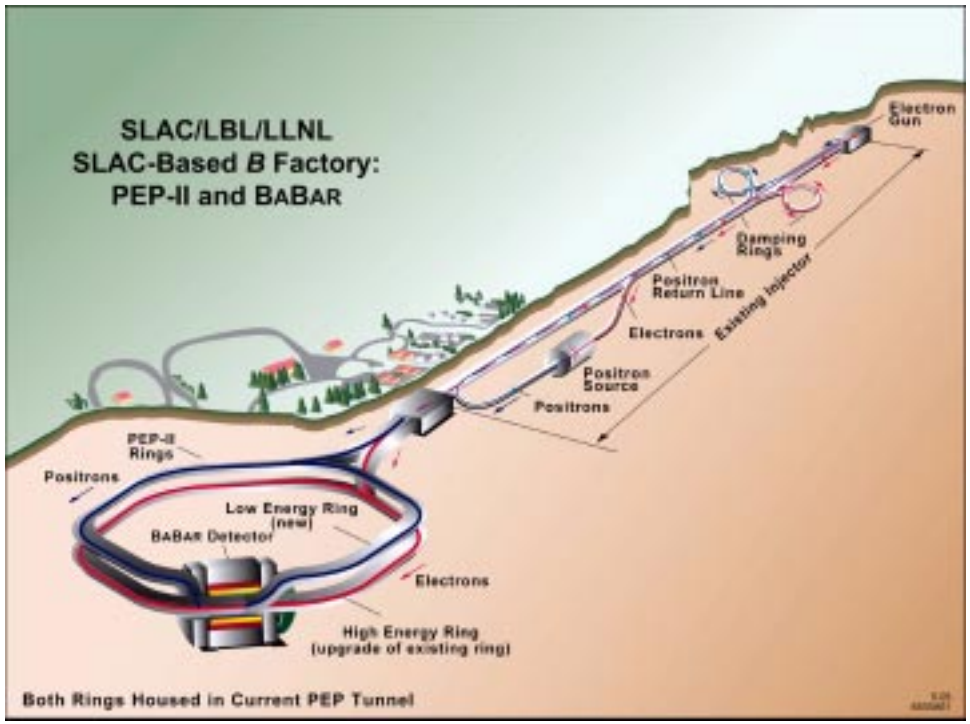
SLAC B Factory



Masahiro Morii

Stanford Linear Accelerator Center

Outline

Physics at SLAC B Factory

- Physics Motivation
- Experimental Challenge

PEP-II Storage Ring

- Design
- Construction
- Commissioning

BABAR Detector

- Subdetectors:
  SVT, DCH, DIRC, EMC, IFR
- Electronics, Trigger
- DAQ and Online Software
- Computing

