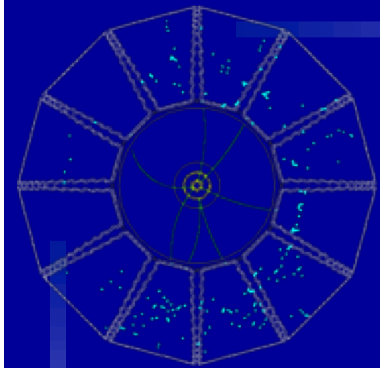


The BaBar DIRC

"Lessons Learned"

Outline:

- BABAR DIRC Fundamentals
- Detector R&D and Construction
  - Fused Silica
  - Ingots
  - Bars and Bar Boxes
- Operational Experience
- Detector Performance

Jochen Schwiening

BaBar DIRC Collaboration

I. Adam,[1] R. Aleksan,[2] L. Amerman,[3] E. Antokhin,[4] D. Aston,[1] P. Bailly,[5] C. Beigbeder,[6] M. Benkebil,[6] P. Besson,[2] G. Bonneaud,[7] Ph. Bourgeois,[2] D. Breton,[6] H. Briand,[5] F. Brochard,[7] D. N. Brown,[3] A. Buzykaev,[4] J. Chauveau,[5] R. Cizeron,[6] J. Cohen-Tanugi,[7] M. Convery,[1] S. Dardin,[3] P. David,[5] G. De Domenico,[2] C. de la Vaissiere,[5] A. de Lesquen,[2] F. Dohou,[7] M. Doser,[1] S. Emery,[2] S. Ferrag,[7] G. Fouque,[7] A. Gaidot,[2] S. Ganzhur,[4] F. Gastaldi,[7] T. Geld,[8] J.-F. Genat,[5] P.F. Giraud,[2] L. Gosset,[2] Ph. Grenier,[7] T. Haas,[1] T. Hadig,[1] D. Hale,[9] G. Hamel de Monchenault,[2] O. Hamon,[5] B. Hartfiel,[12] C. Hast,[6] A. Hoecker,[6] M. John,[5] R. W. Kadel,[3] J. Kadyk,[3] M. Karolak,[2] H. Kawahara,[1] M. Krishnamurthy,[10,11] H. Lacker,[6] H. Lebbolo,[5] F. Le Diberder,[5] M. Legendre,[2] Ph. Leruste,[5] J. Libby,[1] G. W. London,[2] M. Long,[3] J. Lory,[5] A. Lu,[9] A.-M. Lutz,[6] G. Lynch,[3] R. Malchow,[10] J. Malcles,[5] G. Mancinelli,[8] M. McCulloch,[1] D. McShurley,[1] F. Martinez-Vidal,[5] P. Matricon,[7] B. Mayer,[2] B. T. Meadows,[8] S. Mikhailov,[4] Ll. L. Mir,[3] D. Muller,[1] J.-M. Noppe,[6] J. Ocariz,[5] I. Ofte,[8] A. Onuchin,[4] D. Oshatz,[3] G. Oxoby,[1] T. Petersen,[6] M. Pivk,[5] S. Plaszczynski,[6] W. Pope,[3] M. Pripstein,[3] J. Rasson,[3] B. N. Ratcliff,[1] R. Reif,[1] C. Renard,[7] L. Roos,[5] E. Roussot,[7] A. Salnikov,[2] X. Sarazin,[1] S. Schrenk,[7] M.-H. Schune,[6] J. Schwiening,[1] S. Sen,[6] V. Shelkov,[3] M. D. Sokoloff,[8] S. Spanier,[1,11] H. Staengle,[10] J. Stark,[5] P. Stiles,[1] R. Stone,[3] J. D. Taylor,[3] A. V. Telnov,[3] G. Therin,[5] Ch. Thiebaux,[7] V. Tocut,[6] K. Truong,[6] M.-L. Turluer,[2] A. Vallereau,[5] G. Vasileiadis,[7] G. Vasseur,[2] J. Va'vra,[1] M. Verderi,[7] D. Warner,[10] T. B. Weber,[1] T. F. Weber,[3] W. A. Wenzel,[3] R. J. Wilson,[10,*] G. Wormser,[6] A. Yarritu,[1] Ch. Yéche,[2] S. Yellin,[9] Q. Zeng,[10] B. Zhang,[5] M. Zito[2]

(Author list from 2004 NIM paper)

[1]Stanford Linear Accelerator Center, Stanford, CA 94309, USA.
[2]DAPNIA, Commissariat à l'Energie Atomique/Saclay, F-91191 Gif-sur-Yvette, France.
[3]Lawrence Berkeley National Laboratory and University of California, Berkeley, CA 94720, USA.
[4]Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia.
[5]Universités Paris VI et VII, Lab de Physique Nucléaire H. E., F-75252 Paris, France.
[6]Laboratoire de l'Accélérateur Linéaire, F-91898 Orsay, France.
[7]Ecole Polytechnique, LLR, F-91128 Palaiseau, France.
[8]University of Cincinnati, Cincinnati, OH 45221, USA.
[9]University of California at Santa Barbara, Santa Barbara, CA 93106, USA.
[10]Colorado State University, Fort Collins, CO 80523, USA.
[11]University of Tennessee, Tennessee, TN 37996, USA.

R. Andreassen,[h] N. Arnaud,[d] D. Aston,[a] E. Ben-Haim,[c] J. Benitez,[a] D. Bernard,[e] D.N. Brown,[f] J. Chauveau,[c] C. Dallapiccola,[j] M. Escalier,[b] L. Esteve,[b] G. Grosdidier,[d] J. Kaminski,[a] A.-M. Lutz,[d] G. Mancinelli,[h] B.T. Meadows,[h] A. Perez,[c] B.N. Ratcliff,[a] E. Salvati,[j] J. Serrano,[d] J. Schwiening,[a] M.D. Sokoloff,[h] S. Spanier,[i] A. Stocchi,[d] K. Suzuki,[a] Ch. Thiebaux,[e] G. Vasseur,[b] J. Va'vra,[a] R.J. Wilson,[g] B. Wogsland,[i] G. Wormser,[d] M. Zito[b]

(Current author list)

[a] Stanford Linear Accelerator Center
[b] DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette
[c] LPNHE, IN2P3/CNRS, Universités Paris 6 et Paris 7
[d] LAL, IN2P3/CNRS et Universite Paris-Sud 11
[e] Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Palaiseau
[f] Lawrence Berkeley National Laboratory
[g] Colorado State University
[h] University of Cincinnati
[i] University of Tennessee
[j] University of Massachusetts, Amherst

BABAR DIRC NIM PAPER

2004 NIM paper describes
design, construction, performance of the DIRC:

The DIRC Particle Identification System for the BABAR Experiment.

SLAC-PUB-10516 (Jun 2004), 83pp, Nucl. Instr. Methods **A** 538 (2005) 281-357.

1

The DIRC Particle Identification System for the *BaBar* Experiment

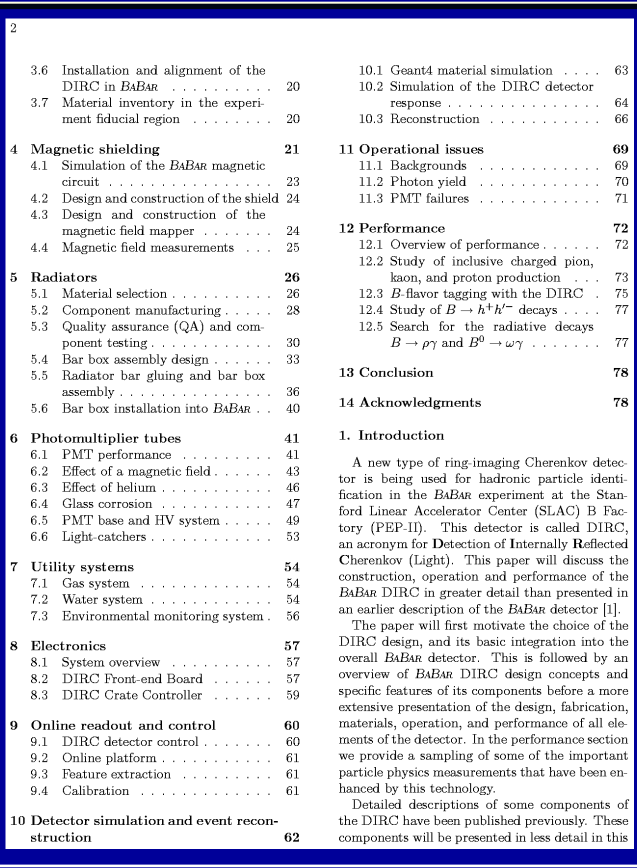
I. Adam,[1] R. Aleksan,[2] L. Amerman,[3] E. Antokhin,[4] D. Aston,[1] P. Bailly,[5] C. Beigbeder,[6] M. Benkebil,[6] P. Besson,[2] G. Bonneaud,[7] Ph. Bourgeois,[2] D. Breton,[6] H. Briand,[5] F. Brochard,[7] D. N. Brown,[3] A. Buzykaev,[4] J. Chauveau,[5] R. Cizeron,[6] J. Cohen-Tanugi,[7] M. Convery,[1] S. Dardin,[3] P. David,[5] G. De Domenico,[2] C. de la Vaissiere,[5] A. de Lesquen,[2] F. Dohou,[7] M. Doser,[1] S. Emery,[2] S. Ferrag,[7] G. Fouque,[7] A. Gaidot,[2] S. Ganzhur,[4] F. Gastaldi,[7] T. Geld,[8] J.-F. Genat,[5] P.F. Giraud,[2] L. Gosset,[2] Ph. Grenier,[7] T. Haas,[1] T. Hadig,[1] D. Hale,[9] G. Hamel de Monchenault,[2] O. Hamon,[5] B. Hartfiel,[12] C. Hast,[6] A. Hoecker,[6] M. John,[5] R. W. Kadel,[3] J. Kadyk,[3] M. Karolak,[2] H. Kawahara,[1] M. Krishnamurthy,[10,11] H. Lacker,[6] H. Lebbolo,[5] F. Le Diberder,[5] M. Legendre,[2] Ph. Leruste,[5] J. Libby,[1] G. W. London,[2] M. Long,[3] J. Lory,[5] A. Lu,[9] A.-M. Lutz,[6] G. Lynch,[3] R. Malchow,[10] J. Malcles,[5] G. Mancinelli,[8] M. McCulloch,[1] D. McShurley,[1] F. Martinez-Vidal,[5] P. Matricon,[7] B. Mayer,[2] B. T. Meadows,[8] S. Mikhailov,[4] Ll. L. Mir,[3] D. Muller,[1] J.-M. Noppe,[6] J. Ocariz,[5] I. Ofte,[8] A. Onuchin,[4] D. Oshatz,[3] G. Oxoby,[1] T. Petersen,[6] M. Pivk,[5] S. Plaszczynski,[6] W. Pope,[3] M. Pripstein,[3] J. Rasson,[3] B. N. Ratcliff,[1] R. Reif,[1] C. Renard,[7] L. Roos,[5] E. Roussot,[7] A. Salnikov,[2] X. Sarazin,[1] S. Schrenk,[7] M.-H. Schune,[6] J. Schwiening,[1] S. Sen,[6] V. Shelkov,[3] M. D. Sokoloff,[8] S. Spanier,[1,11] H. Staengle,[10] J. Stark,[5] P. Stiles,[1] R. Stone,[3] J. D. Taylor,[3] A. V. Telnov,[3] G. Therin,[5] Ch. Thiebaux,[7] V. Tocut,[6] K. Truong,[6] M.-L. Turluer,[2] A. Vallereau,[5] G. Vasileiadis,[7] G. Vasseur,[2] J. Va'vra,[1] M. Verderi,[7] D. Warner,[10] T. B. Weber,[1] T. F. Weber,[3] W. A. Wenzel,[3] R. J. Wilson,[10,*] G. Wormser,[6] A. Yarritu,[1] Ch. Yéche,[2] S. Yellin,[9] Q. Zeng,[10] B. Zhang,[5] M. Zito[2]

[1]Stanford Linear Accelerator Center, Stanford, CA 94309, USA.
[2]DAPNIA, Commissariat à l'Energie Atomique/Saclay, F-91191 Gif-sur-Yvette, France.
[3]Lawrence Berkeley National Laboratory and University of California, Berkeley, CA 94720, USA.
[4]Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia.
[5]Universités Paris VI et VII, Lab de Physique Nucléaire H. E., F-75252 Paris, France.
[6]Laboratoire de l'Accélérateur Linéaire, F-91898 Orsay, France.
[7]Ecole Polytechnique, LLR, F-91128 Palaiseau, France.
[8]University of Cincinnati, Cincinnati, OH 45221, USA.
[9]University of California at Santa Barbara, Santa Barbara, CA 93106, USA.
[10]Colorado State University, Fort Collins, CO 80523, USA.
[11]University of Tennessee, Tennessee, TN 37996, USA.

A new type of ring-imaging Cherenkov detector is being used for hadronic particle identification in the *BaBar* experiment at the SLAC B Factory (PEP-II). This detector is called DIRC, an acronym for **D**etection of **I**nternally **R**eflected **C**herenkov (Light). This paper will discuss the construction, operation and performance of the *BaBar* DIRC in detail.

Contents

*Corresponding author.
Email address: wilson@lamar.colostate.edu (R. J. Wilson).



2

1. Introduction

A new type of ring-imaging Cherenkov detector is being used for hadronic particle identification in the *BaBar* experiment at the Stanford Linear Accelerator Center (SLAC) B Factory (PEP-II). This detector is called DIRC, an acronym for **D**etection of **I**nternally **R**eflected **C**herenkov (Light). This paper will discuss the construction, operation and performance of the *BaBar* DIRC in greater detail than presented in an earlier description of the *BaBar* detector [1].

The paper will first motivate the choice of the DIRC design, and its basic integration into the overall *BaBar* detector. This is followed by an overview of *BaBar* DIRC design concepts and specific features of its components before a more extensive presentation of the design, fabrication, materials, operation, and performance of all elements of the detector. In the performance section we provide a sampling of some of the important particle physics measurements that have been enhanced by this technology.

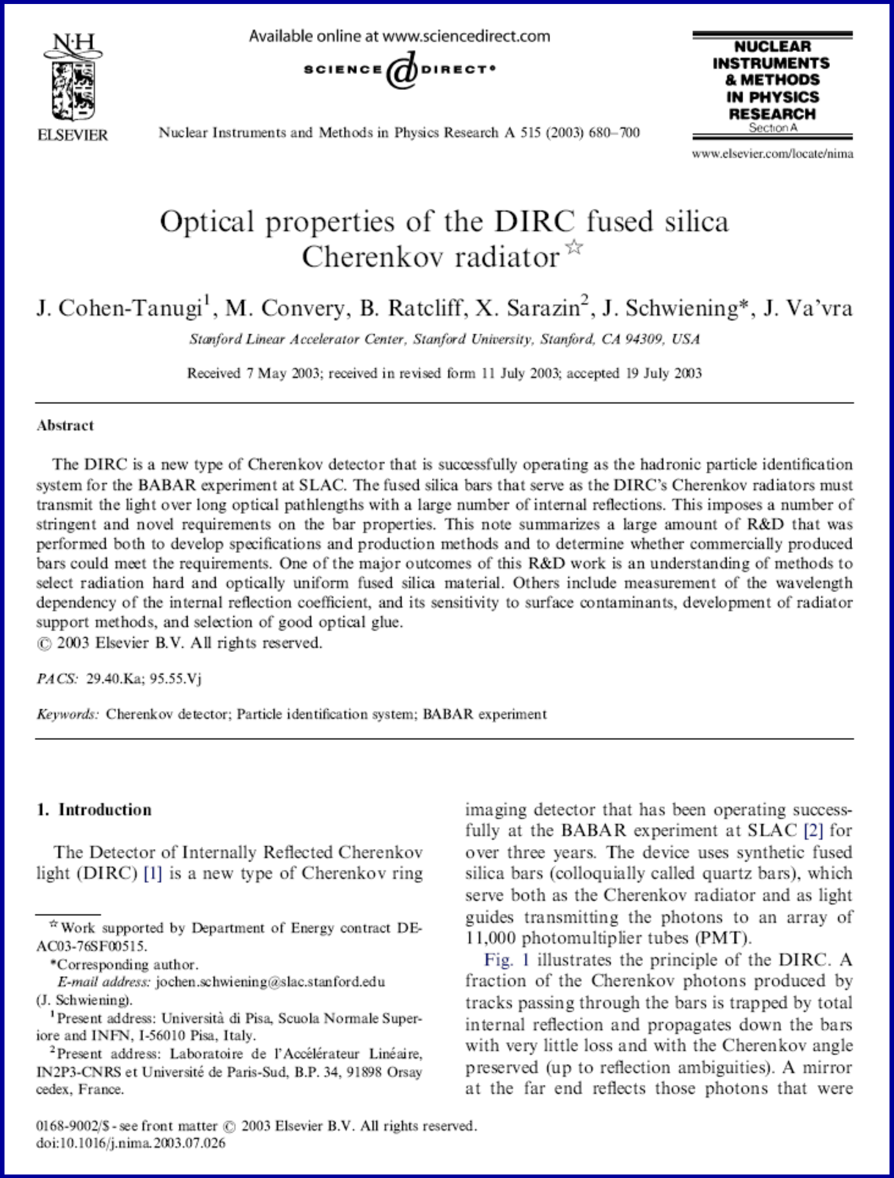
Detailed descriptions of some components of the DIRC have been published previously. These components will be presented in less detail in this

BaBar DIRC NIM Paper

2003 NIM paper with
even more detail on
fused silica R&D
and radiator bar R&D
and Quality Assurance:

SLAC-PUB-9735 (Apr 2003),
Nucl. Instr. Methods **A** 515 (2003) 680-700.

(Plus, about a dozen BABAR-DIRC notes
with all the Nitty Gritty Details.)



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Nuclear Instruments and Methods in Physics Research A 515 (2003) 680–700

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Optical properties of the DIRC fused silica Cherenkov radiator☆

J. Cohen-Tanugi[1], M. Convery, B. Ratcliff, X. Sarazin[2], J. Schwiening*, J. Va'vra

Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309, USA

Received 7 May 2003; received in revised form 11 July 2003; accepted 19 July 2003

Abstract

The DIRC is a new type of Cherenkov detector that is successfully operating as the hadronic particle identification system for the BABAR experiment at SLAC. The fused silica bars that serve as the DIRC's Cherenkov radiators must transmit the light over long optical pathlengths with a large number of internal reflections. This imposes a number of stringent and novel requirements on the bar properties. This note summarizes a large amount of R&D that was performed both to develop specifications and production methods and to determine whether commercially produced bars could meet the requirements. One of the major outcomes of this R&D work is an understanding of methods to select radiation hard and optically uniform fused silica material. Others include measurement of the wavelength dependency of the internal reflection coefficient, and its sensitivity to surface contaminants, development of radiator support methods, and selection of good optical glue.

PACS: 29.40.Ka; 95.55.Vj

Keywords: Cherenkov detector; Particle identification system; BABAR experiment

1. Introduction

The Detector of Internally Reflected Cherenkov light (DIRC) [1] is a new type of Cherenkov ring imaging detector that has been operating successfully at the BABAR experiment at SLAC [2] for over three years. The device uses synthetic fused silica bars (colloquially called quartz bars), which serve both as the Cherenkov radiator and as light guides transmitting the photons to an array of 11,000 photomultiplier tubes (PMT).

Fig. 1 illustrates the principle of the DIRC. A fraction of the Cherenkov photons produced by tracks passing through the bars is trapped by total internal reflection and propagates down the bars with very little loss and with the Cherenkov angle preserved (up to reflection ambiguities). A mirror at the far end reflects those photons that were

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*Corresponding author.
E-mail address: jochen.schwiening@slac.stanford.edu (J. Schwiening).
[1]Present address: Università di Pisa, Scuola Normale Superiore and INFN, I-56010 Pisa, Italy.
[2]Present address: Laboratoire de l'Accélérateur Linéaire, IN2P3-CNRS et Université de Paris-Sud, B.P. 34, 91898 Orsay cedex, France.

0168-9002/$ - see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2003.07.026

DIRC PRINCIPLE

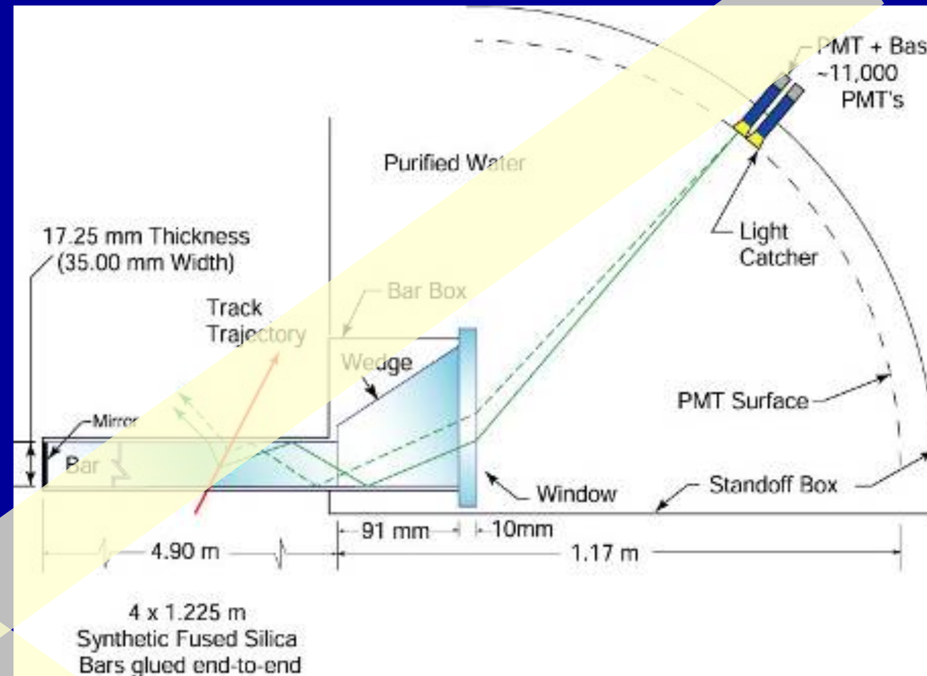
No need for the usual DIRC slides…

You know this stuff already…

- 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)

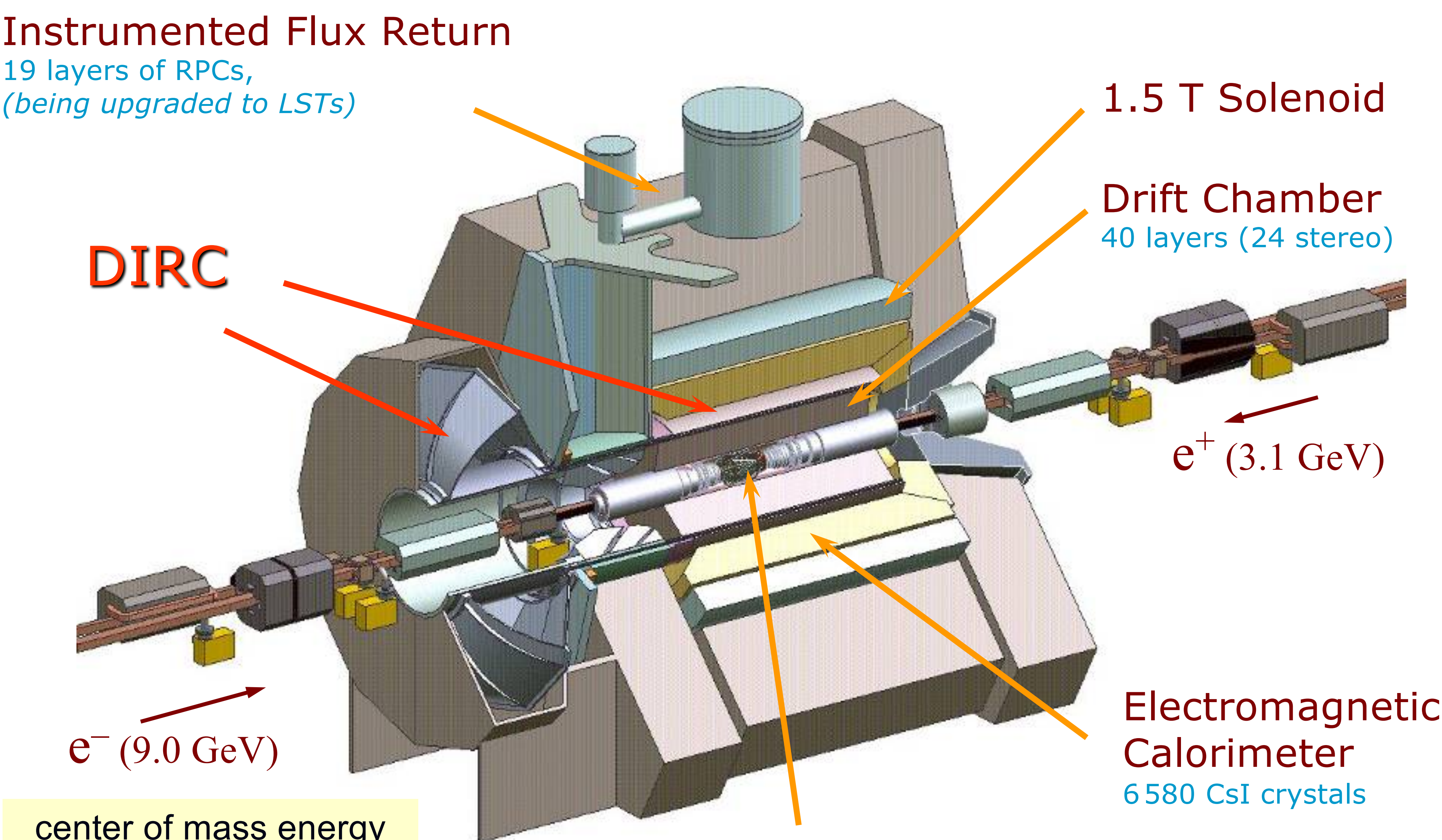


- Photons exit via wedge into expansion region (filled with 6m³ pure, de-ionized water).

- 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 ~1.5nsec, ~30mm diameter)

- DIRC is a 3-D device, measuring: x, y and time of Cherenkov photons, defining θ_c, ϕ_c, $t_{propagation}$ of photon.

