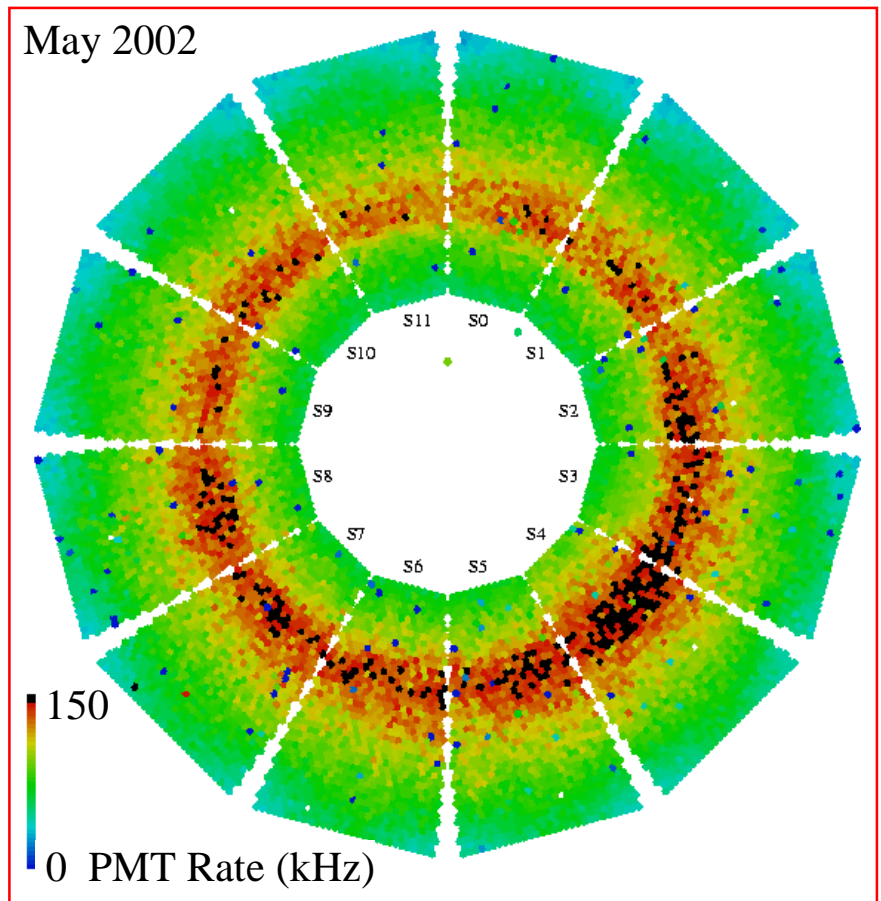
Effect of Shielding on Rate per PMT

Example: installation of integrated shielding
(after-before, corrected for machine parameters)

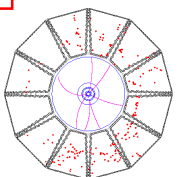


Rate per PMT 20-25kHz lower
in area targeted by shielding

PMT Rates in Typical Run



Rates vary between 50-150kHz.

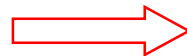


DIRC OPERATIONAL EXPERIENCE: BACKGROUNDS VI

Background model

Special runs with

- HER beam only,
- LER beam only,
- HER+LER w/o collision



Av. Rate per PMT (kHz) =

$$\begin{aligned} & \text{HER (A)} * 13 \text{ kHz} \\ & + \text{LER (A)} * 18 \text{ kHz} \\ & + \text{Lumi (10}^{33}\text{/s}\cdot\text{cm}^2) * 10 \text{ kHz} \end{aligned}$$

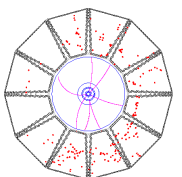
Typical (“Design”)

86	(78)
1.0	(0.75)
1.7	(2.14)
4.2	(3.0)

Current shielding configuration “background safe” through 2002.

New TDC chips (faster, deeper buffering) to be installed during shutdown Fall 2002:

<5% deadtime at 2.5MHz rate.

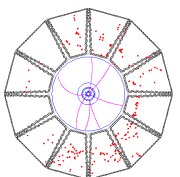
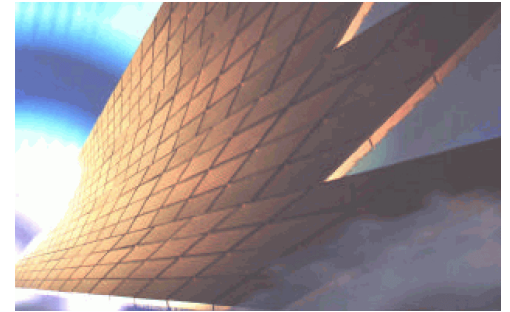


DIRC UPGRADE R&D

What about DIRC at 10^{34} and beyond? (timescale ~2004/5)

R&D program for DIRC upgrade has started:

- Large water tank is dominant source of background.
- Try to design more compact optics but keep radiator bars.
- Replace conventional PMT array with pixelated detectors, i.e.,
 - Hamamatsu “flat panel” 8*8 channel multi-anode PMTs, or
 - Hybrid Photodiodes (HPDs),
 - ... (see J. Va’vra talk)
- Improve θ_c resolution and time resolution
(at 200ps time information becomes competitive with spatial information in determining Cherenkov angle; decrease chromatic smearing)
- Cosmic telescope facility under construction at SLAC to test new optics and new photon detector using full scale DIRC barbox.



CONCLUSIONS

- The DIRC is a novel type of particle identification system, well matched to asymmetric B-factory environment, capable of π -K separation for momenta up to ~ 4 GeV/c.
- Three years of experience in PEP-II/BABAR B-factory mode: DIRC very reliable, robust, easy to operate, 99.2% of channels fully functional.
- Machine backgrounds up to 200 kHz/PMT at $4 \cdot 10^{33}/\text{cm}^2 \cdot \text{s}$ no problem for reconstruction; will install new TDC chips during Fall 2002 shutdown (for $10^{34}/\text{cm}^2 \cdot \text{s}$ luminosity).
- Front glass corrosion of PMTs in ultra-pure water observed, due to Sodium leaching. Bad batch of PMT glass in ~ 50 PMTs, breaking tests show no problems.
- Photon yield shows small loss at rate of 1-2%/year, no problem for PID performance.
- Single photon time and Cherenkov angle resolution and photon yield close to nominal, track Cherenkov angle resolution within 10% of design.
- DIRC plays significant role in almost all BABAR physics analyses published to date.
- R&D program under way to prepare DIRC for $10^{34}/\text{cm}^2 \cdot \text{s}$ and beyond.