Cosmic Ray Run

- Achievements

Detector Roll-On

- Progress

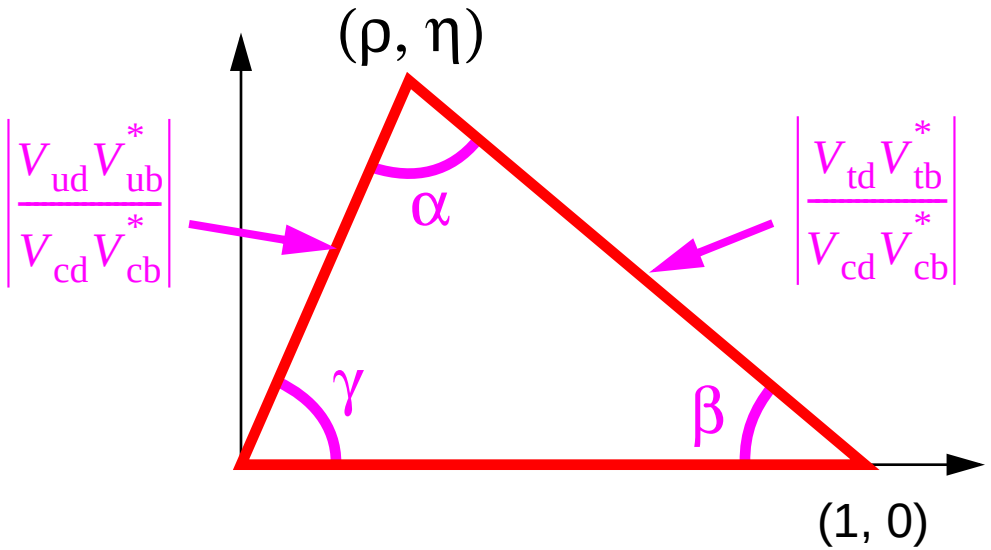
First Physics Run

- Schedule
- Background
- Physics Readiness

Conclusion

Physics at SLAC B Factory

Measure CP violation in the *B* system.



Over-constrain the Unitarity Triangle:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{sd}V_{sb}^* = 0$$

→ Can the Standard Model explain CP violation?

Why CP Violation?

CP violation exists.

- Observed in *K* decays, e.g. $\Gamma(K_L \to \pi^- l^+ \nu) \neq \Gamma(K_L \to \pi^+ l^- \bar{\nu})$.
- Origin of the matter-dominant universe.

The Standard Model can explain CP violation.

- Imaginary phase in the CKM matrix — Key ingredient of the SM.

But, is the SM the true answer? → Unknown yet.

Experimental constraints are weak.

- Observed only in the *K* system.
- Measurement in the *K* system difficult to interpret.
  - ➤ Small effects ($\varepsilon = 3\times10^{-3}$) and large hadronic uncertainties.
  - ➤ Theoretically clean signals, e.g. $K_L \to \pi^0 \nu\bar{\nu}$, hard to reach ($BR \sim 10^{-11}$).
- New KTeV result, $\varepsilon'/\varepsilon = (28.0\pm4.1)\times10^{-4}$, stretches the Standard Model.
- Baryogenesis suggests larger CP violation than the SM allows.

→ *B* system can shed new light.

CP Violation in the *B* System

Large CP violation expected.

- sin2β ~ 0.7 compared with $\varepsilon = 3\times10^{-3}$ for the *K* system.

Reachable branching ratios for theoretically clean modes.

- *BR* ~ 4×10^{-4} for the "Gold Plated Mode," $B^0 \to J/\psi K_S$.

With ~10^7 B^0's we can:

- Unmistakably detect CP violation.
- Measure sin2β with experimental error <0.2.
  (cf. CDF, sin2β = 0.79 + 0.41 - 0.44.)

→ Test if CP is violated as the Standard Model predicts.

With ~10^8 B^0's we can:

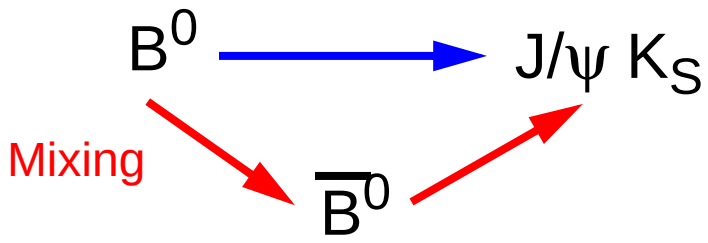
- Improve measurement accuracies.
- Measure more CKM parameters, using different decay modes.

→ Test internal consistencies of the Standard Model.

How CP is violated in the *B* System

Most easily accessible by experiments:

- Take advantage of the large B^0 -$\bar{B}^0$ mixing.
- Interference between "mixed" and "non-mixed" decay amplitudes.



Time-dependent asymmetry:

$$A_{CP}(t) = \frac{\Gamma(B^0(t) \to J/\psi K_S) - \Gamma(\bar{B}^0(t) \to J/\psi K_S)}{\Gamma(B^0(t) \to J/\psi K_S) + \Gamma(\bar{B}^0(t) \to J/\psi K_S)} = \sin 2\beta \cdot \sin \frac{\Delta m \cdot t}{\Gamma}$$

Detecting CP Violation

Time-dependent asymmetry requires:

- Measurement of decay time.
- Determination of the original flavor (B^0 or anti-B^0).

Asymmetric e^+e^- collider running at $E_{CM} = m(\Upsilon_{4S})$.