THE BABAR DETECTOR



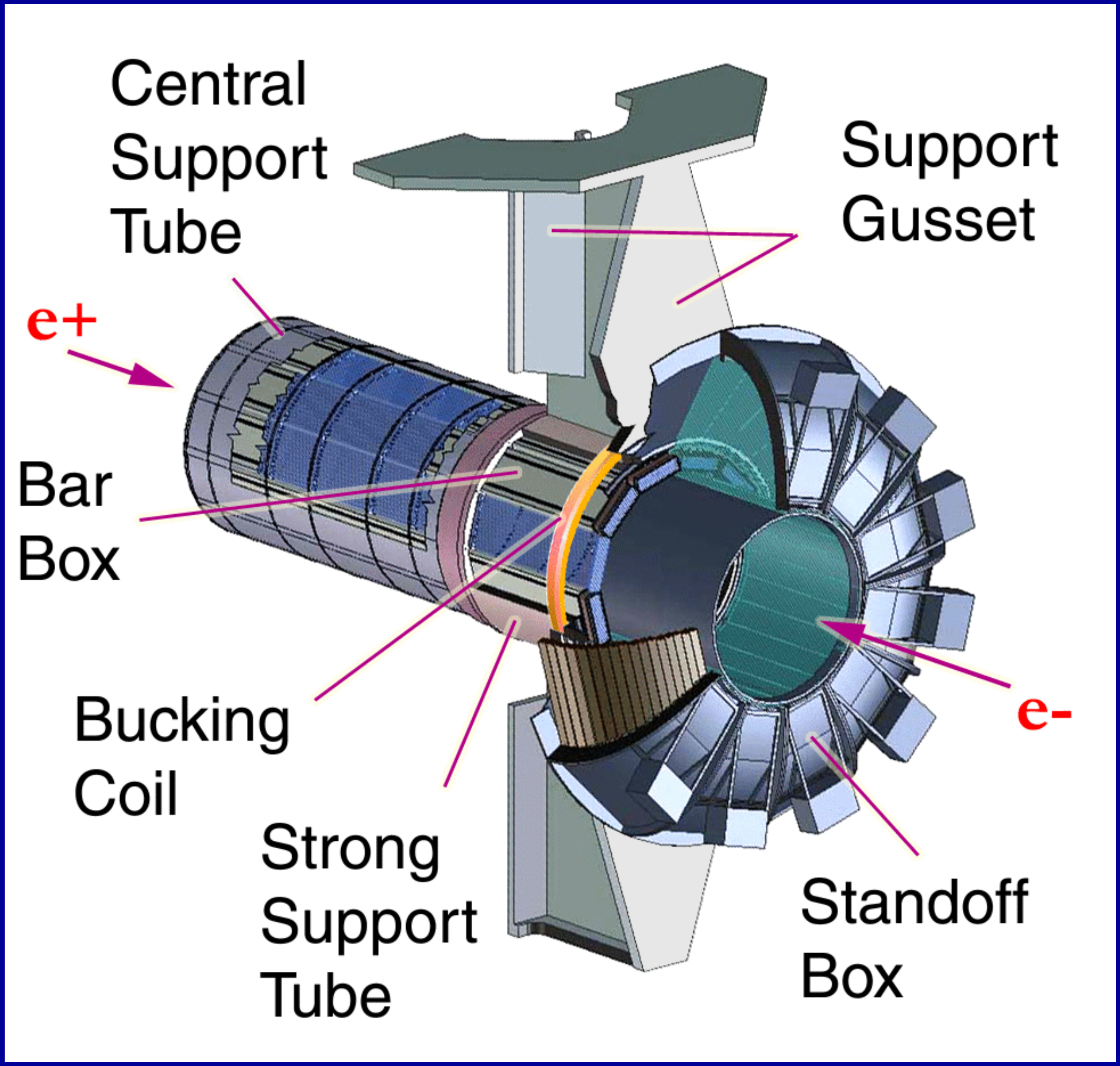
center of mass energy
$\approx M_{\Upsilon(4S)} = 10.58\ \mathrm{GeV}/c^2$
$\beta\gamma = 0.56$

THE DIRC IN BABAR

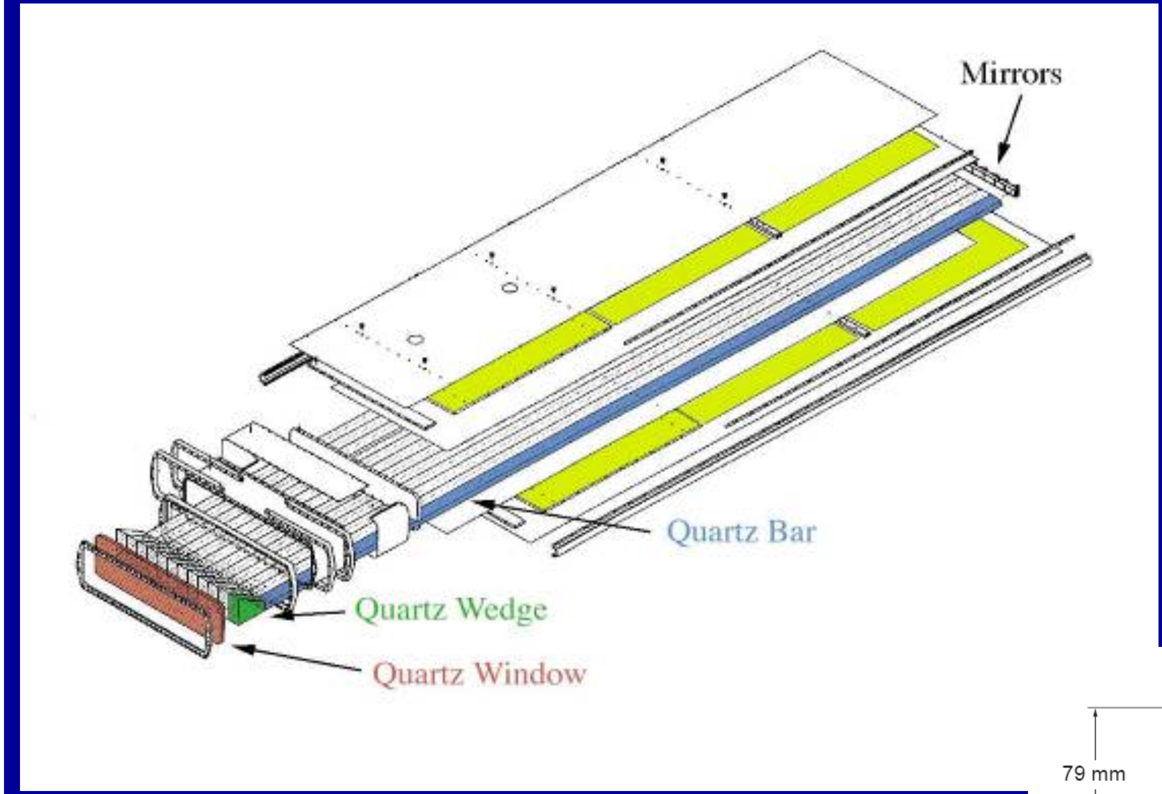
DIRC thickness:
- 8 cm radial incl. supports
- 19% radiation length at normal incidence

DIRC radiators cover:
- 94% azimuth,
- 83% c.m. polar angle

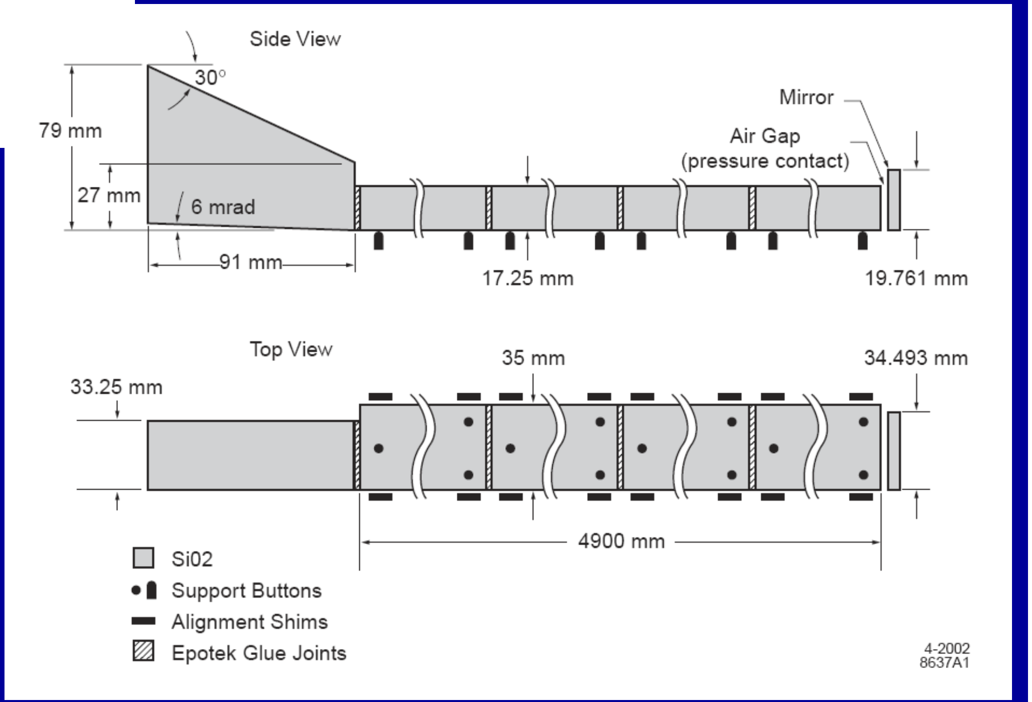
DIRC photon detection array:
- 10,752 PMTs ETL 9125



THE DIRC IN BABAR



Bar box: 12 bar boxes in BABAR
12 long (4.9m) bars per box
150µm air gap between bars
dry nitrogen flow



Long bar: 4 short (1.225m) bars
Mirror on forward end
Wedge on readout end

DIRC TIME LINE

BABAR-DIRC Timeline:

- 1992: first publication of DIRC concept (Blair Ratcliff);
- 1993 – 1994: conceptual DIRC prototype in cosmic ray setup at SLAC;
- Nov 1994: decision in favor of DIRC for hadronic PID for BABAR;
- 1995 – 1996: large scale DIRC prototype in particle beam at CERN;
- 1997: synthetic fused silica selected as material for DIRC bars;
- 1997 – 1999: bar fabrication at Boeing, Albuquerque, NM;
- Nov 1998: installed SOB and one prototype bar box; PMTs immersed in water; start of cosmic ray run, commissioning run
- Jan 1999 – Sep 1999: bar box assembly at SLAC;
- April 1999: BABAR moves into beam line, added 4 more bar boxes;
- Nov 1999: all 12 bar boxes installed, start of first physics run.
- April 2008: last event recorded with BABAR.

PEP-II peak luminosity: 12.07×10^{33} cm^{-2}sec^{-1} (4 × design)

BABAR total recorded: ~ 467M $B\bar{B}$ pairs.

DIRC PROTOTYPE 1

1993 – 1994: conceptual DIRC prototype in cosmic ray setup at SLAC;

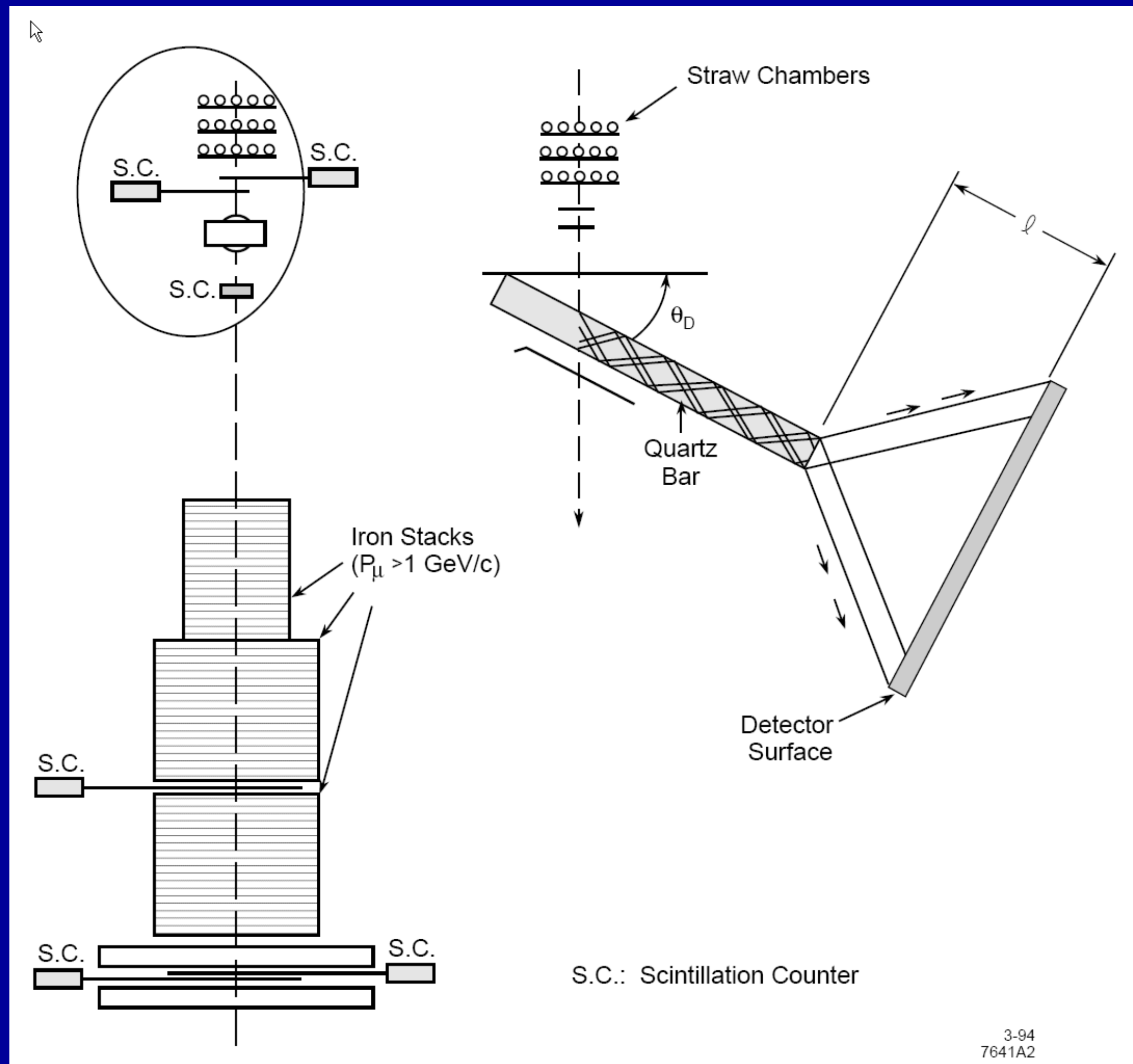
Single 1.2m long bar or
one 2.4m long bar made by
gluing two 1.2m long bars

Bars made from natural fused silica
(Vitreosil-F) built by Zygo Corp.

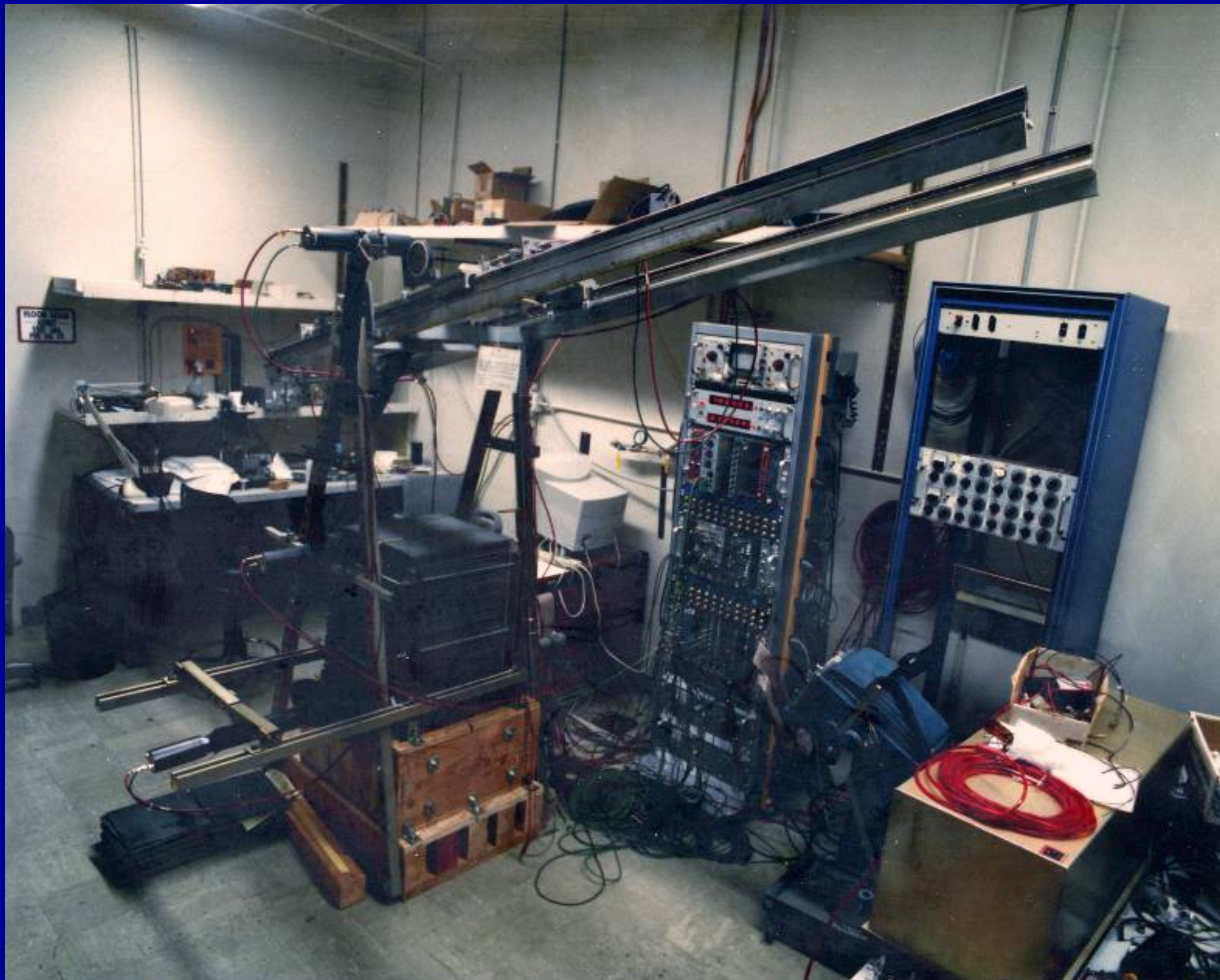
Iron stack to select high-mom muons

Scintillation counters and straw chambers
for trigger and tracking

Limited photon detector coverage



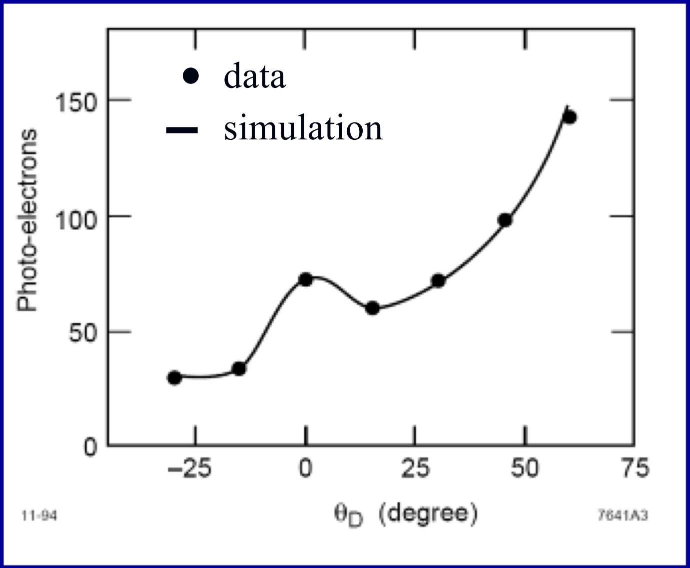
DIRC PROTOTYPE 1



DIRC PROTOTYPE 1

Provided proof-of-principle

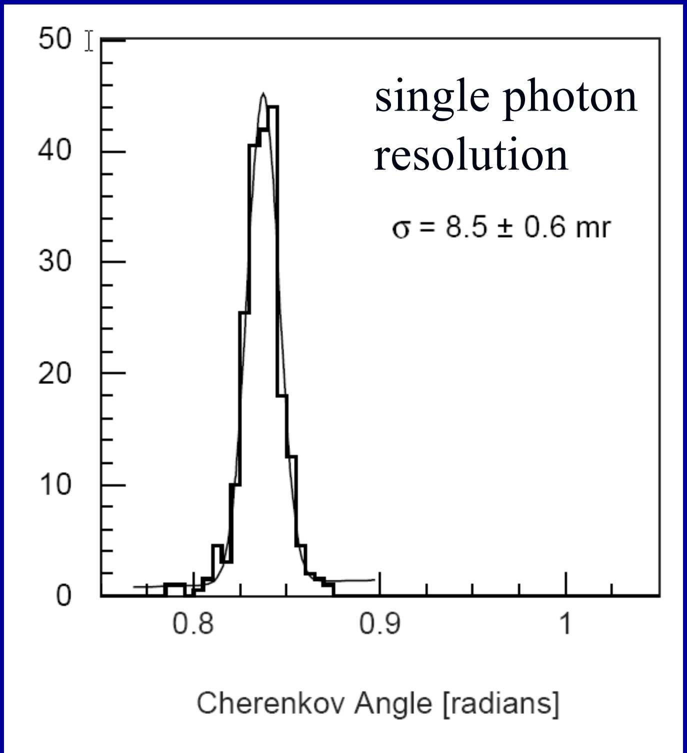
Photo-electron yield vs. polar angle
- agrees well with simulation, good match
- to event topology at asymmetric B Factory
- photon attenuation in bar ~10%/m



Cherenkov angle resolution
- agrees with expectation

No problems with glue boundary

No issues with structures in bulk material



Main features well understood, adequate for full-scale device with 5m long bars

→ IEEE Trans.Nucl.Sci.42:534-538,1995

DIRC PROTOTYPE 2

June 1995 – June 1996: large scale DIRC prototype in particle beam at CERN

Two bars, 1.2m long, side by side or
one 2.4m long bar made by
gluing two 1.2m long bars end to end

Bars made from natural fused silica
(Vitreosil-F) built by Zygo Corp.

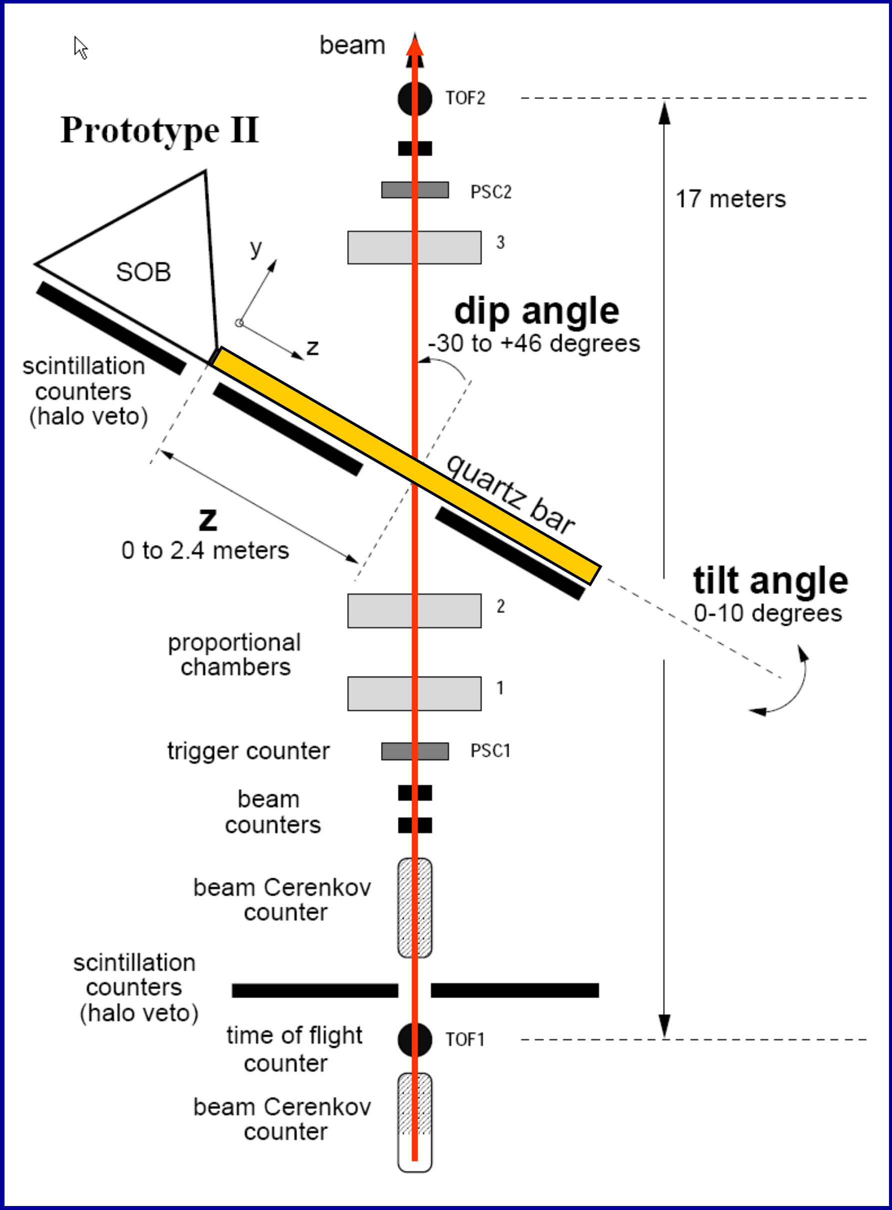
Water-filled standoff box

Fully instrumented beamline for trigger,
tracking, PID

Limited photon detector coverage

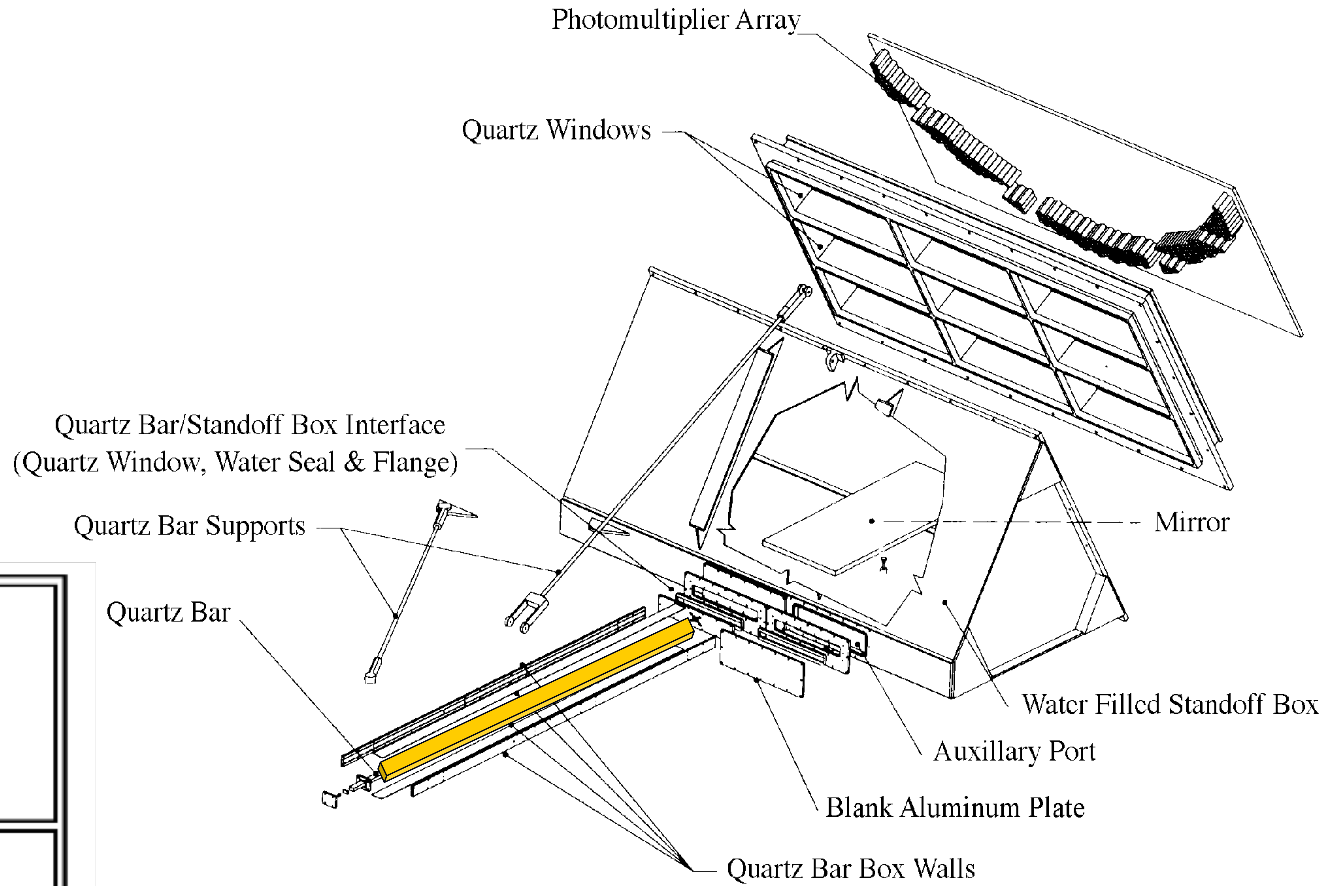
Refined earlier measurements, confirmed
stable and robust operation

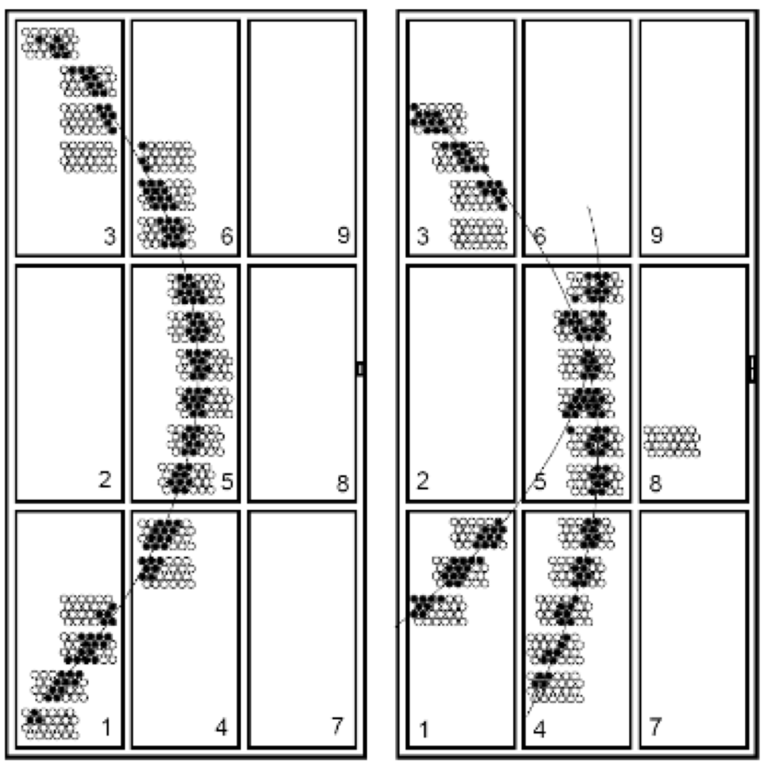
No surprises.



DIRC PROTOTYPE 2

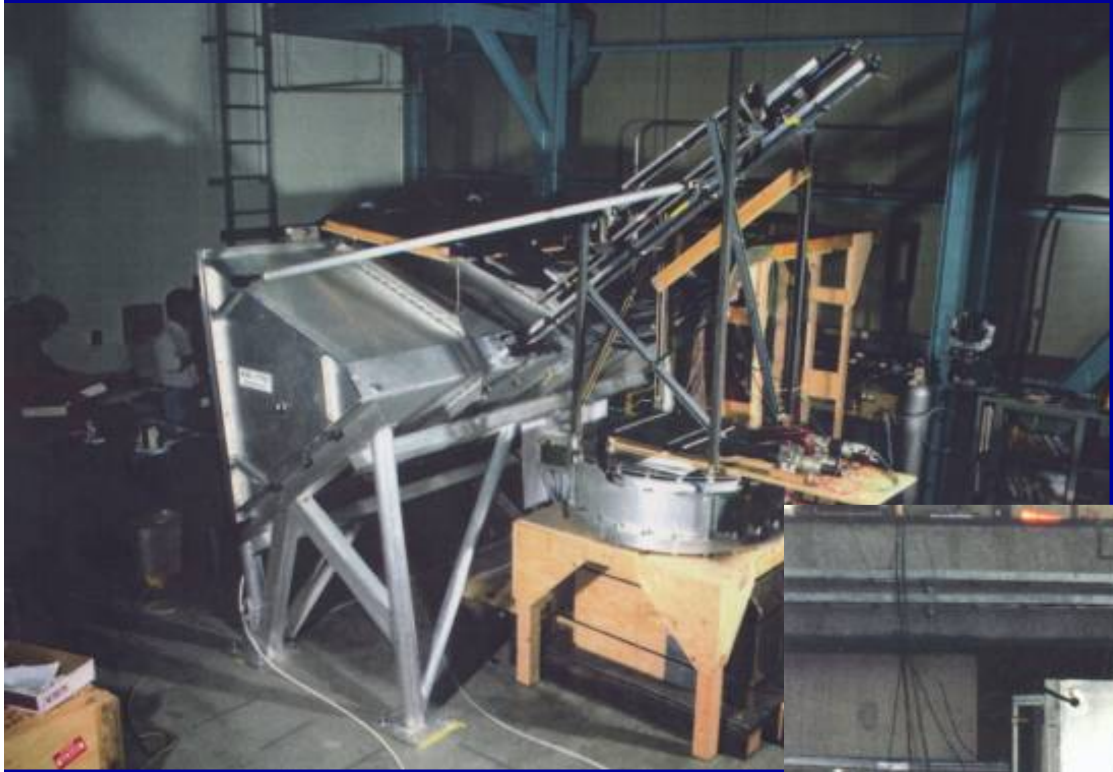
Bar box and standoff box





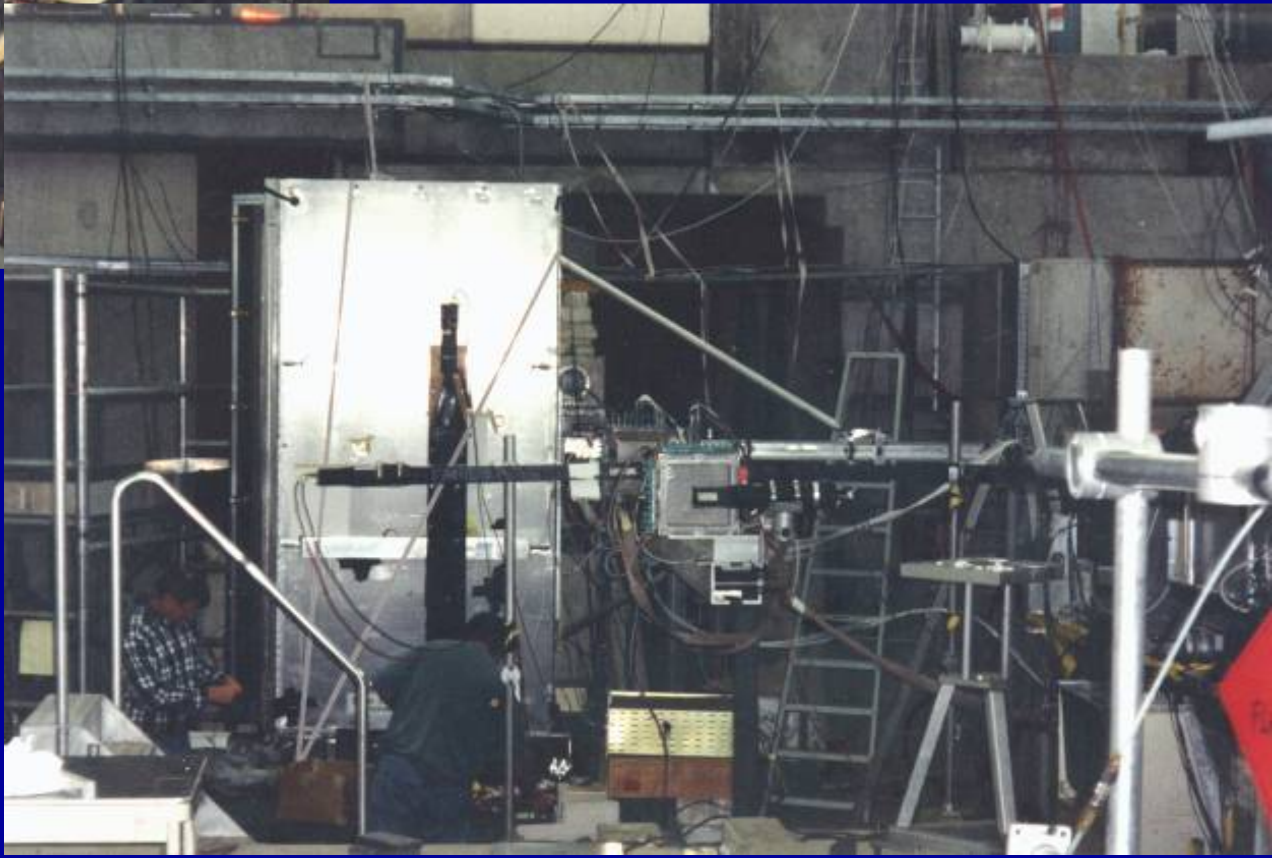
PMT configurations

DIRC PROTOTYPE 2

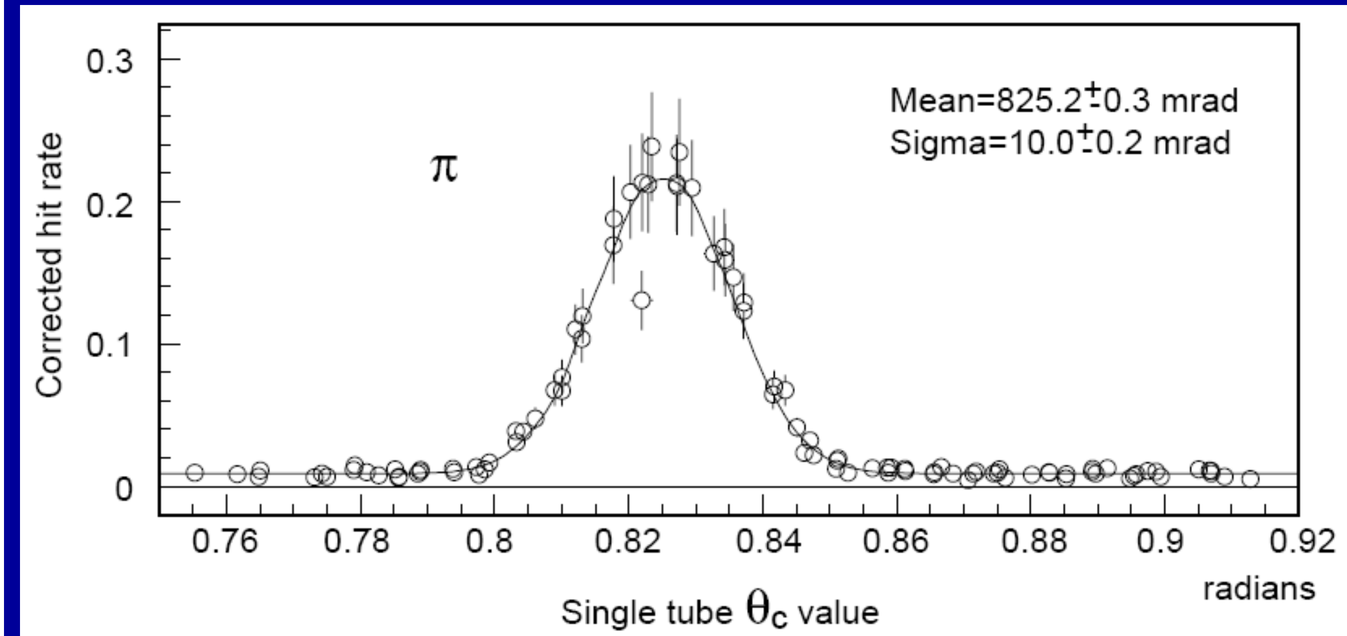


In cosmic ray setup at LBNL.

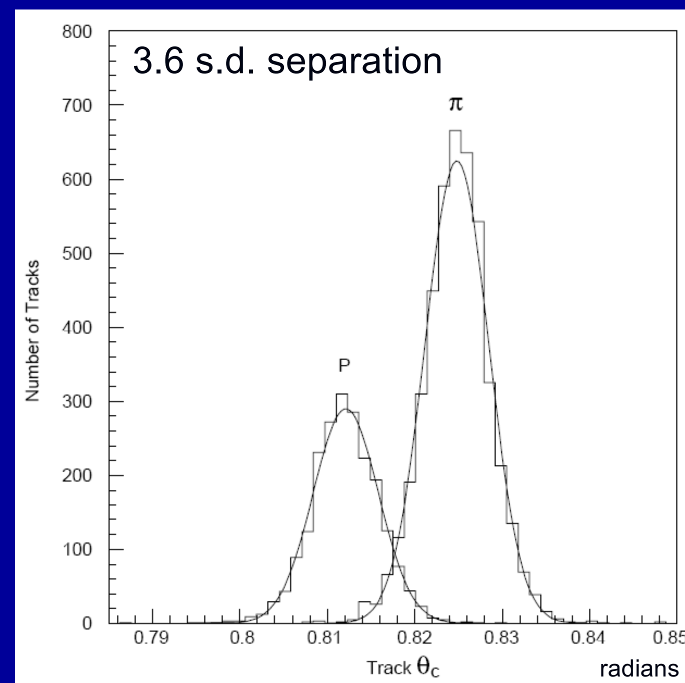
In test beam at CERN.



DIRC PROTOTYPE 2



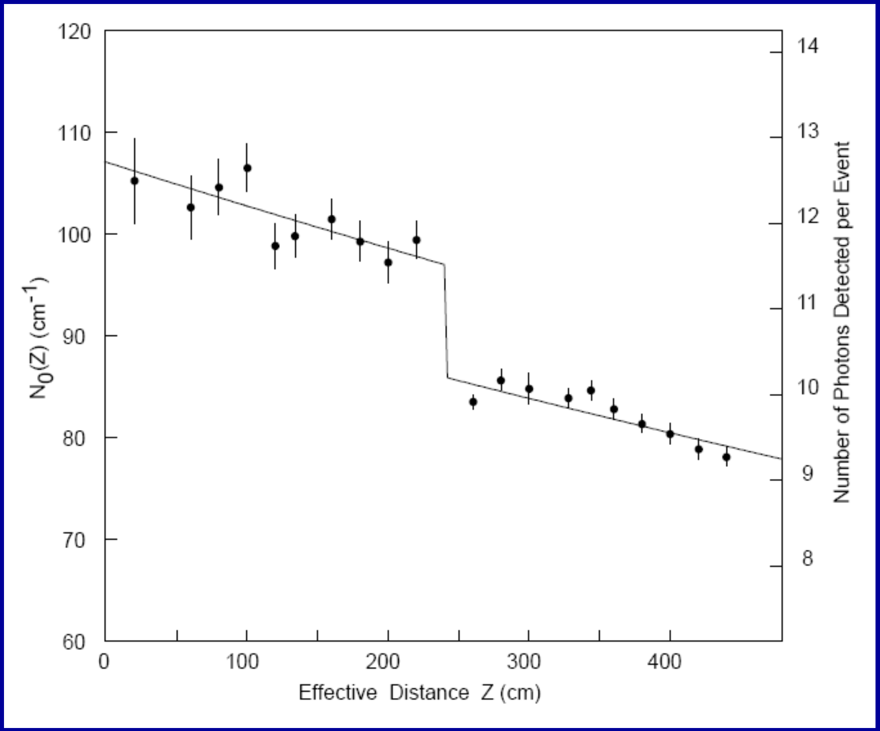
Single photon resolution and track resolution consistent with design expectation, simulation, and earlier prototype



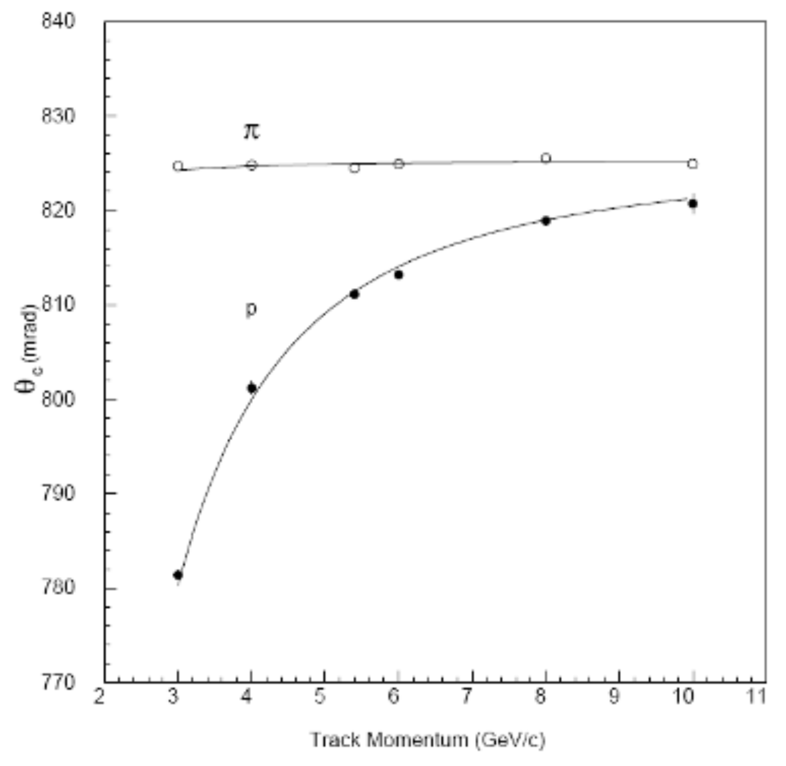
DIRC PROTOTYPE 2

Photon yield consistent with expectation.

Attenuation after bar cleaning 4.1±0.7%/m
much better than in prototype 1



Effective index of refraction 1.474±0.001 (stat)



Final system expected to yield excellent π/K separation (nearly four standard deviations or better) over entire acceptance region for all of the products from B decay.

→ Nuclear Instruments and Methods A 397 (1997) 261

Fused Silica R&D

During early stage of DIRC R&D tested natural and synthetic fused silica as well as plexiglass as bar candidate materials.

Fused silica bars had much better optical properties, polishability, and sharper corners.

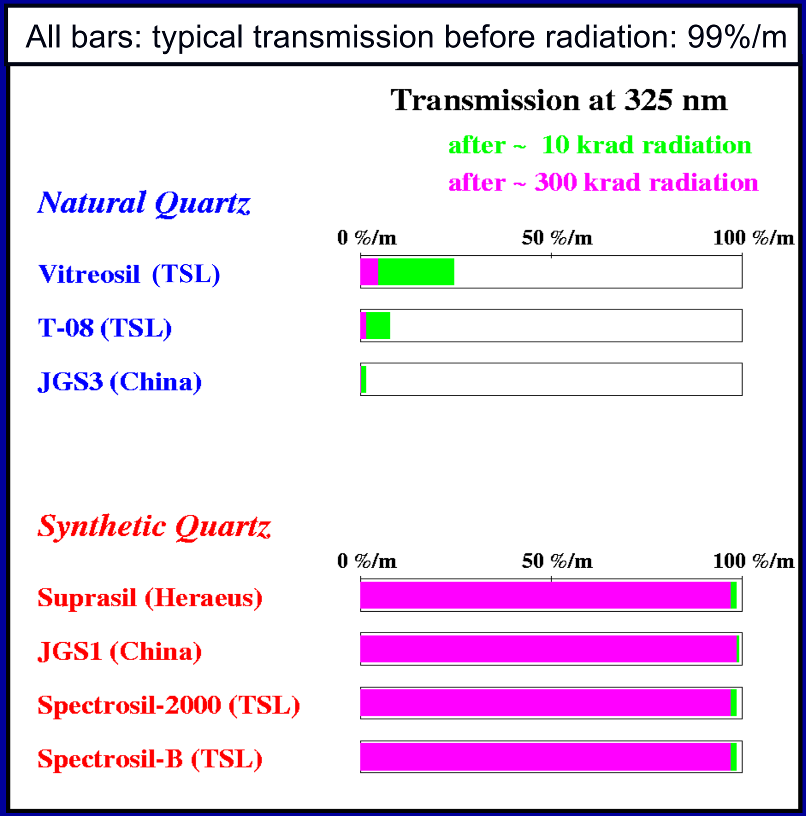
Selected natural fused silica (Vitreosil-F, TSL) for prototype; bars produced by Zygo Corp.

Very good results in two prototypes.

1995/1996 series of tests of radiation hardness

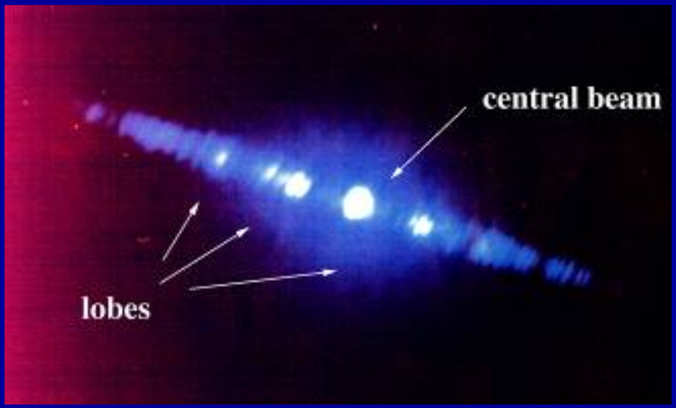
→ Vitreosil shows serious radiation damage (Co^{60} source) at levels expected in BABAR

All synthetic fused silica materials rad hard.



FUSED SILICA R&D

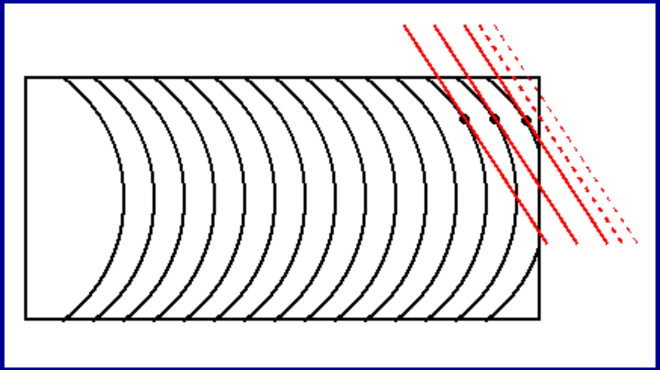
While studying internally reflected laser beams in polished bars made from synthetic fused silica candidate materials noticed "lobes", diffraction-like pattern.



Affected both primary candidate materials, Heraeus Suprasil and TSL Spectrosil.

Thought to be product of periodic optical inhomogeneity created during ingot production.

Show up only when laser beam tangent to layers.



Lobe power factor 100 stronger in Suprasil.

In Spectrosil lobes only appear at very steep angles (not relevant DIRC application).

→ selected TSL Spectrosil 2000 (few ingots Spectrosil B)

Synthetic Fused Silica Ingot

Spectrosil 2000 & Spectrosil B

produced in UK at TSL

20cm diameter, 127cm length, 90kg weight

Shipped to SLAC

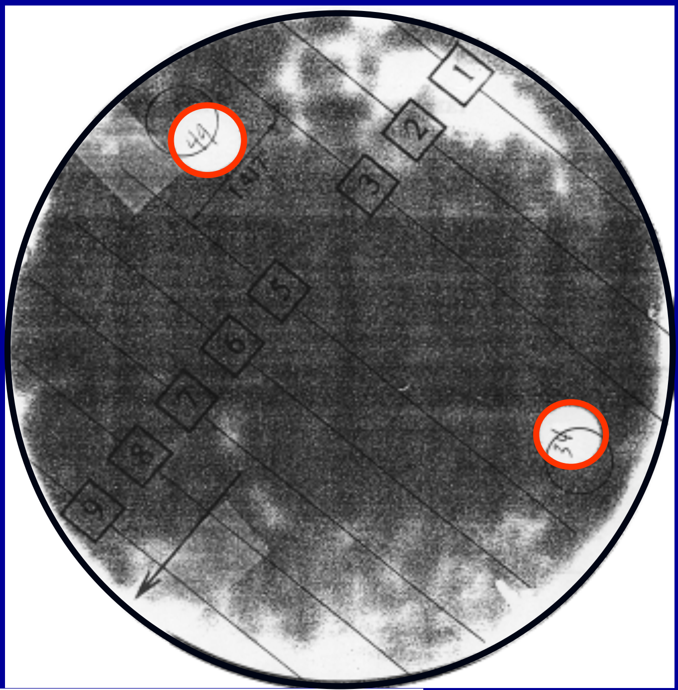
QA at SLAC

use laser to test for layers/lobes

found typically 1-2 large (5-15mm) bubbles

map bubbles, produce template for cutting

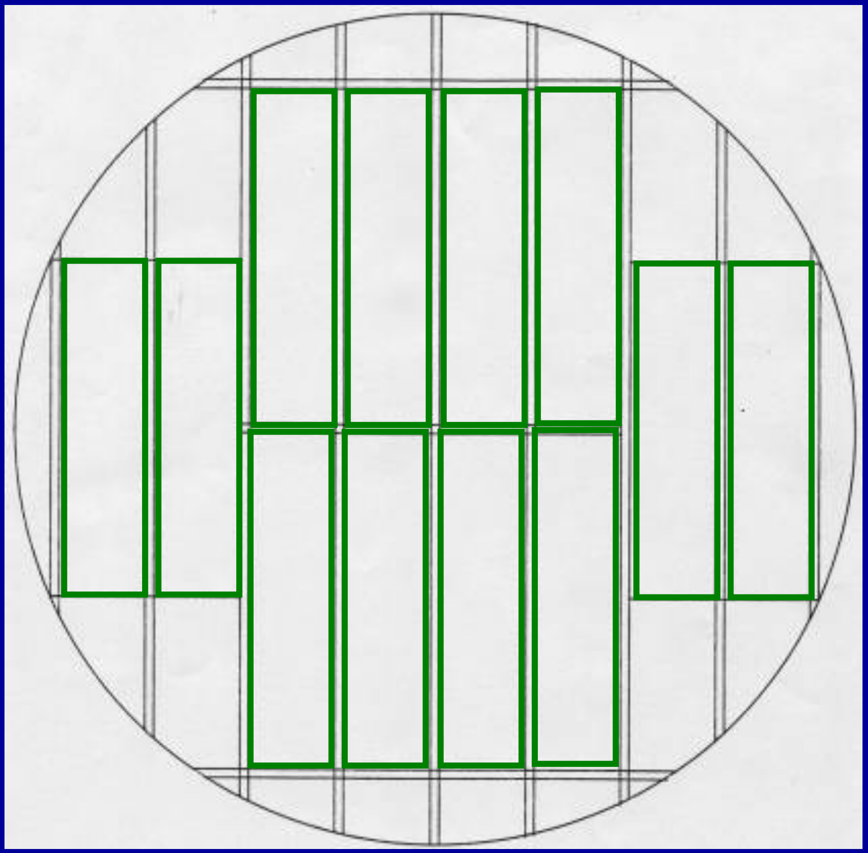
(optimize yield)



SYNTHETIC FUSED SILICA INGOT

Take ingot to Ideal Quartz Machining, Manteca

- cut ingot into two-bar planks (band saw, chop saw)
  - (1.95cm×7.8cm×124cm)
  - up to 12 planks per ingot
  - typical yield: 10 planks per ingot
- keep residual pieces and parts with bubbles
  - for windows and wedges



Ship two-bar planks to Boeing, New Mexico
- for bar fabrication

BAR FABRICATION

Zygo Corp had produced the high-quality DIRC prototype bars (0.3nm rms polish)

- was not able to fill full 600+ bar order for BABAR

Obtained bids from all available facilities with large (13-14 ft) planetary polisher

Rockwell/Boeing won bid based on price and proposed methodology

- Custom optics fabrication plant located in Albuquerque, NM.
- Initially part of Rockwell International, purchased by Boeing in 1997, today InSync, Inc.
- Sale of plant from Rockwell to Boeing caused upheaval and delays early on.