- Coherent production of $e^+e^- \to \Upsilon_{4S} \to B^0\bar{B}^0$.
- Boost turns decay time into flight length in z.
- Kinematical constraint from the beam energy.
- Good S/N ratio: $\sigma(ee \to bb) = 1.05nb$, $\sigma(ee \to qq) = 3.39nb$.

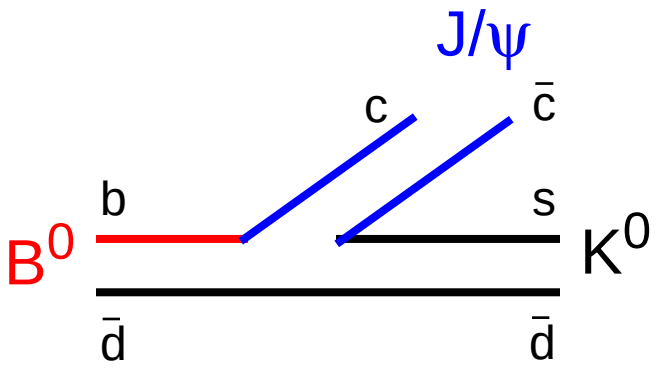
Experiment must measure:

- Flavor of "the other" B at decay.
  - ➤ Semileptonic decays — Lepton charge.
  - ➤ Hadronic decays — K from the $b \to c \to s$ chain.
- Difference between the flight lengths of two B's.
  - ➤ Vertex reconstruction.

Gold-Plated Mode: $B^0 \to J/\psi\, K_S$

Measures sin2β cleanly.

- Dominated by single amplitude → Theoretically clean.



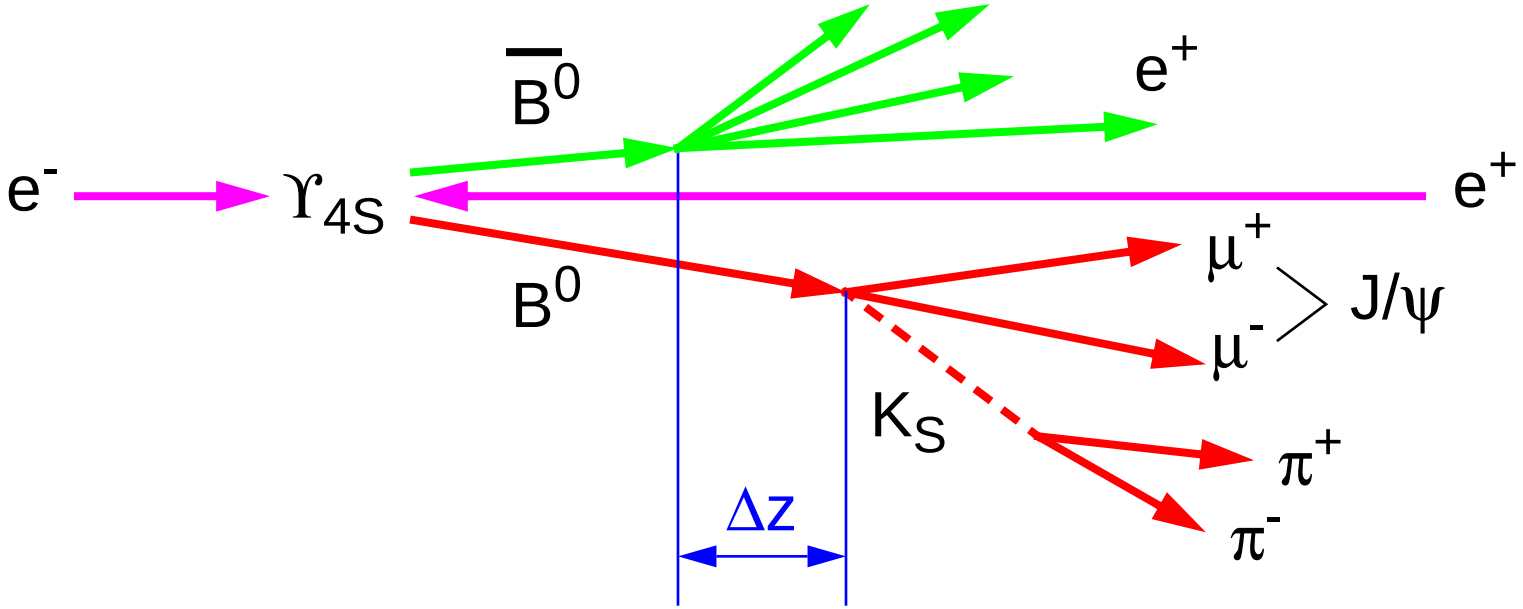
- Event signature is easy to select → Experimentally clean.