14 Foot (4.3 Meter) Diameter Polishing Machine

BAR FABRICATION

Challenge: large bars, mechanical tolerances on flatness, squareness and parallelism with optical finish and sharp corners – not something these plants are used to

Steep learning curve from initial model for bar fabrication towards successful production of over 660 bars during pre-production and production – slow startup.

Fabrication methodology modified many times in response to production issues

- Initial process: start with ends, use glass plates with UV setting glue to protect ends.
  - End plates fell off, caused chips and scratches, UV glue was difficult to remove.
- Friction on lappers "rolled" the bars, causing "barrel-like" rounding of bar sides

Multiple delays caused by production issues

- massive chipping during final lapping stage – chips embedded in soft iron of lapper
  - table had to be reconditioned: several months down time
- pitch polishing – art vs. science: sometimes set of bars polished in days, sometimes weeks

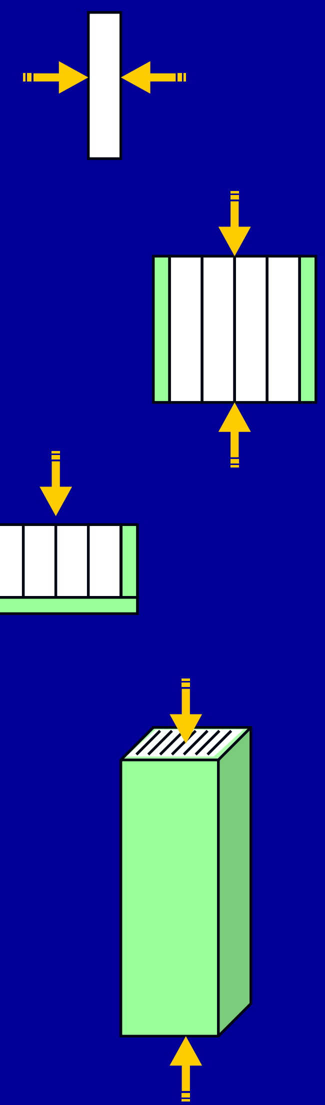
Rockwell/Boeing committed to success: added manpower and acquired additional equipment.

Feedback between manufacturer and SLAC essential, one DIRC physicist located on-site at plant for over two years with complete access to equipment and personnel.

BAR FABRICATION

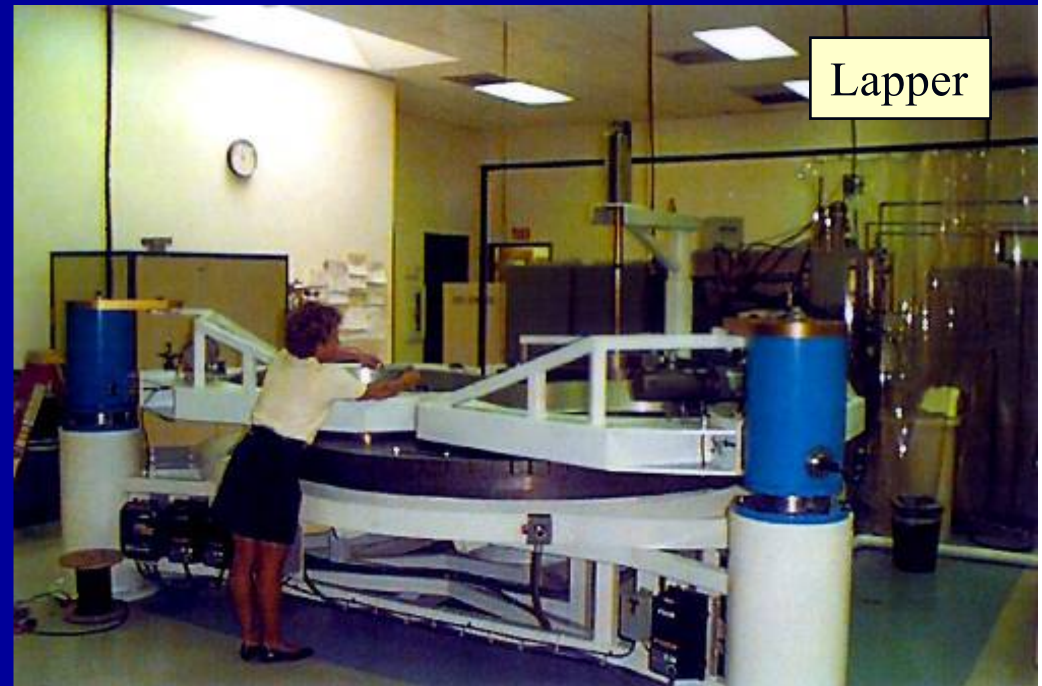
Start with two-bar plank delivered to Boeing

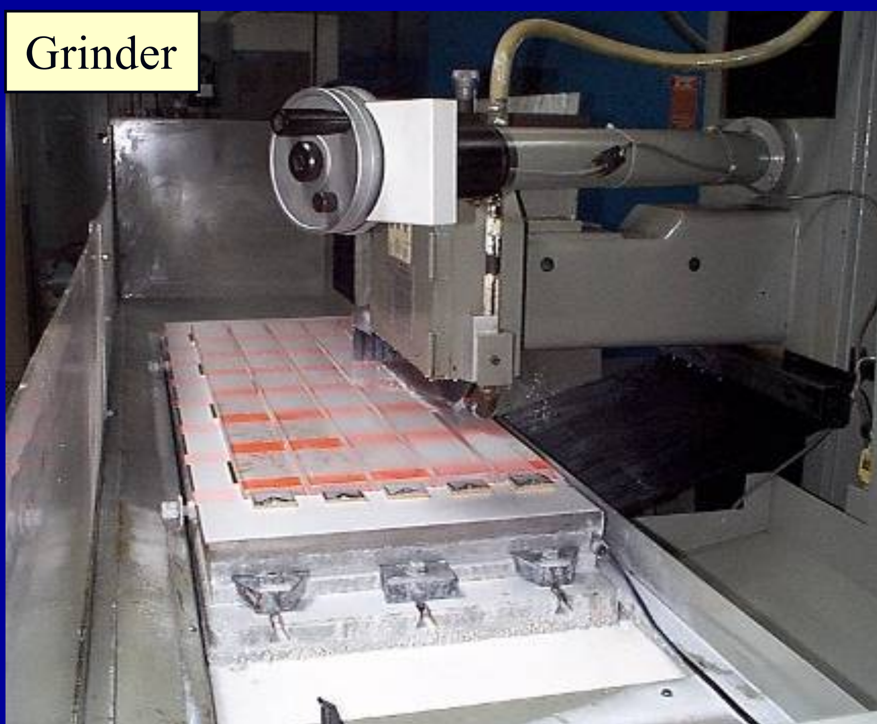
- grind, lap, polish large faces
  - → 2 high quality parallel faces, excellent polish
- combine 4 two-bar planks, glue with heat setting wax, outer plank faces protected with glass planks
- grind, lap, polish sides of blocks
- cut block in half with band saw
- grind, lap, polish sides of blocks
  - → all long faces now parallel, excellent polish
- combine 8 4-bar unites for end processing
- grind, lap, polish ends
- disassembly, final QA, cleaning
  - → finished bar, ship to SLAC



BAR FABRICATION

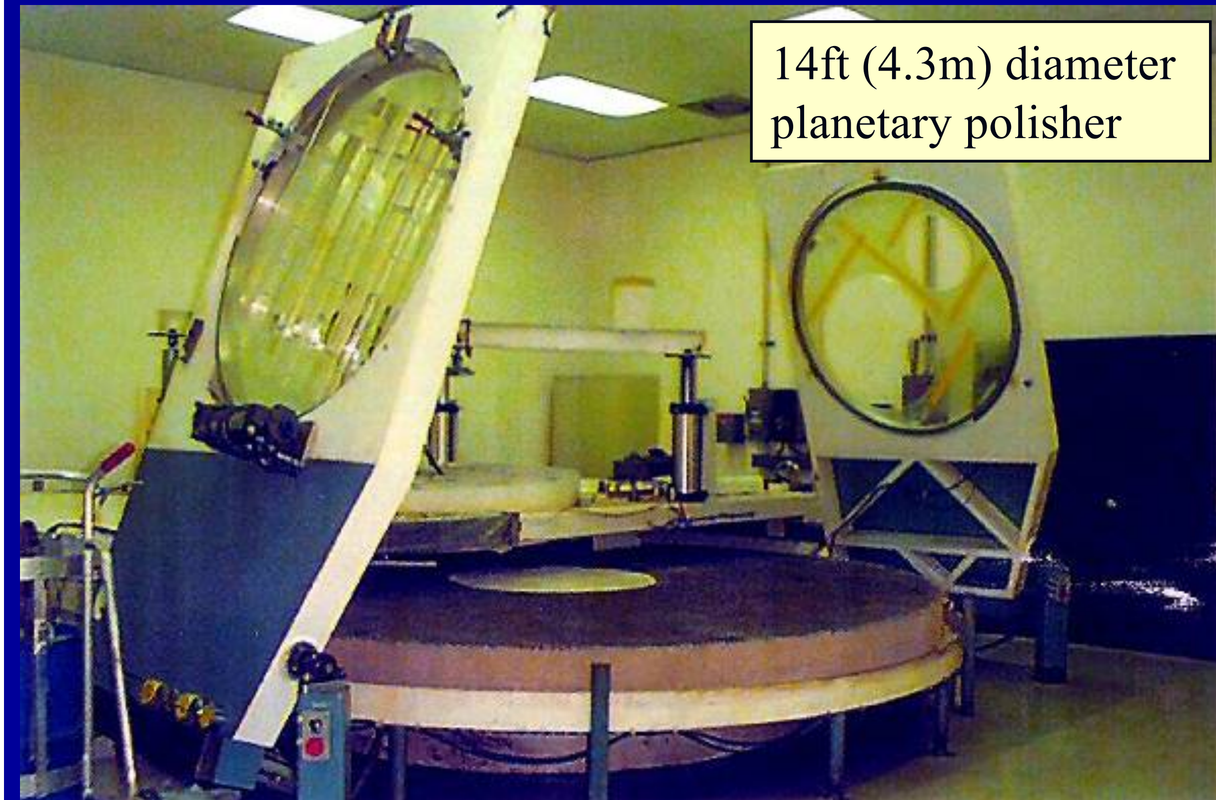

Ingot on band saw


Lapper


Grinder

Bars on lapper

BAR FABRICATION



14ft (4.3m) diameter planetary polisher

Zygo interferometer

Two-bar planks in storage

Over-arm lapper/polisher

BAR FABRICATION

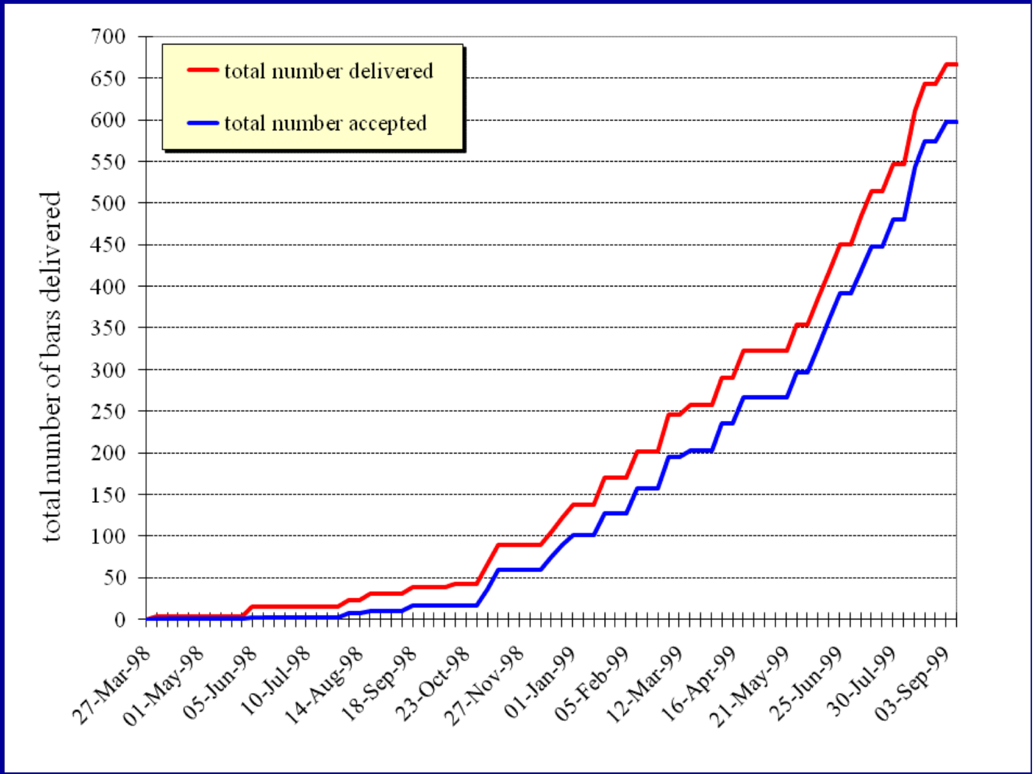
Prototype bars delivered to SLAC March and June 1998

First real production bars arrived in November 1998, fairly smooth sailing after that.

Final bars received Oct. 1st, 1999.

Received ~600 accepted high-quality bars
(576 installed in BABAR DIRC)

After start-up issues approx.
95% of delivered bars accepted



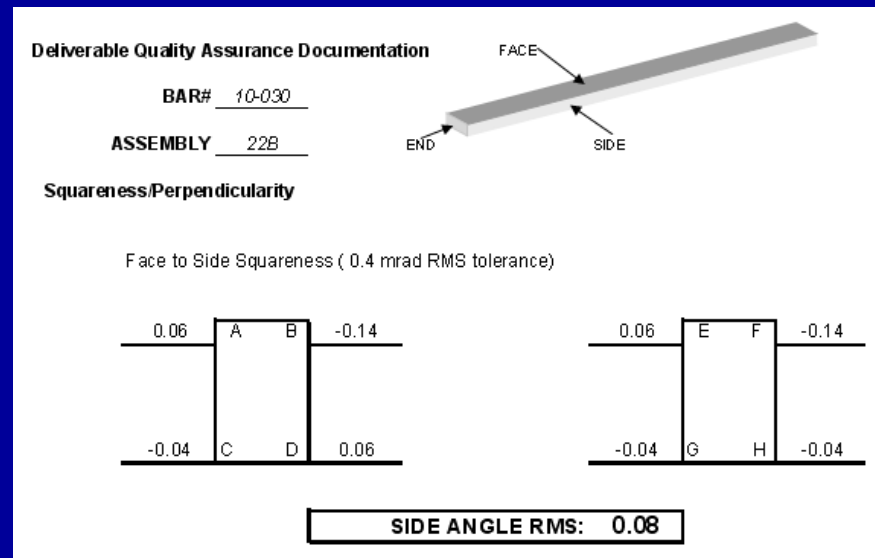
Boeing primary QA for every bar – angles, dimensions, surface polish

Micrometer-based mechanical fixture to measure all angles, accuracy 0.02mrad
calibrated with autocollimator

Zygo interferometer for rms surface polish
sample area of 1cm^2, accuracy 0.1nm

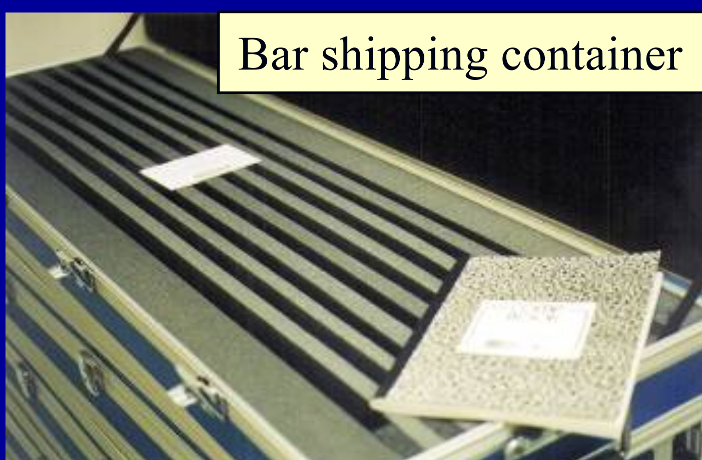
data sheet of all QA measurements available to SLAC

clean bars, package (wrapped in cleanroom cloth,
polyprop sheet, place in Styrofoam clam-shell)
ship to SLAC in custom container



Dimensions			END 1	MIDPOINT	END 2
Thickness (Face-Face)	0.6594	0.6791	0.6628	0.6638	0.6636
Width (Side-Side)	1.3583	1.3779	1.31435	1.31505	1.31475
Length (End-End) (32 bar assembly)	48.209	48.228	48.216		

Surface Quality		SURFACE 1 max	SURFACE 2 max
Faces	< 5 Angstroms rms (3 plcs)	4.09	4.40
Sides	< 5 Angstroms rms (3 plcs)	4.97	7.16
Ends	< 20 Angstroms rms (12 plcs) (32 bar assembly)	7.91	6.73



Bar shipping container

BAR QA

SLAC goal: cross-check Boeing QA results

provide feedback on fabrication changes

unpack bars in cleanroom, create QA traveler sheet,

unique ID for electronic database containing

all Boeing and SLAC QA results for all bars

inspect for damage and cleanliness

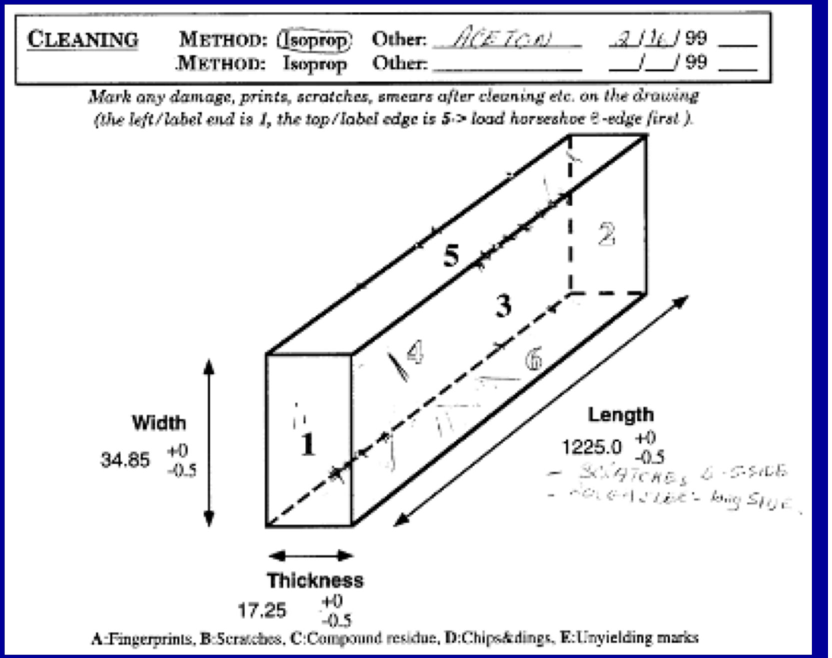
if required: clean bars with acetone and isopropyl

alcohol or alumina powder/water

place bar in plastic holders

(never touch bar surface or edges throughout process)

store in cleanroom in rack under HEPA filters



for some bars:

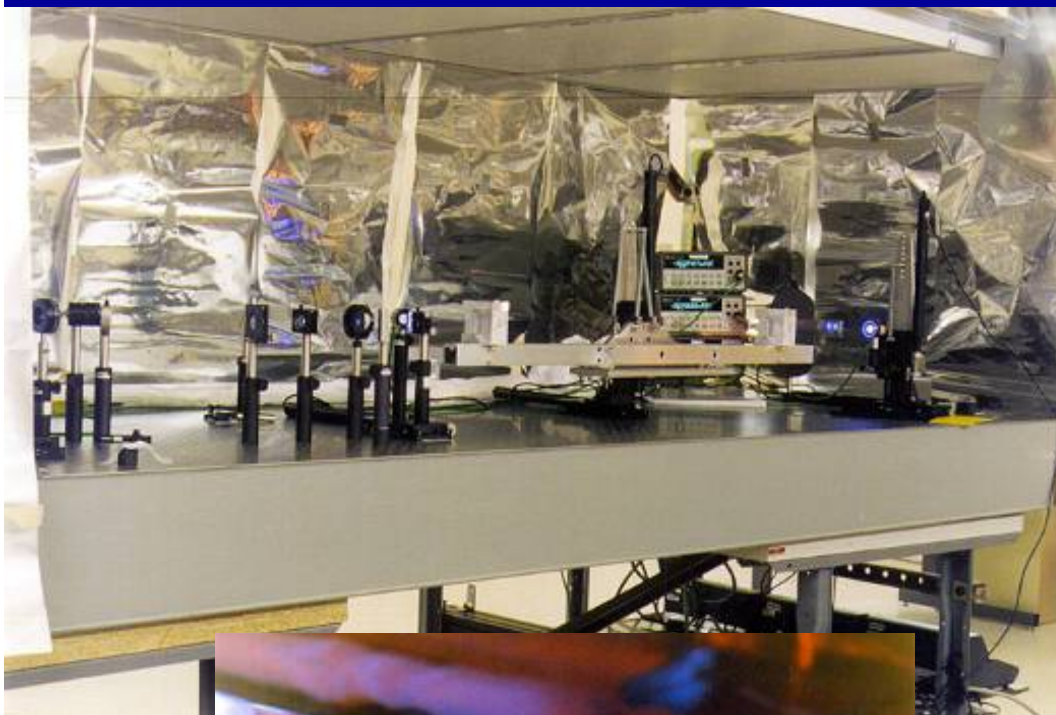
use digital microscope to measure squareness and edge defects

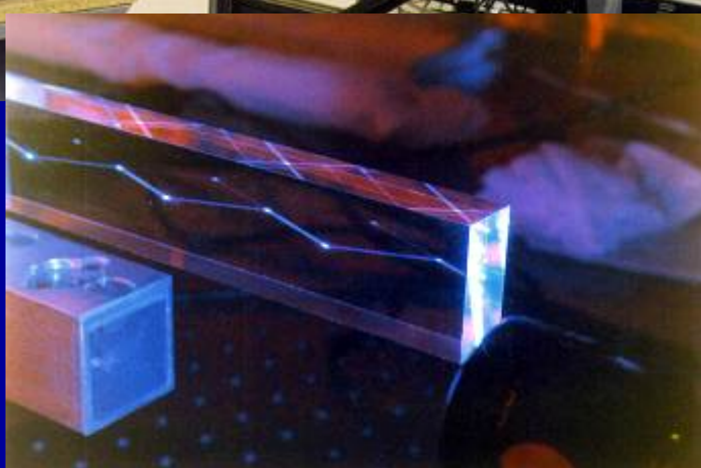
use HeCd laser to measure transmission and surface reflectivity and check for “lobes”

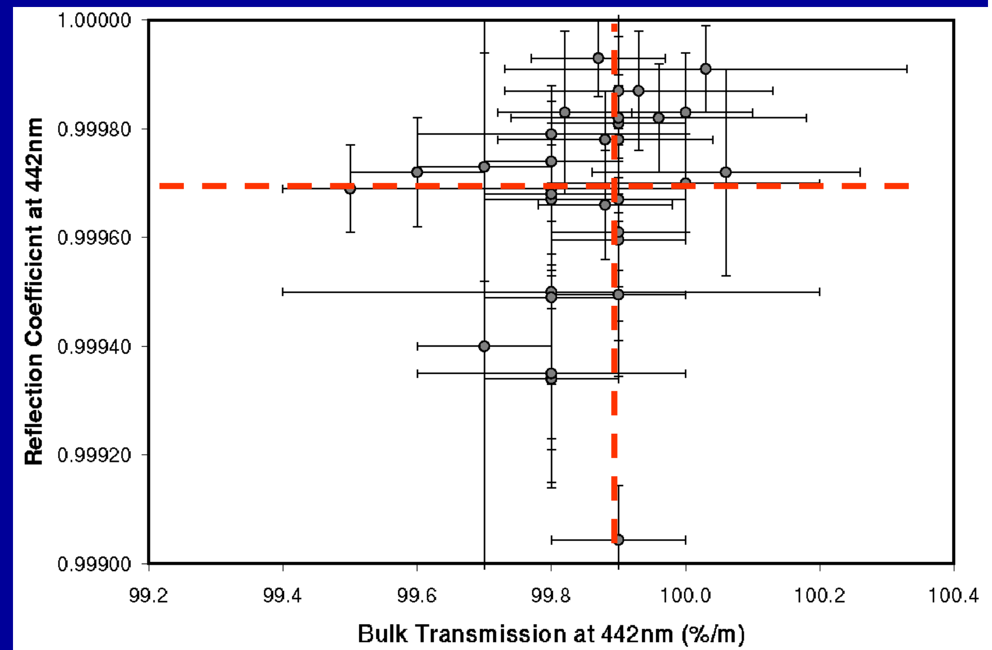
use Coordinate Measurement Machine to measure dimensions and angles

Bar QA

Automated motion-controlled setup to measure bar transmission and surface reflectivity at 325nm or 442nm







Average at 442nm:

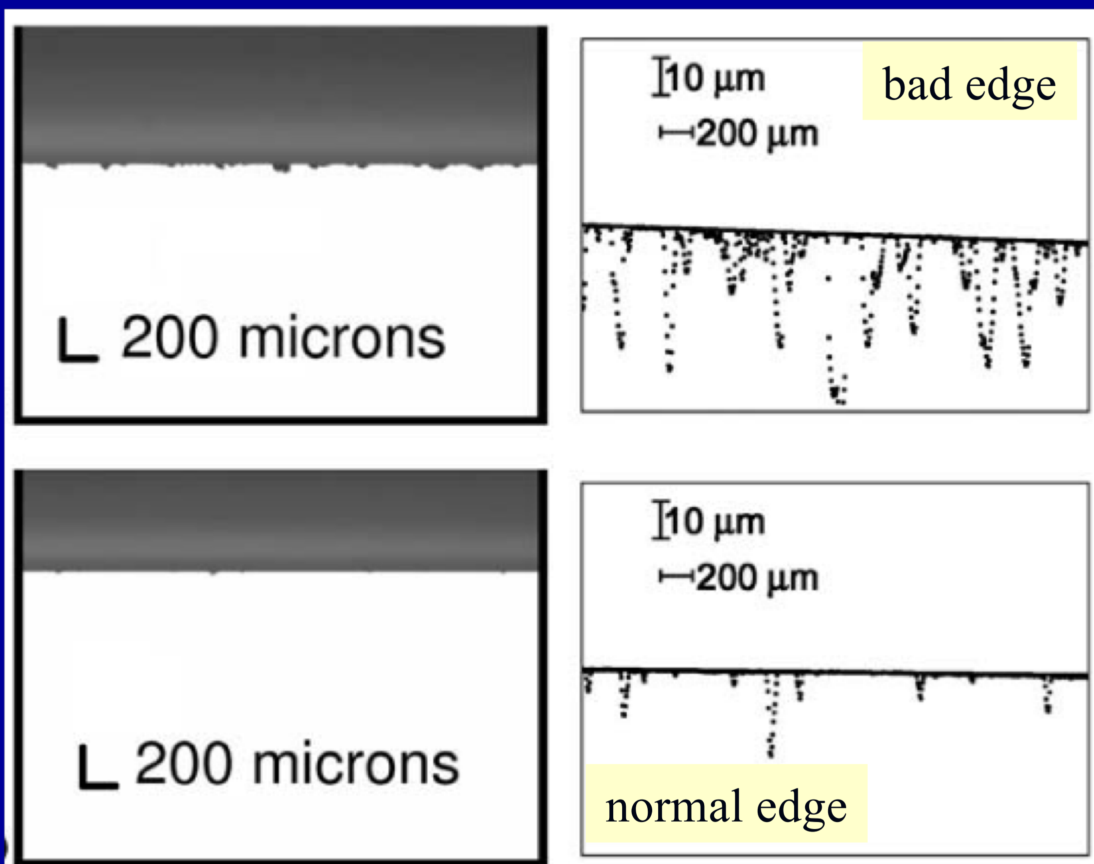
Transmission	99.9±0.1%/m
Reflection coefficient	0.9997±0.0001

Bar QA

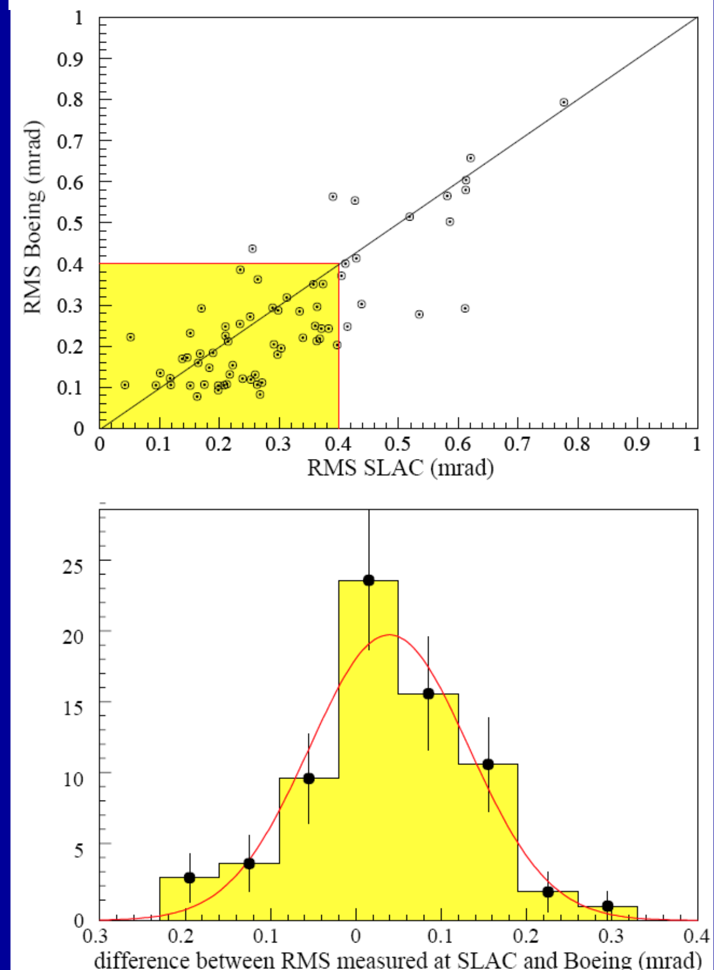
Study edges and bar angles with custom-built digital microscope plus imaging software

Use edge-finding algorithm on grey-scale pixels to find edges
calculate face-to-side and side-to-end angles

Good agreement with Boeing QA data



Comparison of SLAC QA
to Boeing QA results



BAR QA

SLAC measurement of surface reflectivity consistent with Boeing rms data

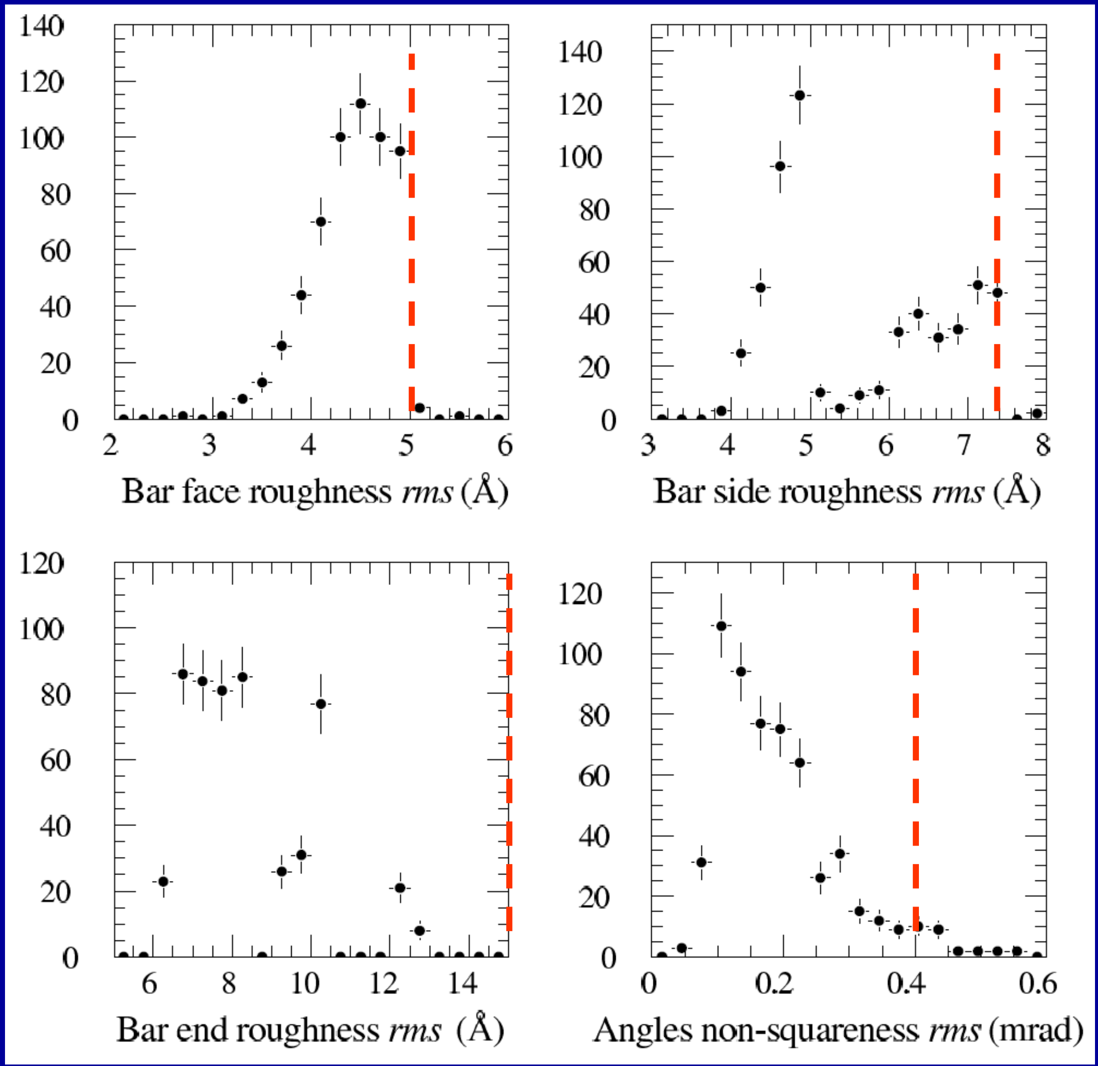
No bars rejected due to polish

Most bars did not require additional cleaning at SLAC

Edge quality QA performed by visual comparison to reference bar when bars illuminated from one end in dark room

Bar dimensions (width and thickness) measured with calibrated calipers prior to assembly

Summary of QA results for polish and angles



BAR BOX ASSEMBLY

Bars selected and placed in fixtures in cleanroom

Major effort to ensure that all reference points (bumpers, clamps, etc) on optical table and granite assembly table are level to better than 25µm.

Select bars in long bar from same Boeing 4-bar group (same with, thickness, shape)

Measure thickness/width with calibrated calipers

Epotek 301-2 takes approx. 48 hours to cure, requires neighboring elements to be securely clamped throughout

Glue joint thickness 25µm

Clean surfaces vitally important to good glue joint

Cleanroom temperature controlled ±2 deg C

To avoid stress from differential temp. expansion only elements adjacent to active glue joint clamped

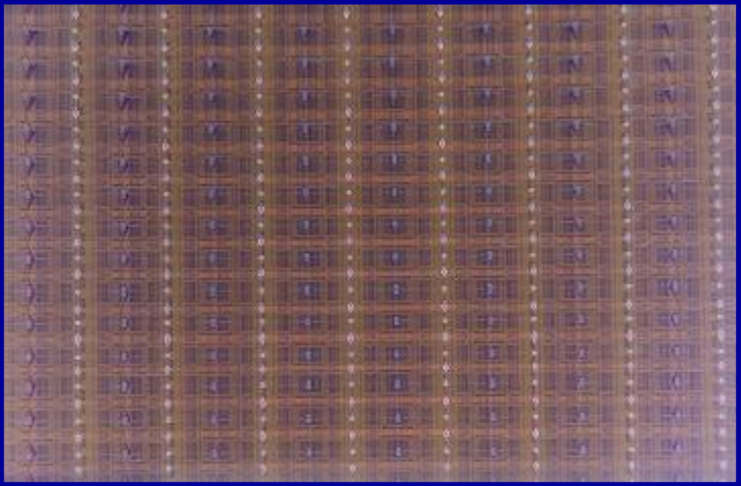
Introduce few drops of glue on top of joint, capillary action draws glue into void, remove excess after 24 and 48 hours

BAR BOX ASSEMBLY

Once 12 long-bars glued together move from optical table to open bar box on granite table

Shine HeNe laser down length of bar to verify integrity of all glue bonds

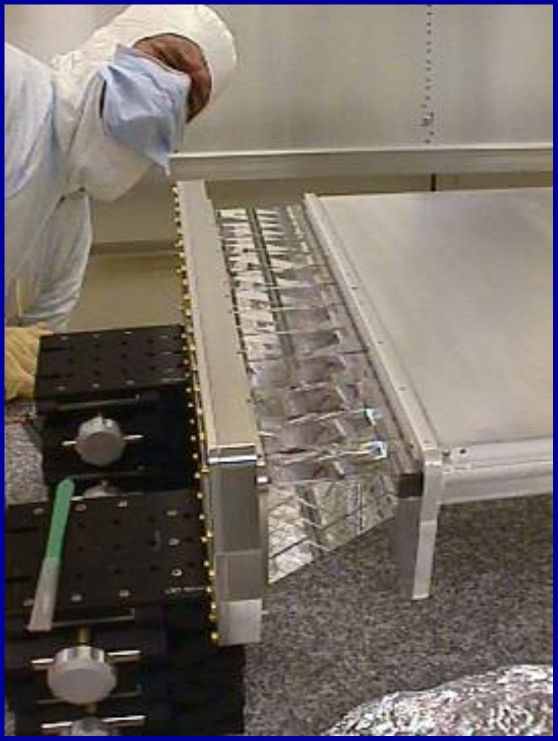
Take photo of internal reflections looking into the long bars



BAR BOX ASSEMBLY

Gluing of 12 wedges to one window particularly sensitive to clean surfaces

Even minor dust and residue would lead to bubbles in the glue joint



BAR BOX ASSEMBLY

Once procedure streamlined: 13 days to build one bar box

- majority of time (8 days) for wedge-to-bar and bar-to-bar gluing
- assemble one bar box while gluing bars for second box
- store completed bar box in temperature controlled container

Aug 1998: produced first prototype bar box for cosmic ray and commissioning run

- bar selected: 36 Zygo bars and 12 early Boeing bars

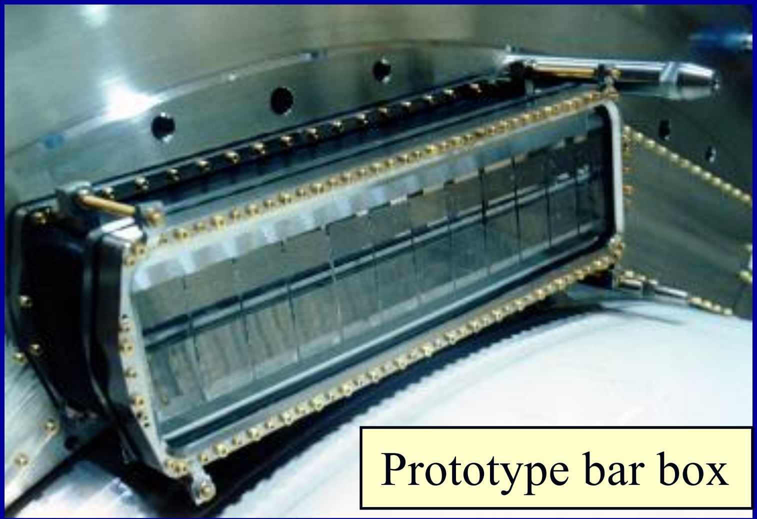
First “real” DIRC bar box completed in January 1999.

Final bar box completed in September 1999.

Nov 1998: installed prototype bar box

April 1999: installed four final bar boxes

Oct 1999: removed prototype bar box,
installed remaining 8 final bar boxes


Prototype bar box

BAR BOX INSTALLATION

Installation fixture

- prevent bending/flexing of bar box
- align box with rail system in slot
- laser alignment system

Installed two bar boxes per day

Final bar box installed Oct 10, 1999

DIRC Production Conclusions

- Aggressive prototype program, short time between first idea and BABAR decision.
  Learned much about bar properties, handling, cleaning, DIRC performance
- Continued R&D studies in parallel, identified issues with radiation hardness and lobes,
  tested glue properties, material outgassing, assembly procedure, etc.
- Fabrication complicated by change in manufacturer.
- Communication between manufacturer and SLAC essential.
- Bar production not a turnkey operation – much fiddling, constant QA checks required.
- For every bar and bar box detailed and well-documented QA program.
- Bars protected at all times with “horseshoe” holders and Hepa filter arrays
  Cleanroom made it safe to leave bars out in gluing fixtures for weeks at a time
- Clean surfaces critical, especially for large wedge to window joint.
- Delays in bar production put to good use – bar box production well-rehearsed.

DIRC ran in factory mode for 8+ years,
PMTs immersed in ultra-pure water for 9+ years

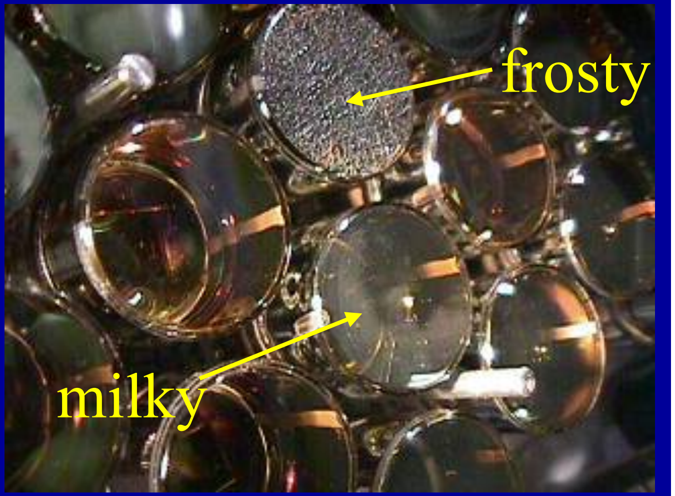
DIRC Operations were Stable and Robust

- Calibration constants stable to typically *rms* < 0.1ns per year.
- No problems with water or gas systems.

The three most significant operational issues:

- Concerns about PMT longevity due to PMT window degradation
- Some damage to electronics due to dust/dirt from civil engineering
- Sensitivity of the DIRC to machine background interacting in the water of the SOB (primarily DAQ issue)

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.

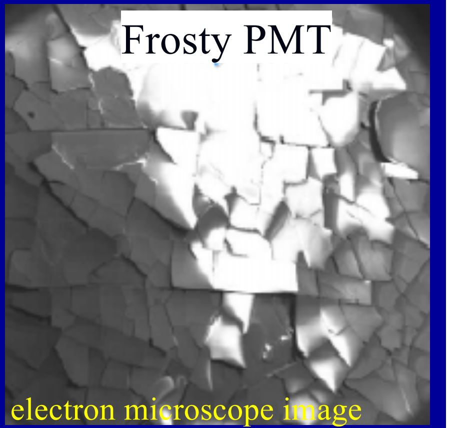
Studies →

- Strongly corroded (*frosty*) tubes are a bad batch of PMT glass (no zinc).
- *Milki*ness 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).



Ultimately, until shutdown in Apr. 2008, no problems with milky or frosty PMTs observed.

DIRC WATER SYSTEM

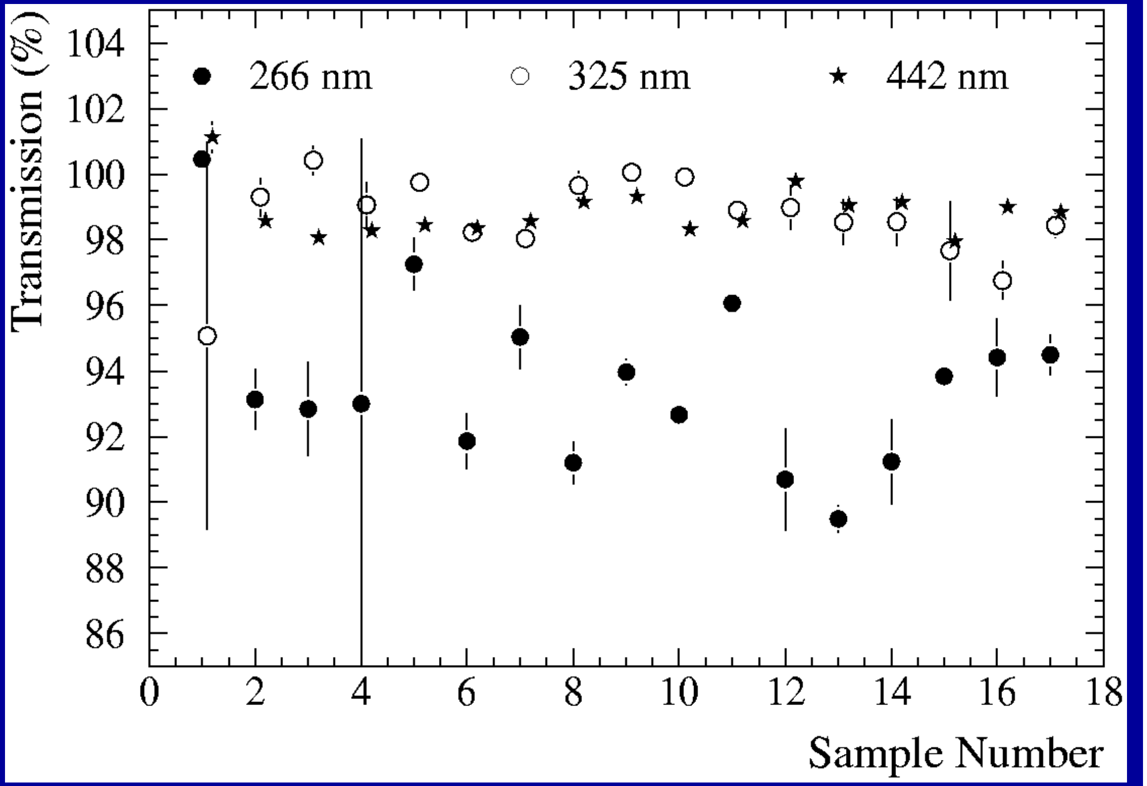
DIRC standoff region filled with ~6000 l ultra-pure water

(recirculated ~2.5 times per day, typical resistivity ≈ 8-10MΩcm, pH ≈6.5)

Analysis of samples of DIRC water system (7+ years of data):

- transparency
  (laser, 3 wavelengths)

  → stable at >98%/m @ 325nm
  >90%/m @ 266nm



- chemical composition
  (spectroscopy, outside company)

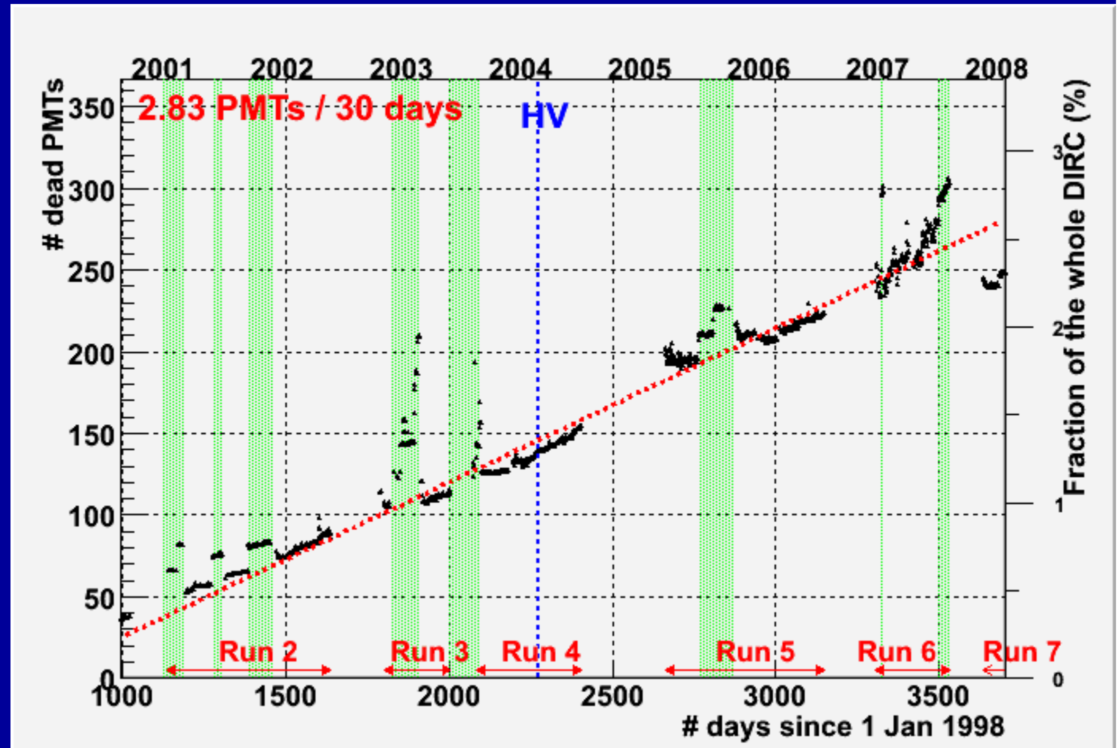
  from sodium content comparison in supply *vs*. return water calculate PMT front glass loss rate

  → ~2-4μm/PMT/year, not a problem

DIRC PHOTON YIELD

Detailed monitoring of photon yield:

- LED pulser calibration;
- PMT aging tests;
- comparison of signal photon yield in real Bhabha and di-muon events;
- observed rates of signal and background in all PMTs;



(green ranges excluded from fit)

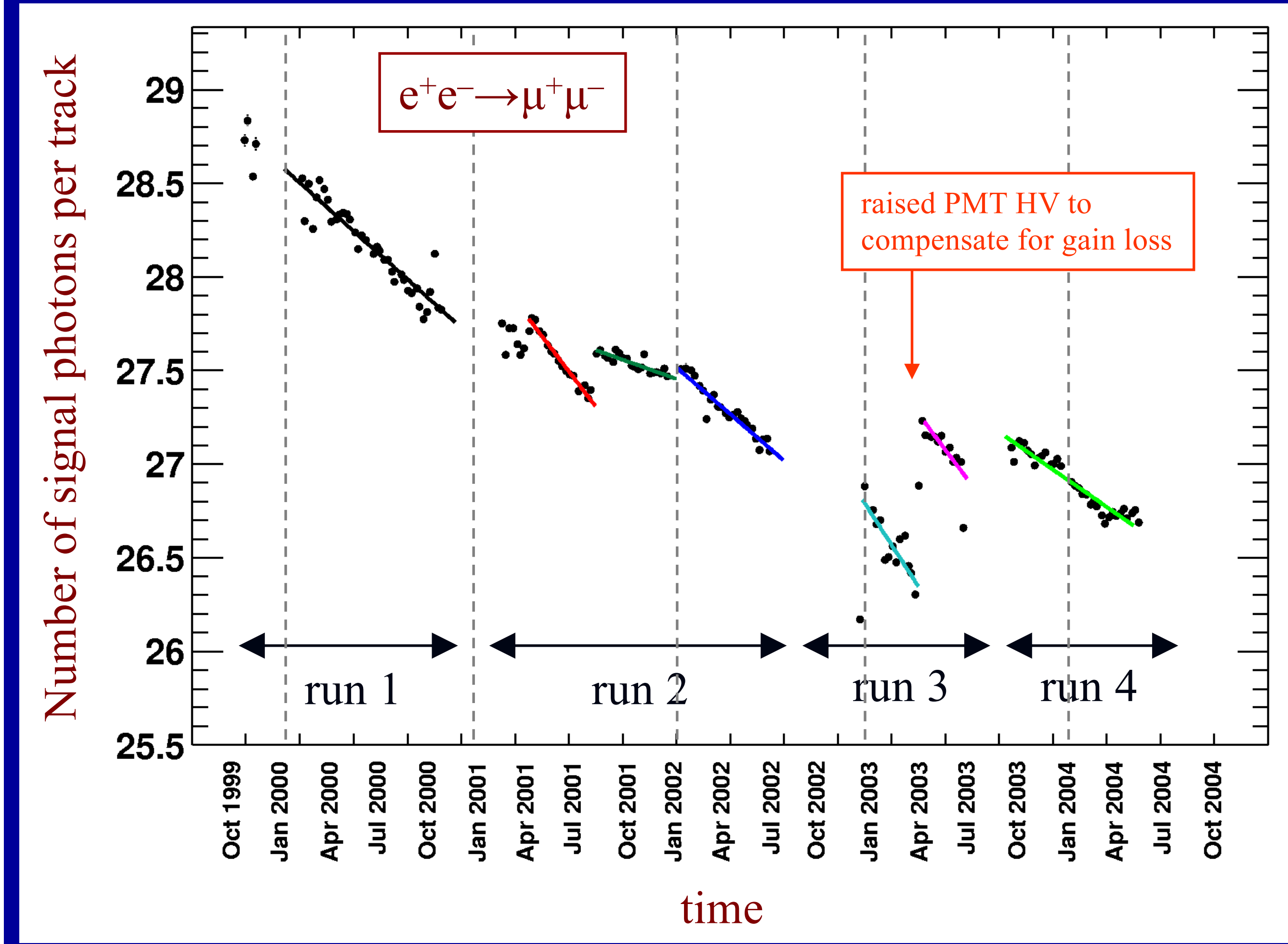
Example: number of "dead PMTs"

- record in each run number of PMTs with rate <<10% of expected hit rate
- loss rate *vs*. time is remarkably god fit to a simple line – loss rate ~2.8 PMTs per month

Final tally April 2008: ~220 dead/inefficient PMTs (out of 10752)

→ 98% of PMTs were still fully functional

DIRC PHOTON YIELD



Example:

di-muon events ($e^+e^- \to \mu^+\mu^-$)

study number of signal photons from fit to "ring" as function of time

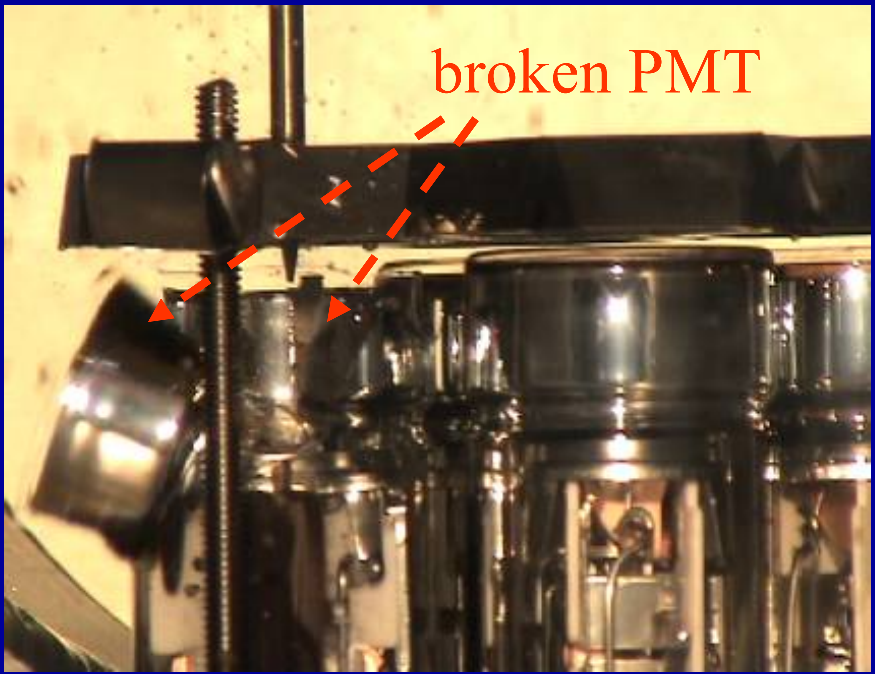
- loss rate few %/year
- interesting variations with time (not fully understood)

Consistent result from all studies:

photon yield loss few % per year.