Useful branching ratio ~ 5 x 10^{-5}

- $BR(B^0 \to J/\psi\, K_S) = 4 \times 10^{-4}$, $BR(J/\psi \to l^+ l^-) = 12\%$.
- Efficiency ~ 60% for the $\pi^+\pi^-$ mode.

→ Expect $\Delta(\sin 2\beta) \sim 0.12$ from 30 fb^{-1} (= 1 year).

Event Signature: $B^0 \to J/\psi\, K_S$



Three steps to observe CP asymmetry:

- Reconstruct one B^0 from J/ψ and K_S.
- Distance between two vertices → Difference between decay times.
- Flavor of the other B^0 must be *tagged*.

Experimental Challenge

High statistics

- High luminosity beam with tolerable background.
- Fast and radiation-hard detector.

Exclusive reconstruction

- Good solid angle coverage and efficiency.
- Mass resolution $\rightarrow$ Dominated by multiple scattering.

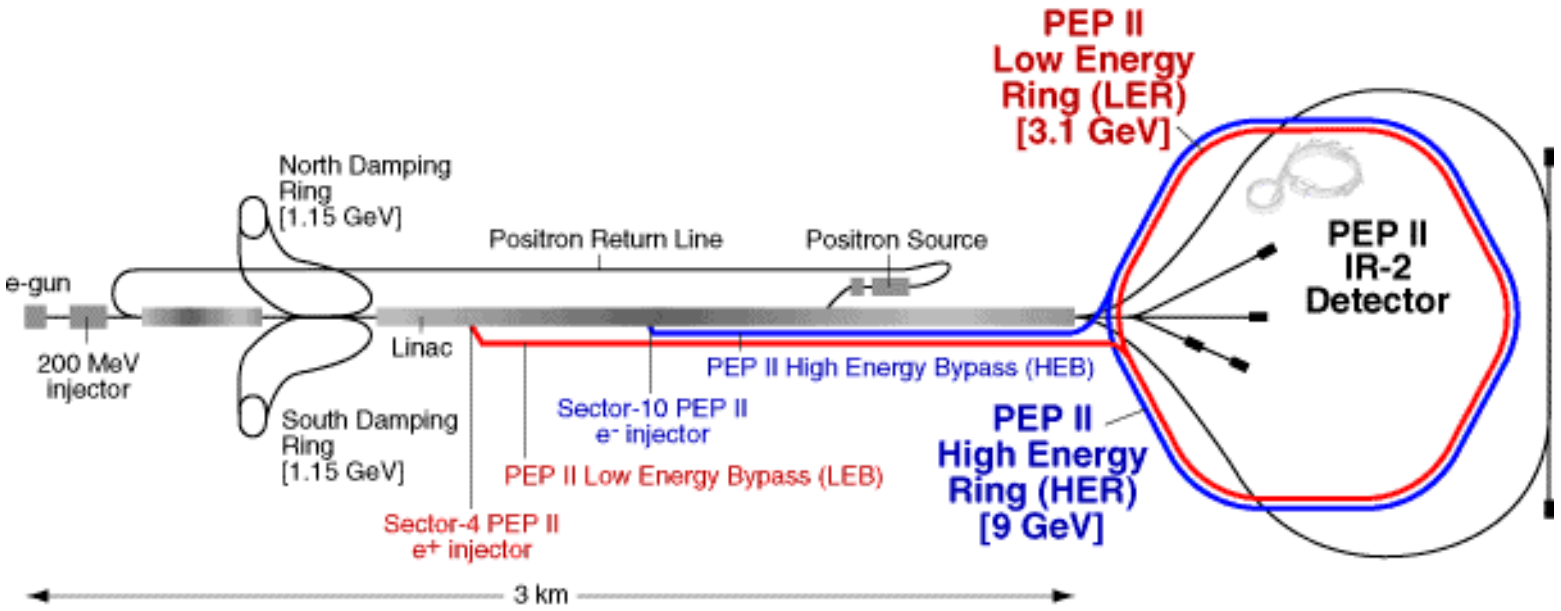
Vertex reconstruction

- High-resolution, wide-coverage vertex detector.