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

DIRC PMT LONGEVITY

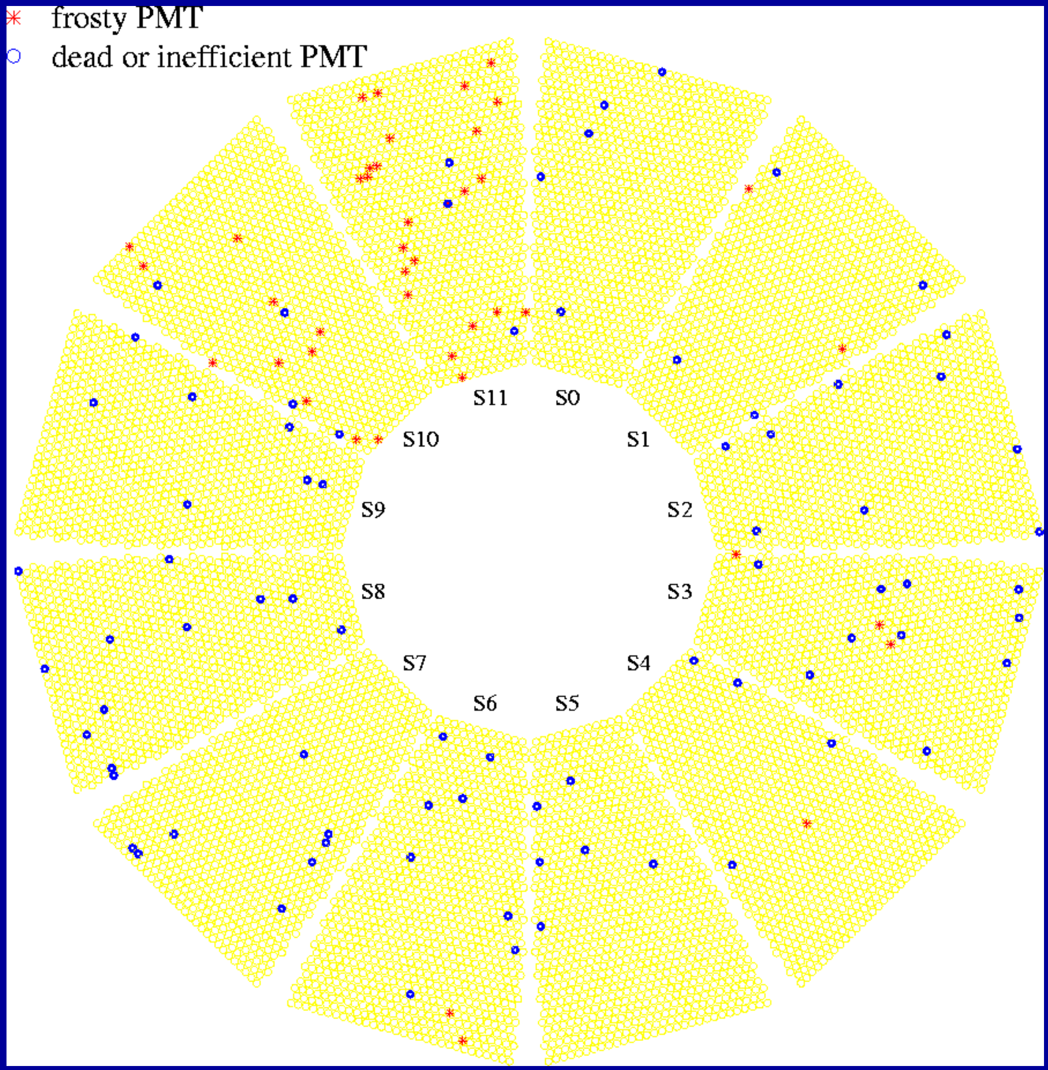


Concern with mechanical stability of PMTs when front glass gets thinner *(Super-K...)*

- 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 PMT LONGEVITY

After over nine years, ~220 PMTs out of 10,752 are dead or inefficient
→ 98% fully functional

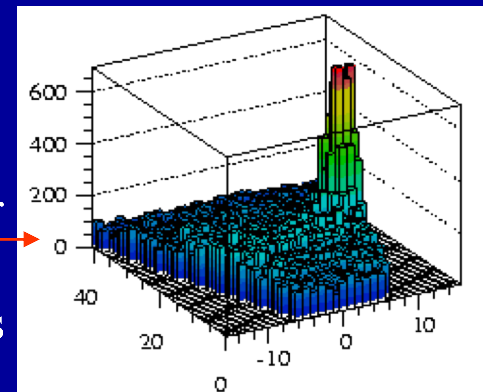


DIRC PMT LONGEVITY

Most spectacular failure mode of PMTs:

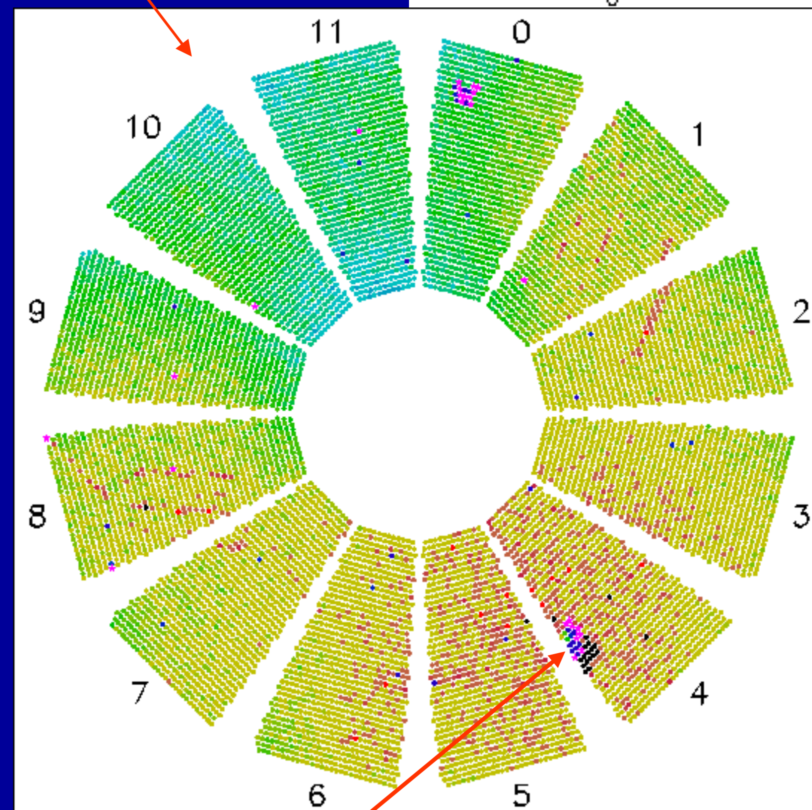
"Christmas Tree"

Rate (kHz) in one sector



Occupancy in all sectors

- 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 group automatically lowered to preserve data quality;



Christmas Tree PMT

Observed rate: 5-6 per year.

DIRC Operations

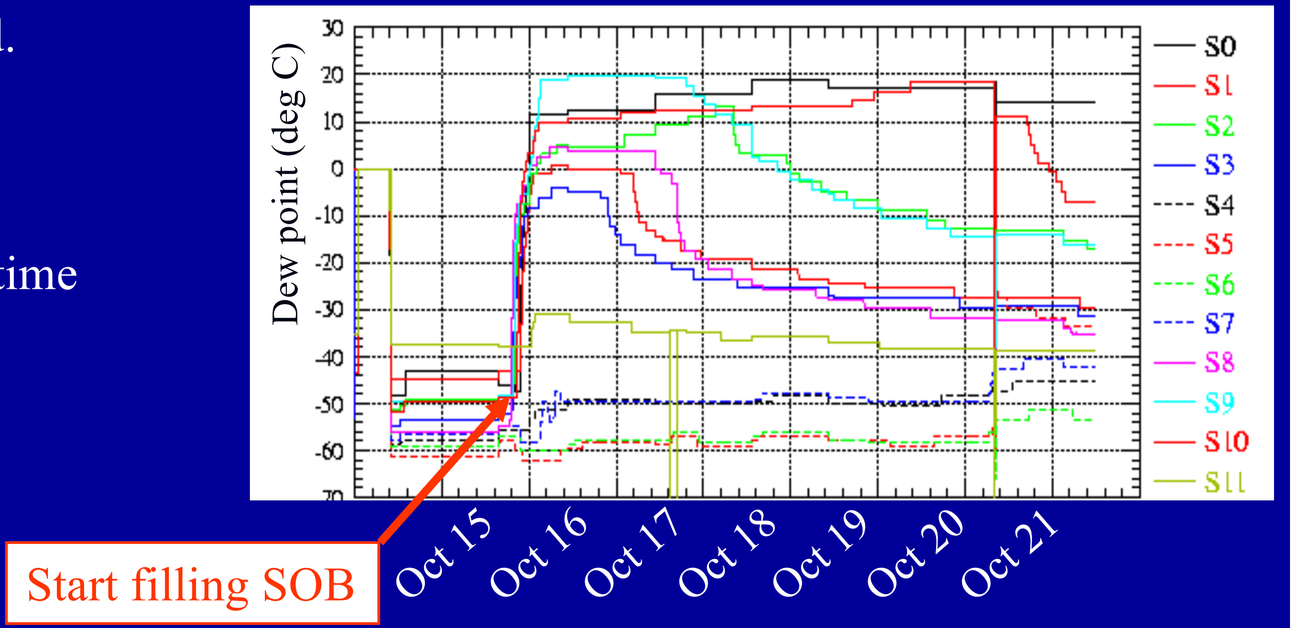
On Oct 15, 1999 filled Standoff box with water after all boxes were installed.

Quickly noticed several micro-leaks at O-rings around window assembly.

Detected by humidity sensor in dry nitrogen return line from bar box: sharp rise in dew point.

Leaks stopped when O-rings settled.

Increased dry nitrogen flow rate stabilized dew point and removed excess humidity over time (days to months).



DIRC Electronics Issues

Many years of stable running – typically fewer than 1 DAQ or HV crate problem per run

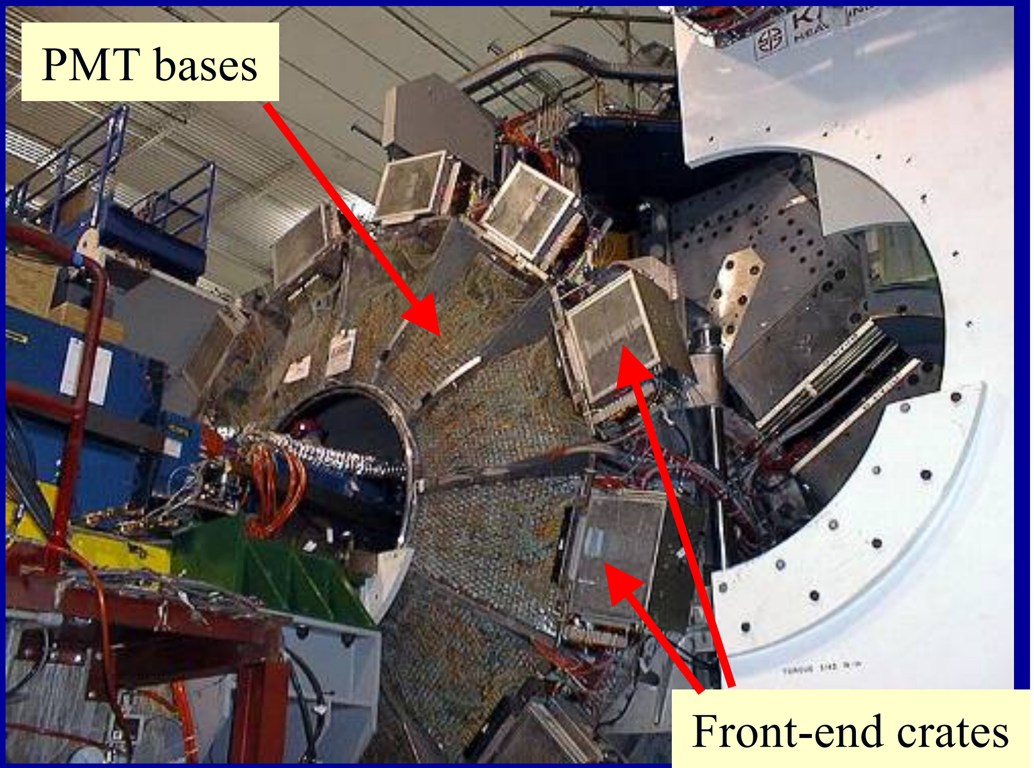
Until scheduled shutdown in Fall 2006:

- Planned only routine DIRC maintenance (replace flaky board, clean air filters)
- When we turned DIRC front-end and HV back on several power supplies and fan trays failed
- Replaced them with spares but shortly after several more failed, more than available spares
- Some front-end boards did not directly fail but generated many DAQ errors

Lots activity in collider hall during shutdown

Detector was open for installation of new
muon chambers

This exposed DIRC front-end electronics
and high-voltage crates on the backward
end of BABAR



DIRC ELECTRONICS ISSUES

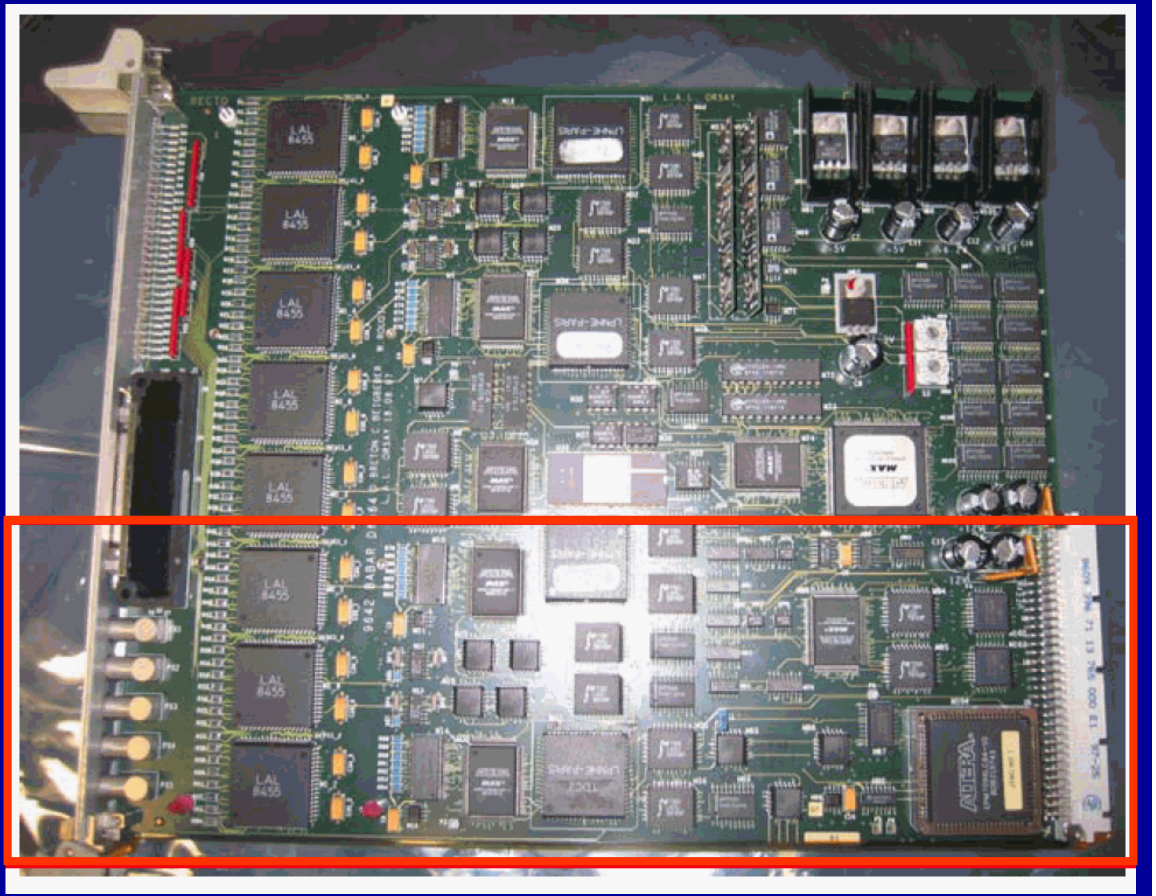
Accessed DIRC front-end electronics, found dust and dirt on boards close to fan.

DIRC crates protected with air filters – but filters unable to deal with dust.

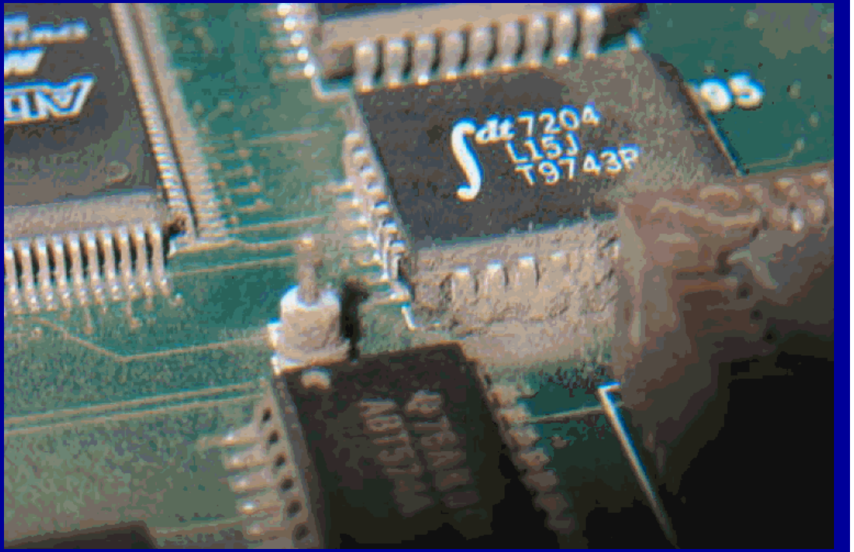
Civil engineering for LCLS project
proceeding outside collider hall
while detector was open

Ceiling fan in collider hall spread dust
across hall, including backward end
of BABAR detector and DIRC FEE

Chemical analysis of dust found
dirt consistent with construction
activity.



DIRC Electronics Issues

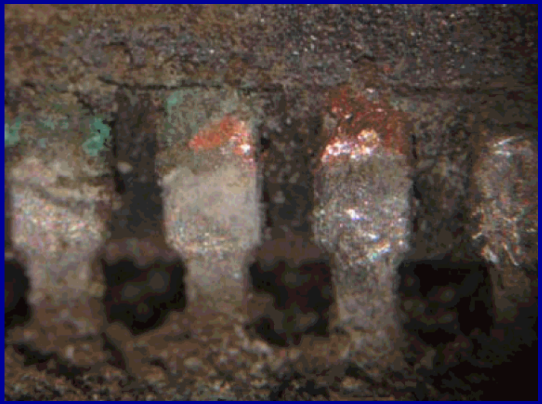


Looked at front-end boards in detail

Found sticky dust coating with
- evidence of corrosion underneath

Some traces corroded rapidly
- Few boards had been just placed into DIRC in early October, showed corrosion 4 weeks later

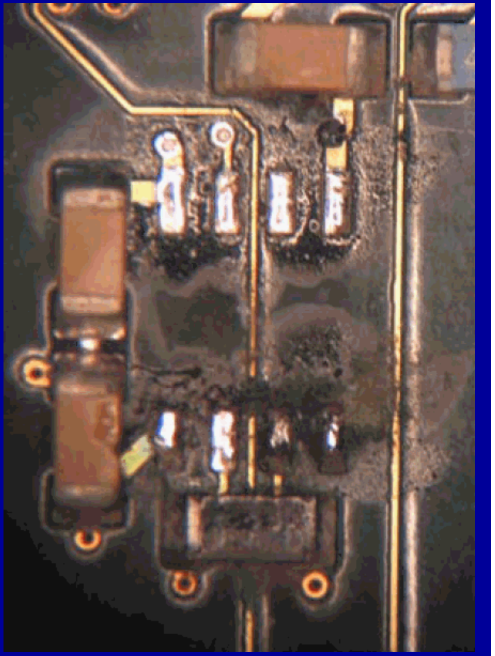
Removed all boards from detector



Cleaned all boards (some at SLAC,
- most cleaned commercially)

Fixed open traces

Added conformal coating
- on areas on boards close to fan



Tested and replaced all boards.

Cleaned all fan trays, added additional air filters.

All this happened over few weeks, massive effort.

Success: all components worked well, no dirt/dust problems since.

BACKGROUNDS IN THE DIRC

After start-up PEP-II Luminosity and currents were rapidly increasing

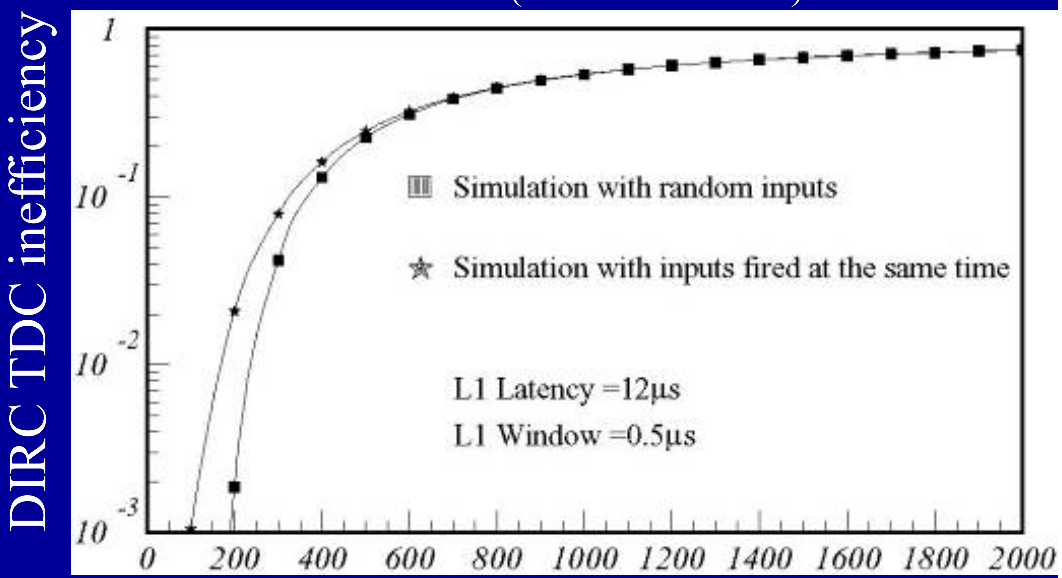
- soon exceeded design $3*10^{33}$ /cm^2·s;
- ultimately reached 4 times design in 2006;
- background rates in DIRC rose very quickly;
- DIRC saw high PMT rates, over 200 kHz, even at 1/3 design lumi.