Flavor tagging

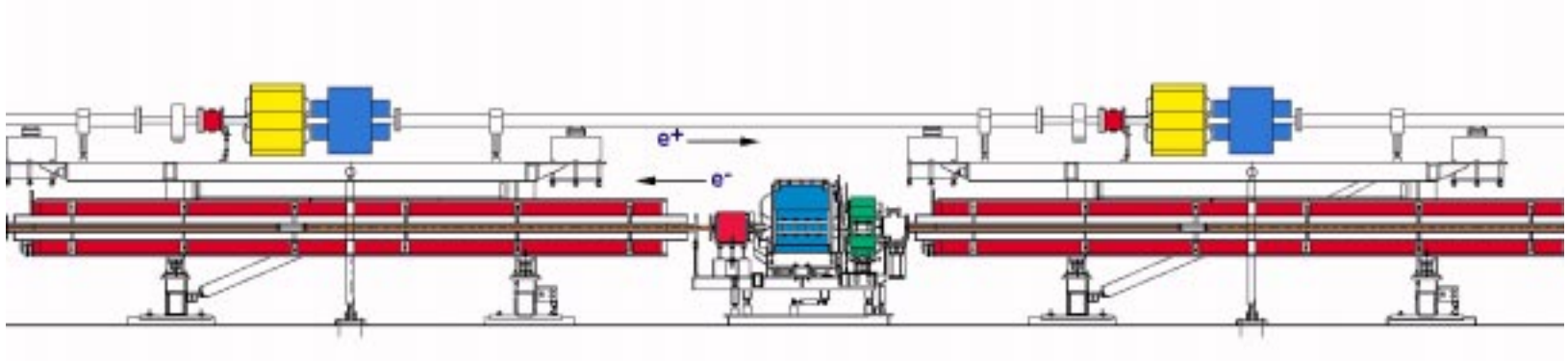
- Particle ID:
  - DIRC and dE/dx (for K/π).
  - Electromagnetic calorimeter (for e).
  - Instrumented flux return (for μ, K_L).

PEP-II Storage Ring



- 9GeV e^- x 3.1GeV e^+. $\beta\gamma = 0.56$.
- Design luminosity $3\times10^{33}cm^{-2}s^{-1}$ to produce 1.5×10^{7} $B^0\bar{B}^0$/year.
- Two rings stacked in the PEP tunnel.
  - ➤ High Energy Ring: Refurbished PEP.
  - ➤ Low Energy Ring: Newly built on top of HER.
- SLC used as the injector. Extract beams at nominal energies.
  - ➤ Low emittance allows efficient injection.

PEP-II Construction



High Energy Ring (HER)

- Stores up to 1A of 9GeV e^- in 1658 bunches.
- Completed in 1997. Commissioning since May 1997.

Low Energy Ring (LER)

- Stores up to 2A of 3.1GeV e^+ in 1658 bunches.
- Completed in 1998. Commissioning since July 1998.