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

But high counting rates caused delays in BABAR DAQ and inefficiency in first version of DIRC TDC chips:

~5% inefficiency at 250 kHz

DIRC TDC 1 (used until 2002)

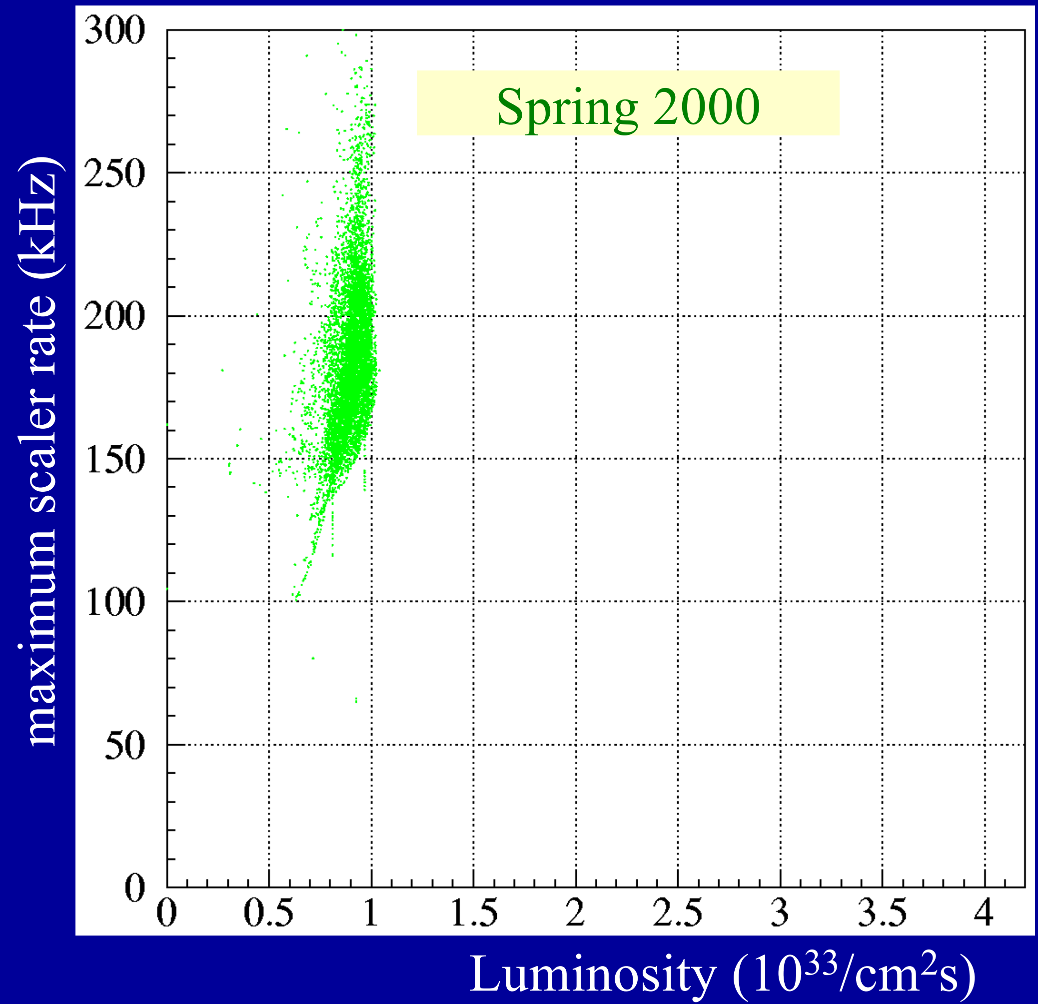


Input frequency (kHz)

BACKGROUNDS IN THE DIRC

Monitor background rates:

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



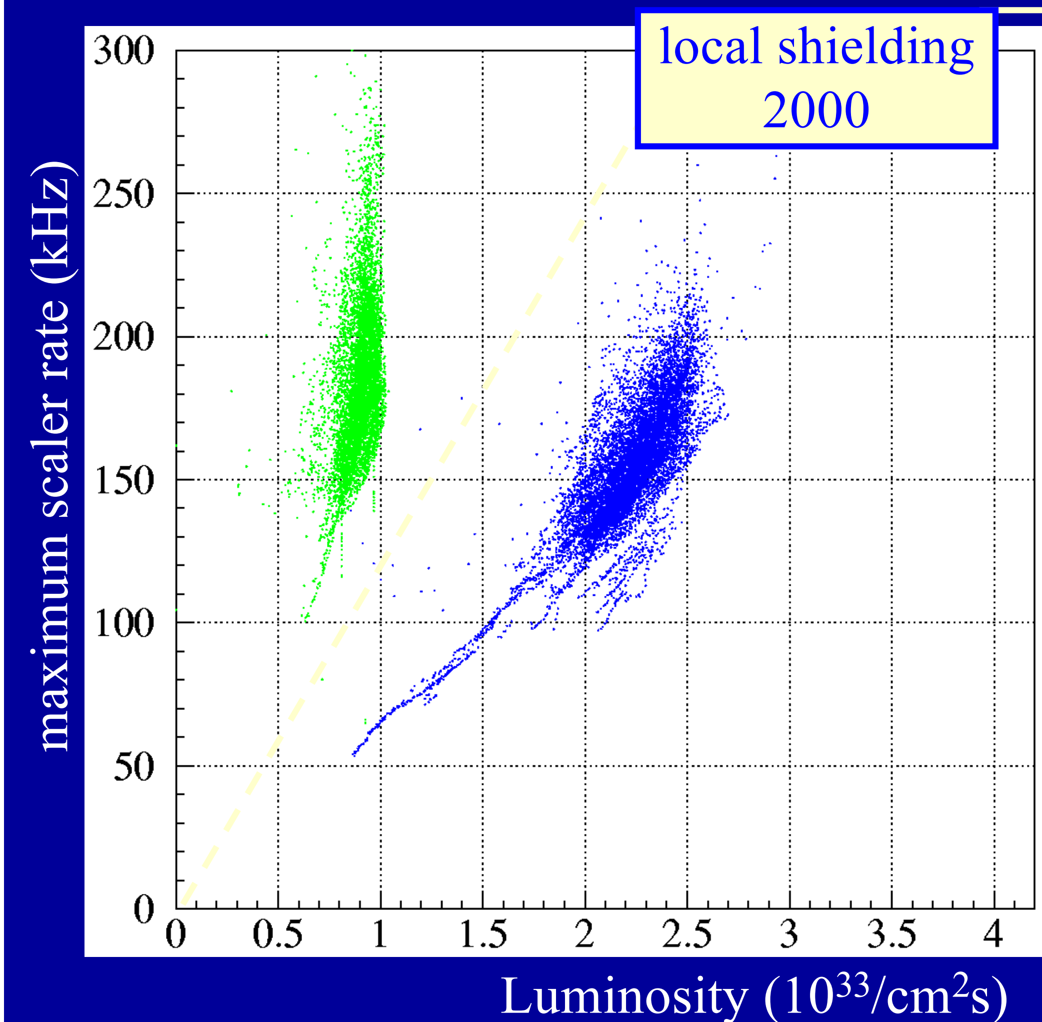
Status during early BABAR running:

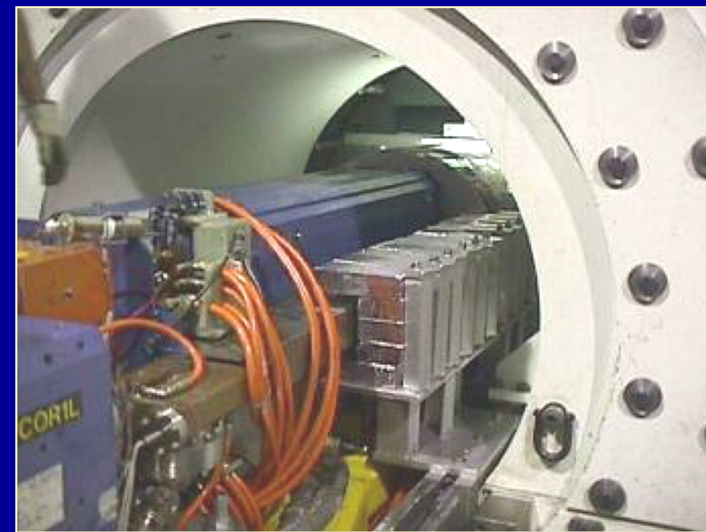
rates of >250kHz causing noticeable TDC deadtimes at 1/3 of design luminosity

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

BACKGROUNDS IN THE DIRC

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



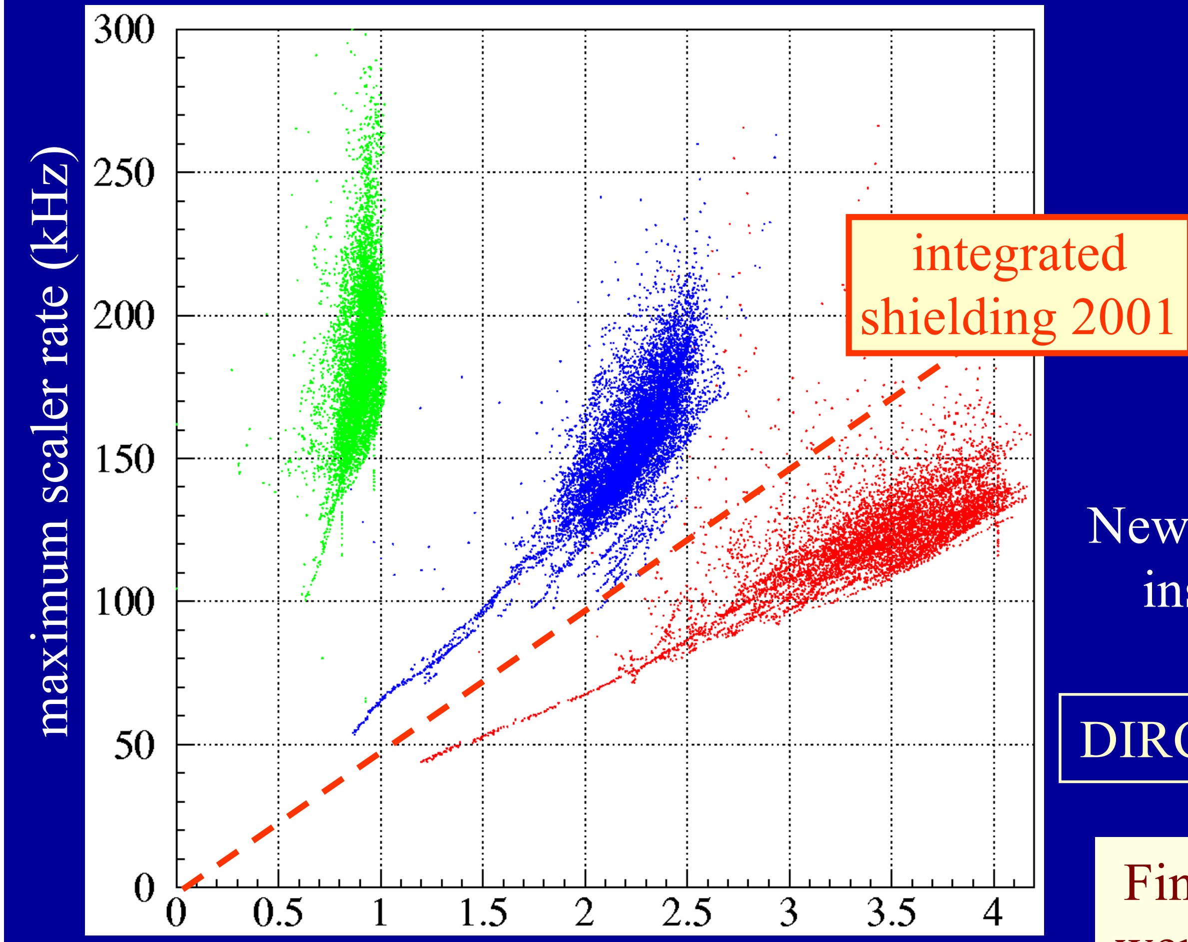


Rate vs. Luminosity showed that lead shielding essential in protecting DIRC from few MeV photon accelerator induced background (radiative Bhabhas, neutrons, etc).

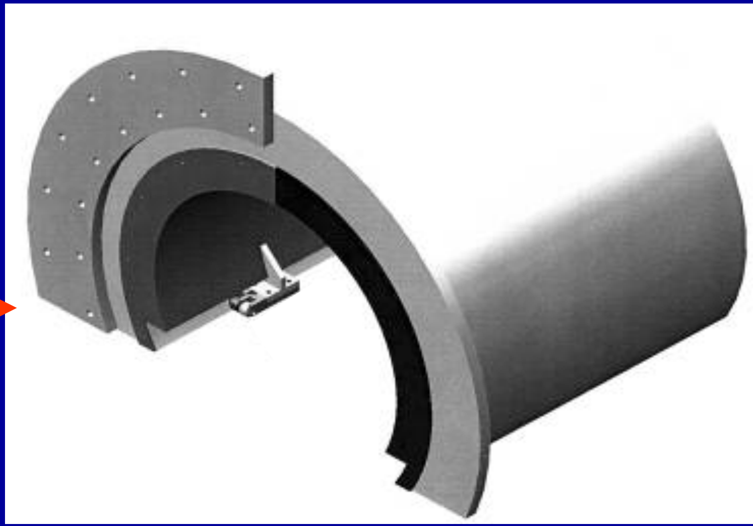
More uniform, complete shielding and easier access to detector required.

BACKGROUNDS IN THE DIRC

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).



Luminosity ($10^{33}/cm^2s$)



New TDC chips (faster, deeper buffering) installed during shutdown Fall 2002.

DIRC TDC2: <5% deadtime at 2.5MHz

Final TDC and shielding configuration were "background safe" at highest lumi.

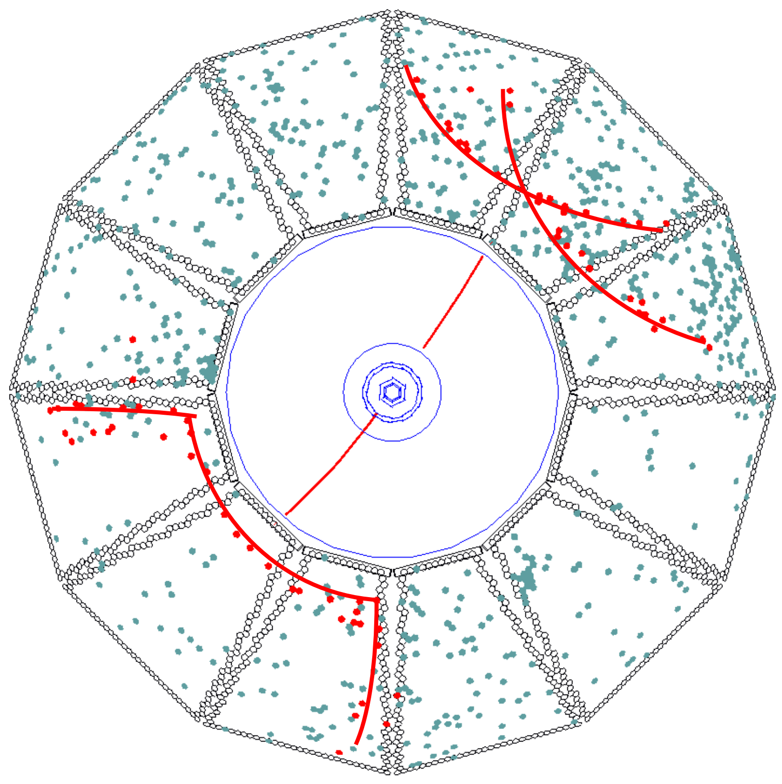
DIRC RECONSTRUCTION

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

80-200 kHz ⊗ 10,752 PMTs ⊗ ± 300 nsec trigger window

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

compared to

50-300 Cherenkov photons

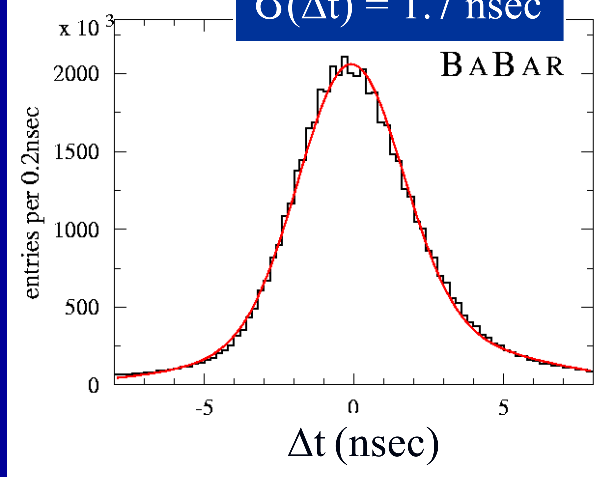
DIRC RECONSTRUCTION

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

Calculate expected arrival time of Cherenkov photon based on

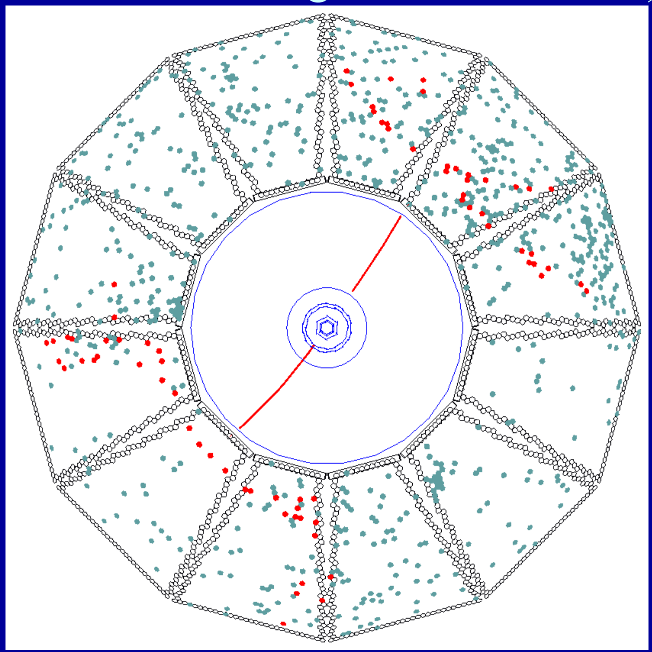
- track TOF
- photon propagation in radiator bar and in water

σ(Δt) = 1.7 nsec

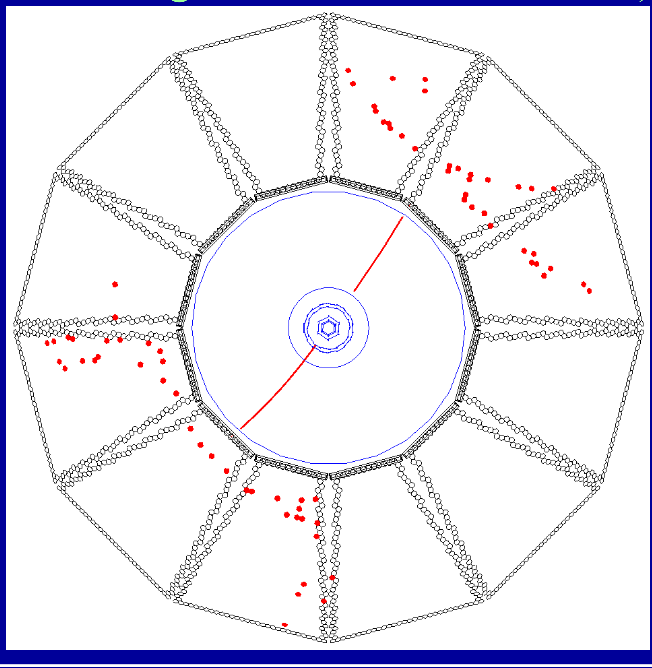


Δt: difference between measured and expected arrival time

± 300 nsec trigger window (~500-1300 background hits/event) → ± 8 nsec Δt window (1-2 background hits/sector/event)



→



DIRC Reconstruction

Calculate unbiased likelihood

for observed PMT signals to originate from e/μ/π/K/p track or from background.

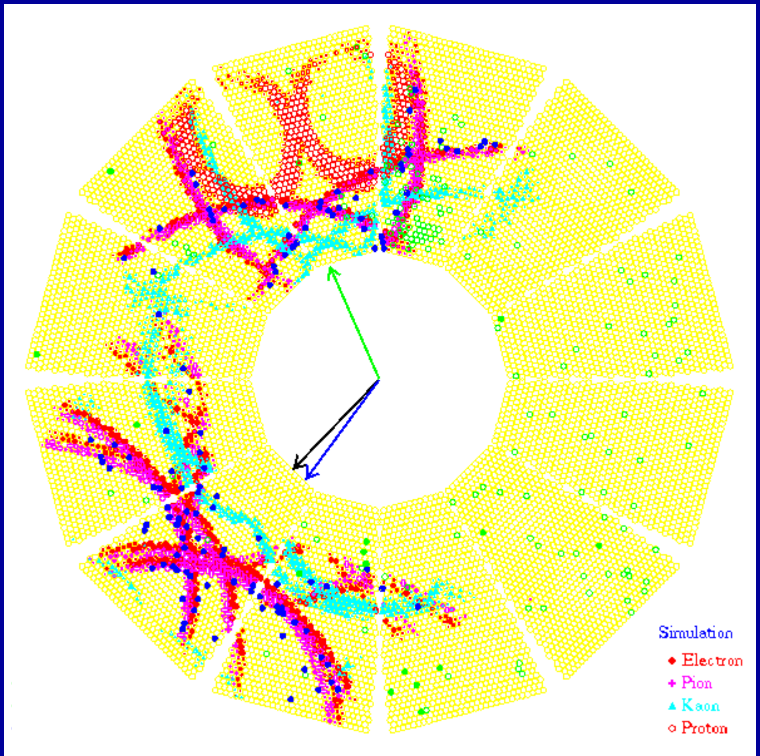
(Likelihood: **Pdf(θ_c) ⊗ Pdf(Δt) ⊗ Pdf(N_γ)**)

Two complementary reconstruction algorithms:

- iterative process to maximize event likelihood, full correlation of all tracks;
- individual track fit provides θ_c, $\sigma(\theta_c)$, number of signal/background photons.

Reflection ambiguities: Δt cut reduces these from up to 16 to typically 2-3

Particle ID is based on log likelihood differences of the five hypotheses.

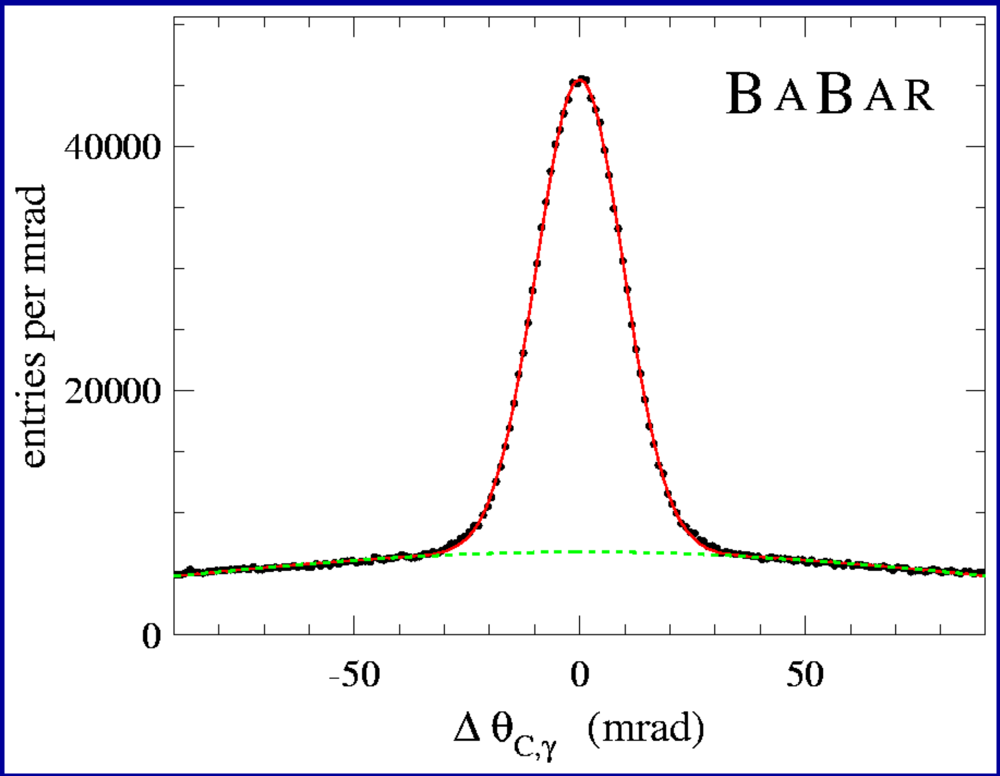


Example: Comparison of real event to simulated response of DIRC to e/π/K/p.

DIRC PERFORMANCE

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 mrad

Expectation: ~9.5 mrad

dominated by:

7mrad from PMT/bar size,

5.4mrad from chromatic term,

2-3mrad from bar imperfections.

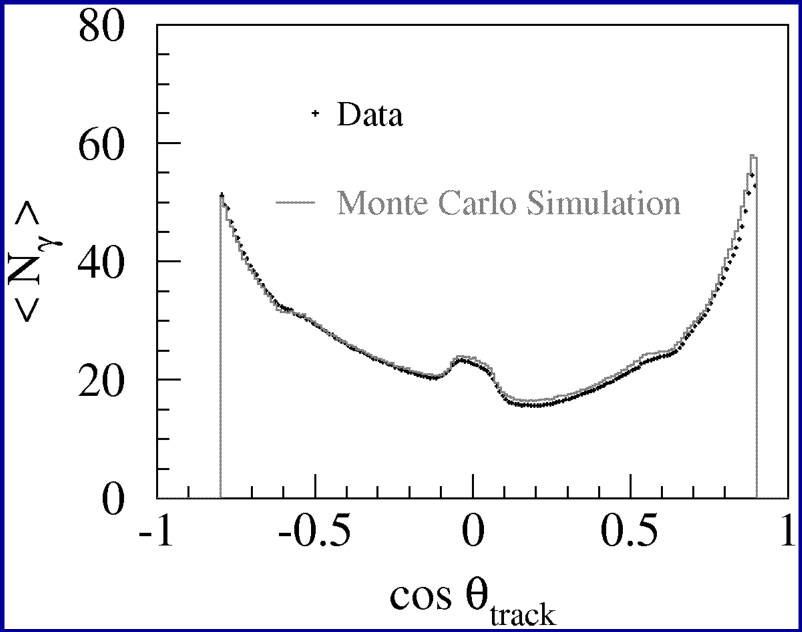
~10% Background under $\Delta\theta_{c,\gamma}$ peak:

combinatoric background, track overlap, accelerator background,

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

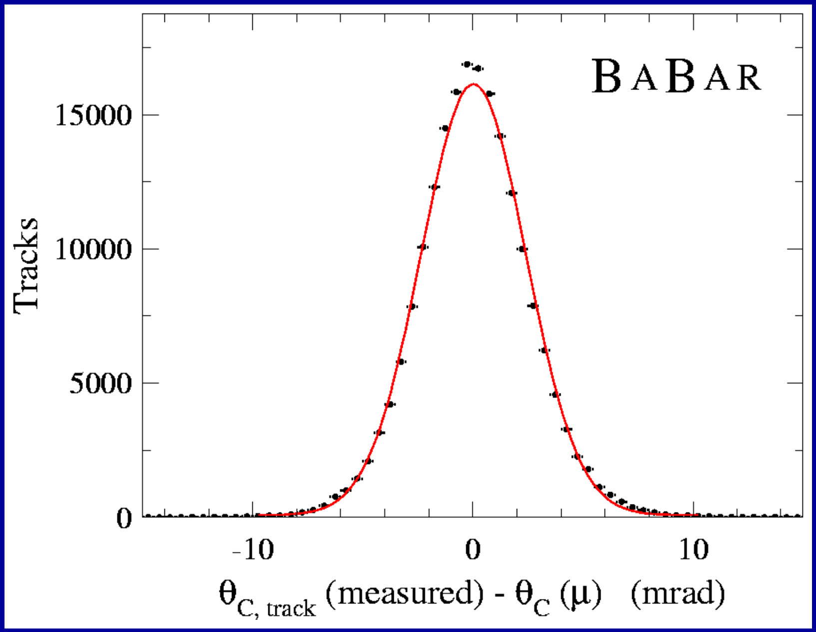
DIRC PERFORMANCE

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



Between 20 and 60 signal photons per track.

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



$\sigma(\Delta\theta_c) = 2.4$ mrad

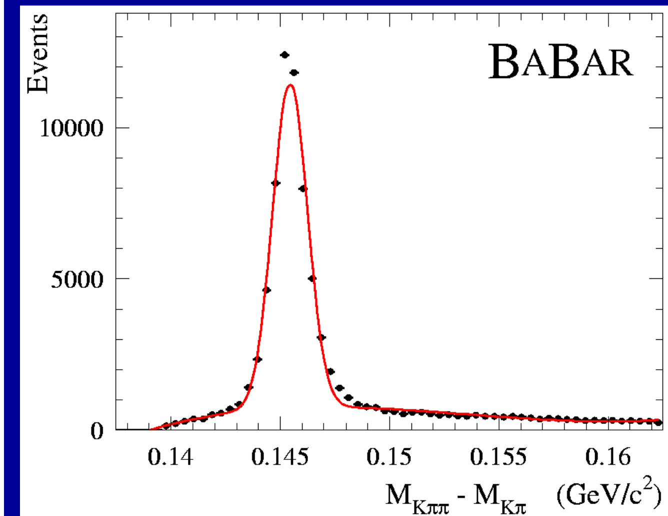
Very useful feature in BABAR environment:
higher momentum correlated with larger polar angle values
→ more signal photons, better resolution ($\sim 1/\sqrt{N}$)

Track Cherenkov angle resolution is within ~10% of design.

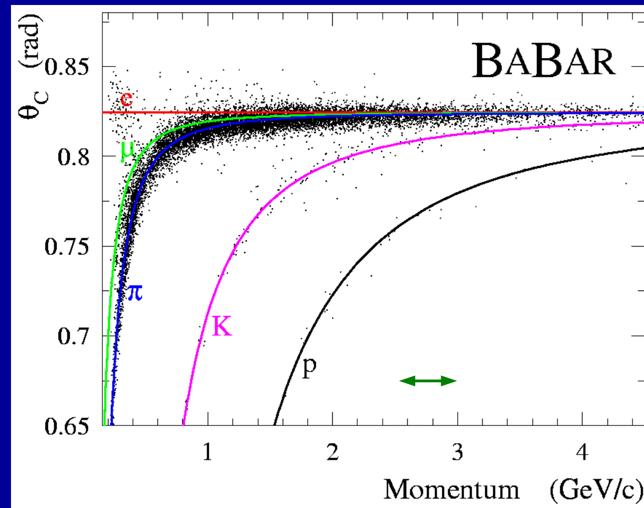
Should improve with advances in track- and DIRC-internal alignment.

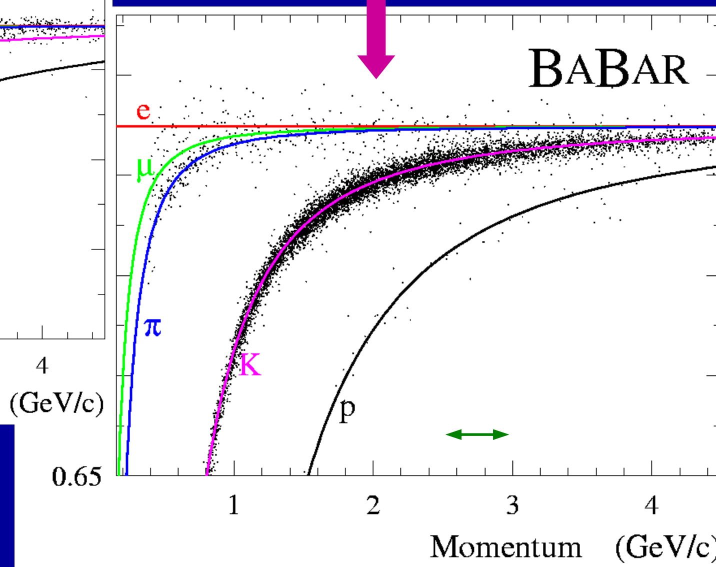
DIRC PERFORMANCE

$D^{*-} \rightarrow D^0 \pi^-$
$\quad \hookrightarrow K^- \pi^+$

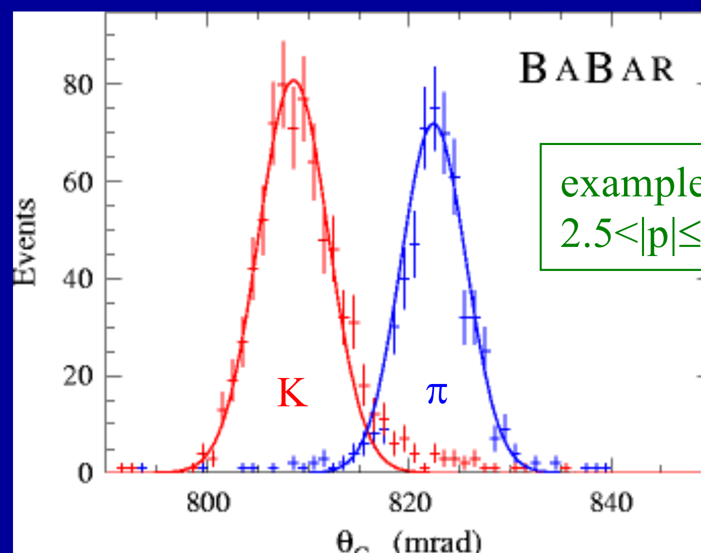


kinematically identified π and K



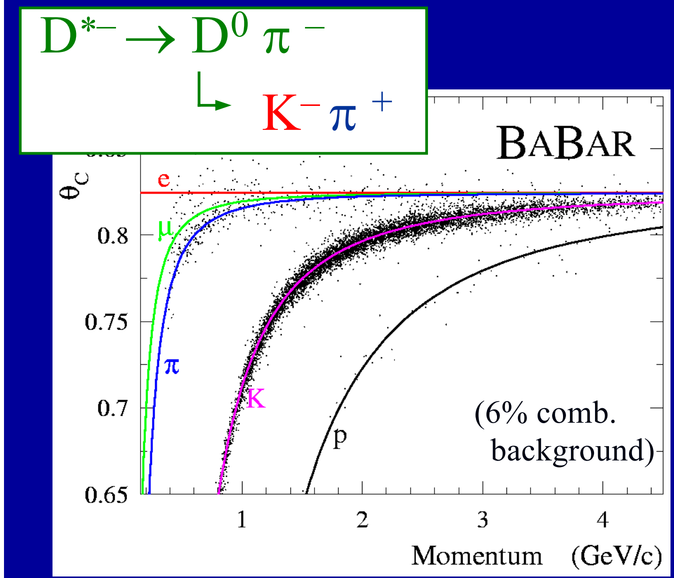


- Select D^0 candidate control sample with mass cut (±0.5 MeV/c^2)
- π and K are kinematically identified
- calculate selection efficiency and mis-id
- Correct for combinatorial background (avg. 6%) with sideband method.



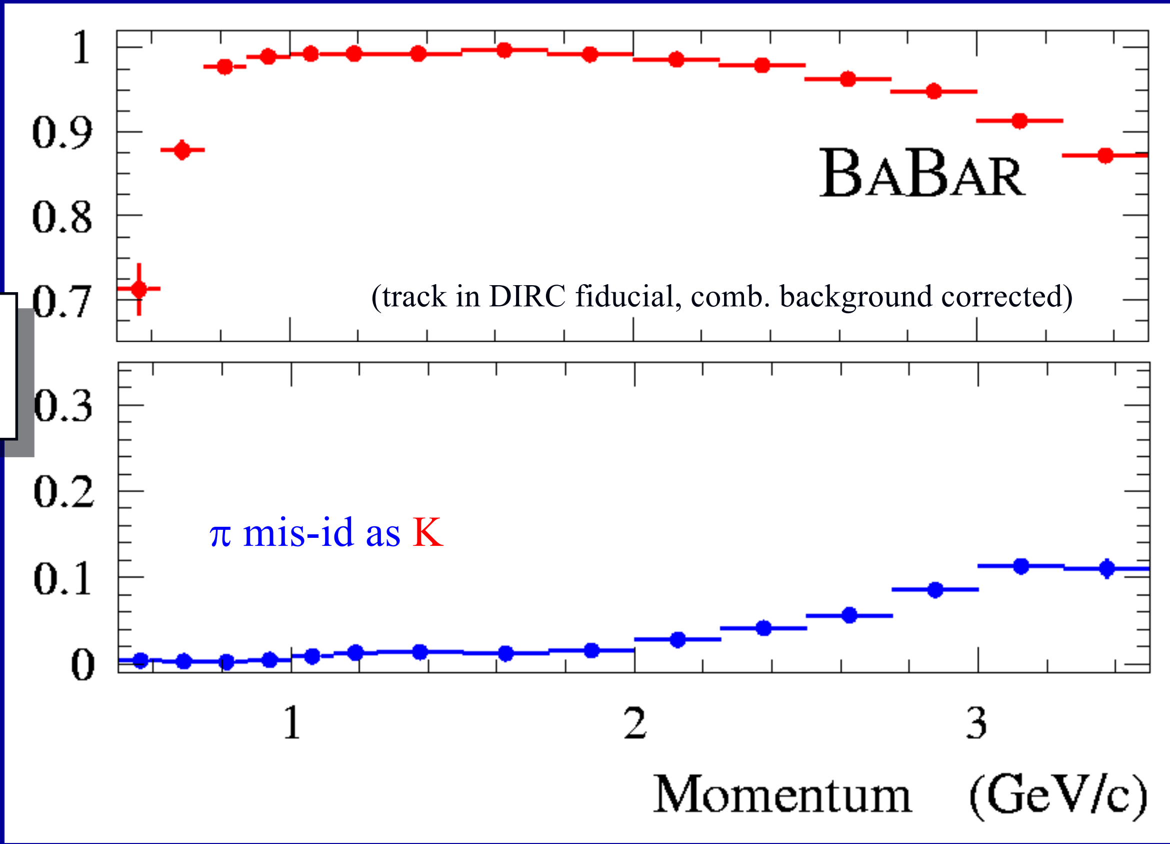
example:
2.5<|p|≤3GeV/c

DIRC PERFORMANCE



Kaon selection efficiency typically above 95% with mis-ID of 2-10% between 0.8-3GeV/c.

Kaon selection efficiency for $\mathcal{L}^K > \mathcal{L}^\pi$

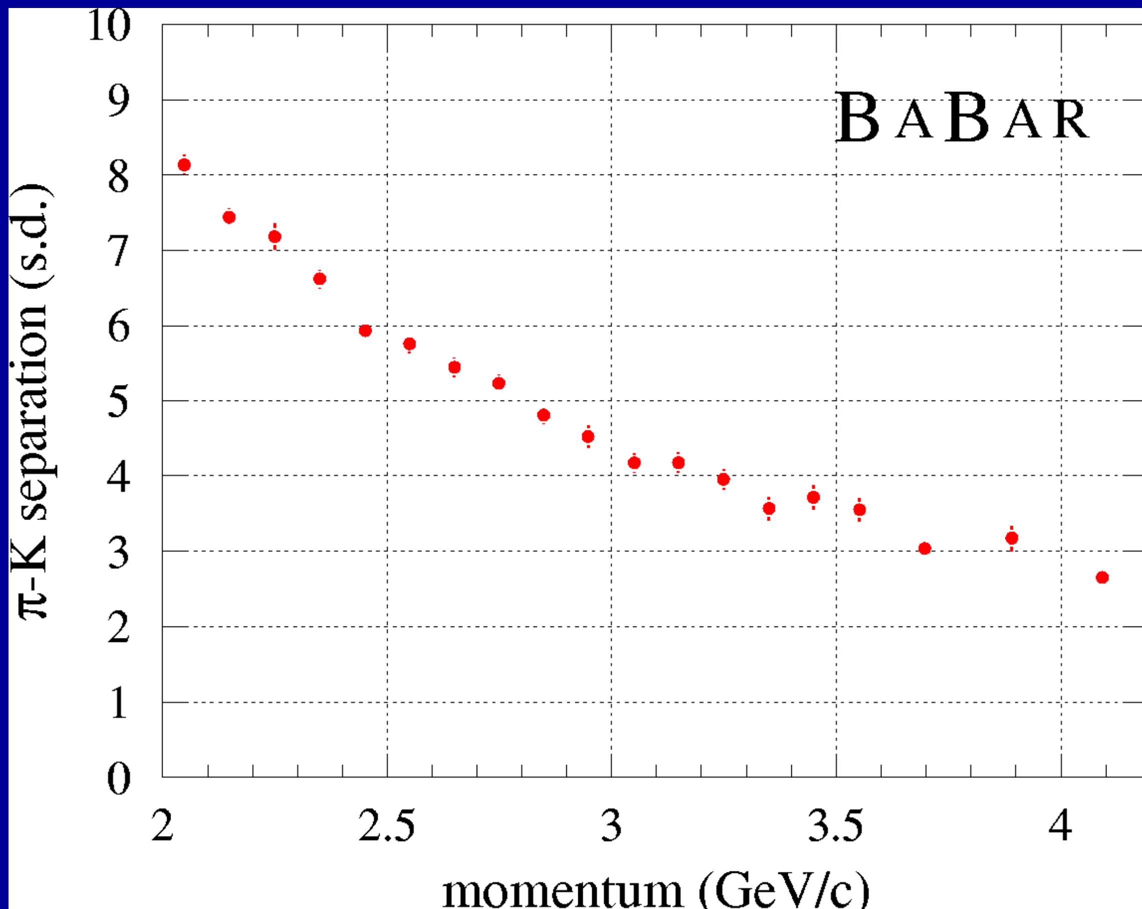


DIRC PERFORMANCE

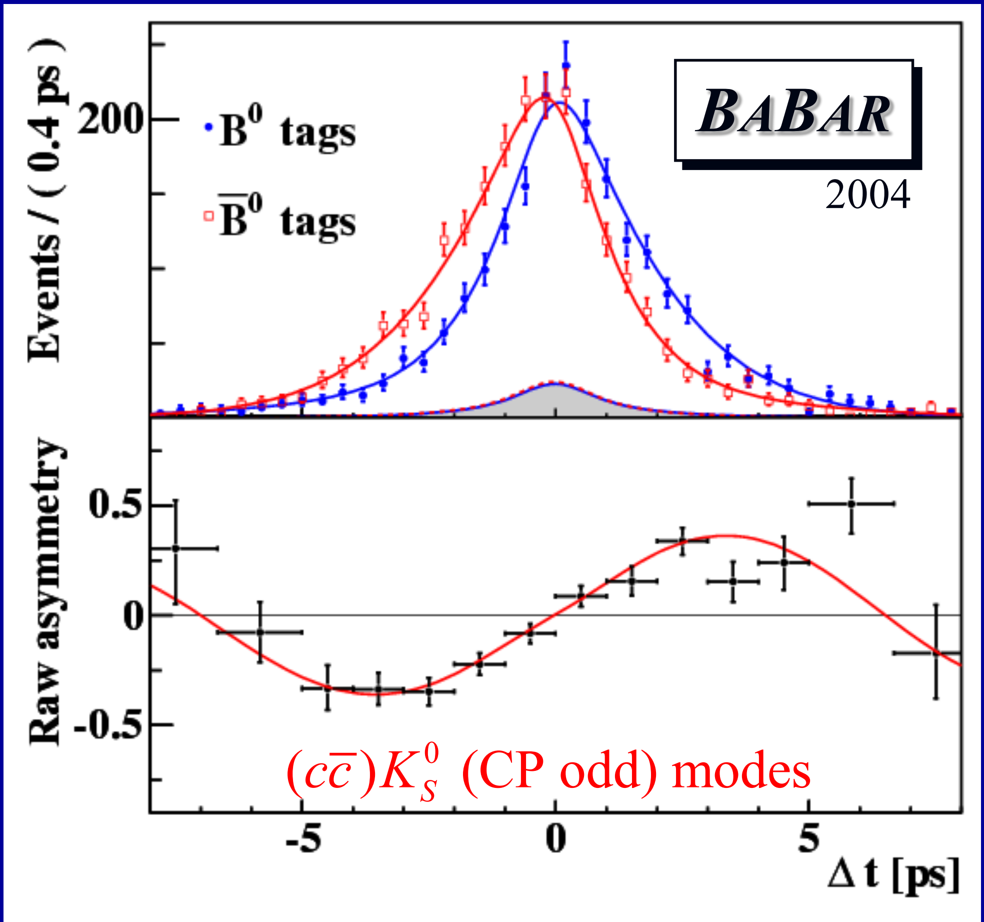
π/K separation power:

Measure Cherenkov angle resolution as function of track momentum for pions and kaons, kinematically identified in D* decays.

→ about 4.3σ separation at 3GeV/c, close to 3σ separation at 4GeV/c



DIRC PERFORMANCE



Kaon Tagging

for *sin*(2β) measurement:

- highest efficiency ε
- low mis-tag fraction *w*
- dominant contribution to measurement

Flavor tag	Efficiency	*w*	Q=ε(1-2*w*)^2
Lepton	9.1±0.2 %	3.3±0.6 %	7.9±0.3 %
Kaon I	16.7±0.2 %	10.0±0.7 %	10.7±0.4 %
Kaon II	19.8±0.3 %	20.9±0.8 %	6.7±0.4 %
Incl.	20.0±0.3 %	31.5±0.9 %	2.7±0.3 %
Total	65.6 ± 0.5 %		**28.1 ± 0.7 %**

Q: effective efficiency

$\sigma(\sin 2\beta) \propto 1/\sqrt{Q.N_{CP}}$

CONCLUSION

- 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.
- Eight+ years of experience in PEP-II/BABAR B-factory mode: DIRC very reliable, robust, easy to operate.
- After 8+ years no evidence of bar surface quality deterioration; 98% of channels fully functional to the end.
- Machine backgrounds up to 300 kHz/PMT at $12 \cdot 10^{33}/cm^2 \cdot s$ no problem for reconstruction due to good timing resolution.
- Lead shielding and new TDC chips, installed in 2002, kept DIRC working safely at four times design luminosity.
- 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.

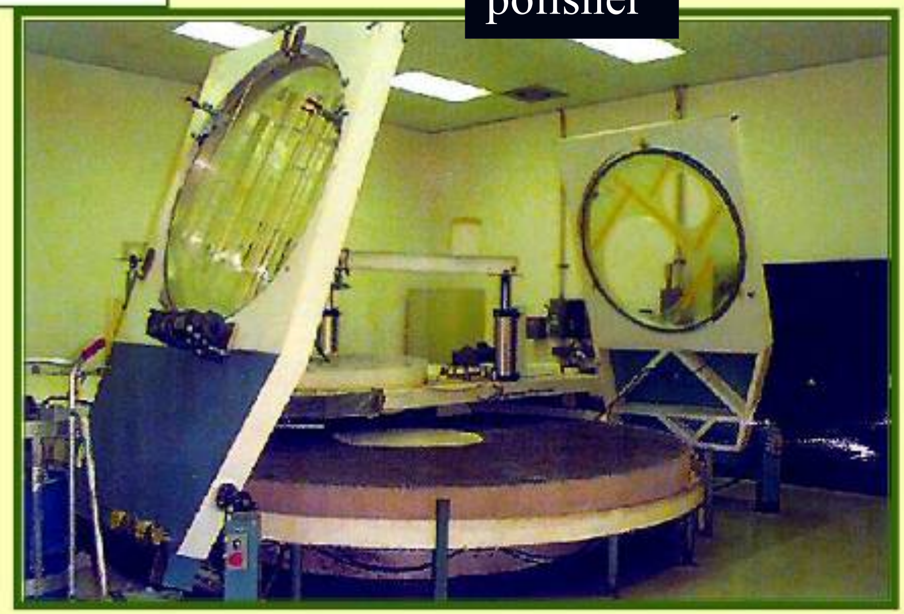
BACKUP SLIDES

overarm polisher

lapper

lapper

polisher



Boeing

Bar Production

Band saw

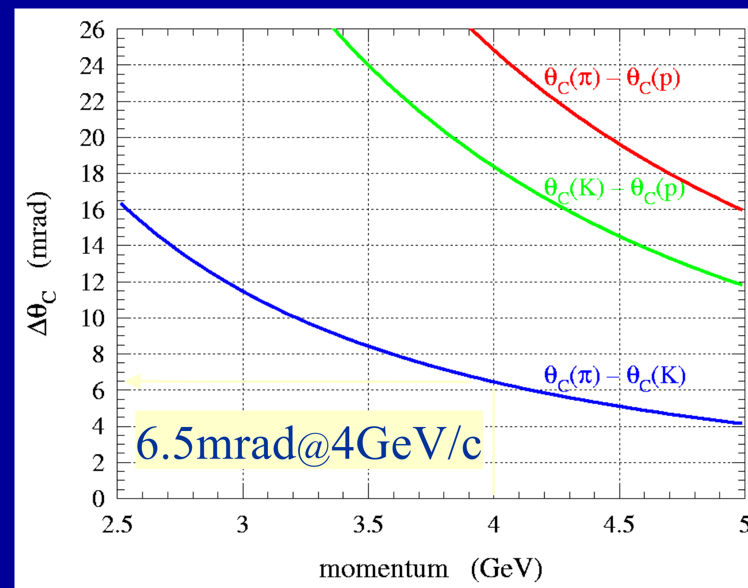
Bridgeport milling machine

Covering all B Decays at BABAR requires
Particle Identification (PID) up to 4.2 GeV/c momentum.

- $1.7 < |p| \lesssim 4.2$ GeV/c
  Pion/Kaon separation in rare charmless decays, e.g., $B \rightarrow \pi^+\pi^-$ / $B \rightarrow \pi^{\pm}K^{\mp}$
  (time dependent decay asymmetry measures sin2α)

- $|p| < 2$ GeV/c
  $B/\overline{B}$ flavor tagging with Kaons
  via $b \rightarrow c \rightarrow s$ cascade *(sin2β measurement)*

PID using dE/dx of the BABAR
Vertex Detector and Drift Chamber
is only effective for $|p| < 0.7$ GeV/c



Design Constraints:

- CsI Calorimeter needs to detect photons down to 20 MeV,
  thus small radiation length (<20%) and small radial size required.
- Radiation robustness (expect 10 krad within 10 year lifetime).
- π/K separation at 4 GeV/c: 6.5 mrad
  $\rightarrow$ 3σ separation requires 2.2 mrad resolution

DIRC Calibration Stability

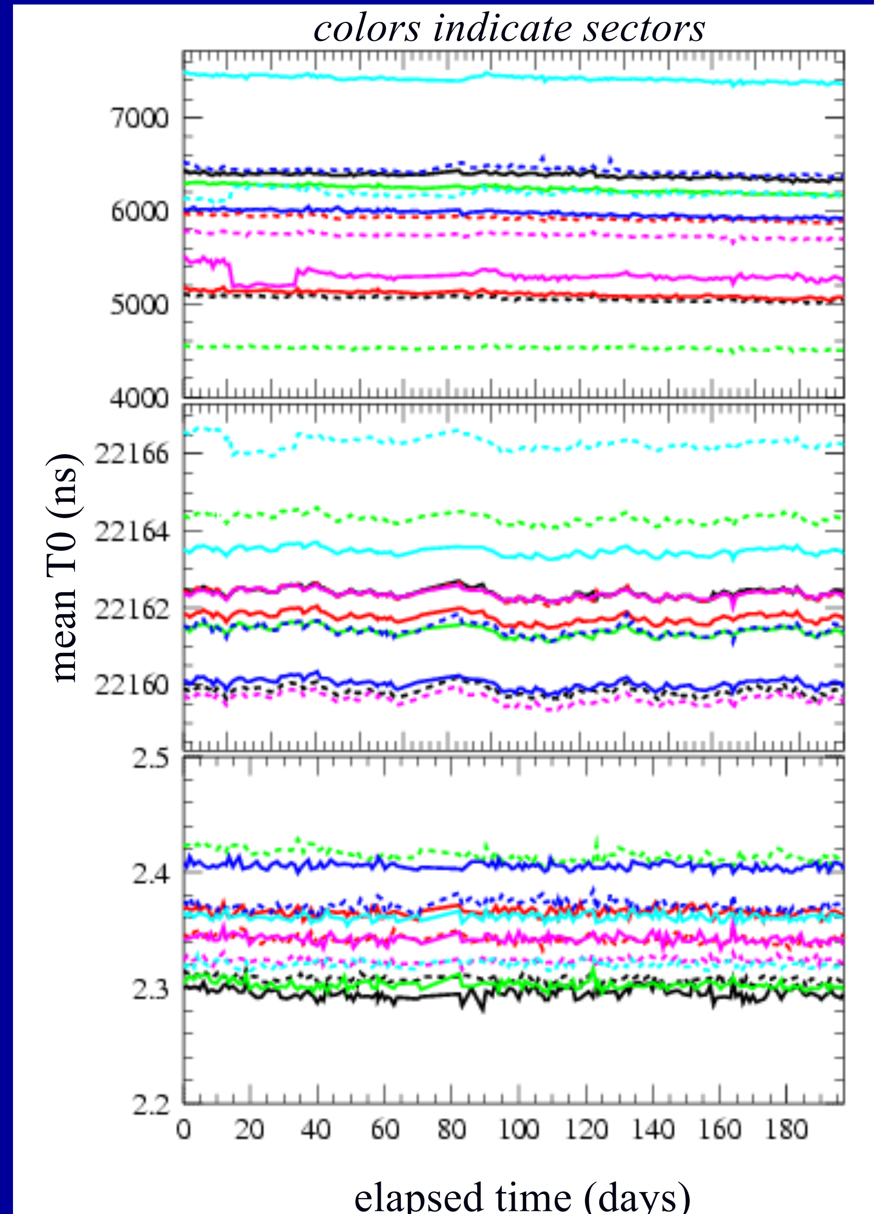
DIRC is Stable and Robust

- Calibration constants stable:
  typical rms of T0 per channel ~ 0.1ns
  (light pulser and data stream).

- Monitor humidity of nitrogen return line from bar box: dew points constant at -45... -55C, no leaks after installation.

- Water purification system keeps resistivity at 18.5MΩcm (input) and 9.5MΩcm (return).

- Water transmission in SOB remains stable at 98%/m (442nm, 325nm), 95%/m (266nm).



DIRC PERFORMANCE

Example for combination of DIRC likelihoods with drift chamber and vertex detector likelihoods

- Charged Hadron Spectra ($\pi^{\pm}$, $K^{\pm}$, $p/\bar{p}$) analysis.
- Cuts optimized to keep Mis-ID < 1-2% everywhere.
- In return, must accept somewhat lower ID efficiency especially at high momenta.