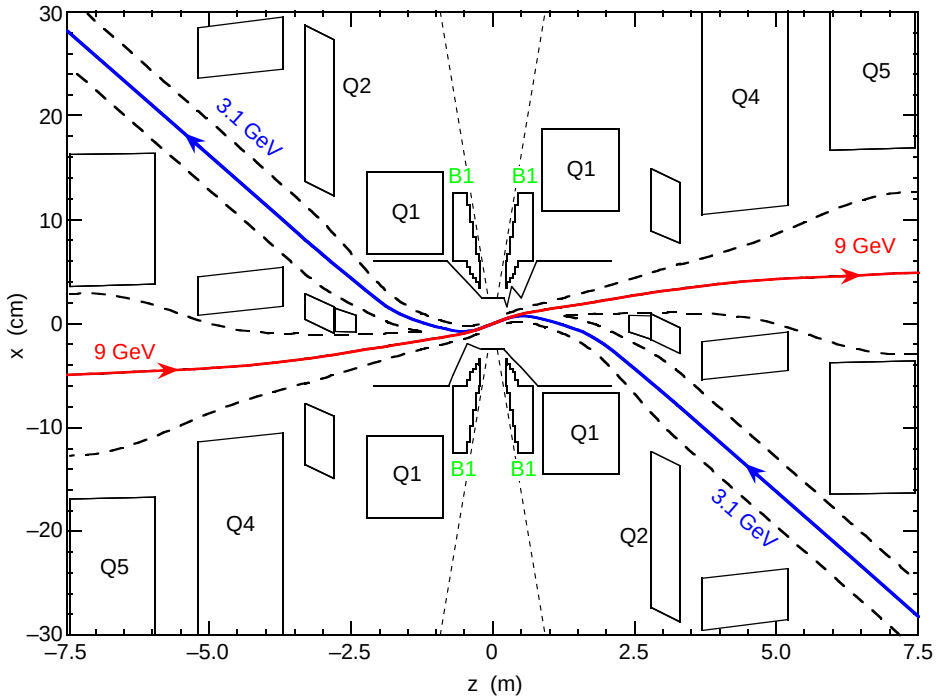
Injector

- Extracts beams from the SLC linac $\rightarrow$ PEP-II.
- Fills PEP-II in 6 min. every 4 hours. Top-off in 3 min. every hour.

Interaction Region

PEP-II has chosen head-on collision.

- Dipole magnets (B1) near the IP separate the beams to avoid parasitic collisions.



Pros:

- Well-established design.
- Avoid the risk of synchro-betatron resonances.

Cons:

- B1's cut into the detector volume.
- Synchrotron radiation from B1 becomes a concern.

Make it easy for PEP-II, tough for BABAR.

- Accelerator performance is the key for success.
- Technology (rad-hard, high-density, high-speed electronics) available.

PEP-II Commissioning

May 1997 → February 1999.

	Feb. '99 Goal	Achieved	Design
No. of bunches	830	1658	1658
Luminosity	$3x10^{32}$	$5.2x10^{32}$	$3x10^{33}$
LER current	1100 mA	1171 mA	2140 mA
HER current	500 mA	750 mA	995 mA
Beam size x		~150 μm	157 μm
Bean size y		8.6 μm	6.8 μm
LER lifetime	1 h at 1A	40 min. at 1A	4 h at 2A
HER lifetime		3 h at 0.5A	4 h at 1A

- Established stable collision and efficient (~100% at 10Hz, 2mA/s) filling.
- Averaged luminosity over 72 hours ~ $2x10^{32}$.
- Integrated current 153 Ah in LER, 115 Ah in HER.
- LER vacuum suffered from a leak in one arc, but recovered.

Beam Background

IR was instrumented with commissioning detectors.

- PIN diodes, RadFETs, X-ray spectrometer.
- Mini-TPC, Straw chamber, Water Cerenkov, Lead-glass.
- SVT module, CsI ring, IFR prototype.

Measured background higher than TDR by x15-20.

- Dominated by lost particles (*not* synchrotron radiation near IP).
- Entire ring contributes (*not* only IR neighborhood).
- Improved with vacuum (TSP activation and scrubbing).
- Dynamic pressure and detector response measured.

Understood (i.e. simulated) within x1.5-2.0.

Still a lot to do and learn in summer.

- Further scrubbing. (Can BABAR survive the dose?)
- Collimators: LER in S4 (fixed), HER in S2 (May 99), LER in S2 (Oct. 99).
- Beam steering optimization near IP.

BABAR Detector

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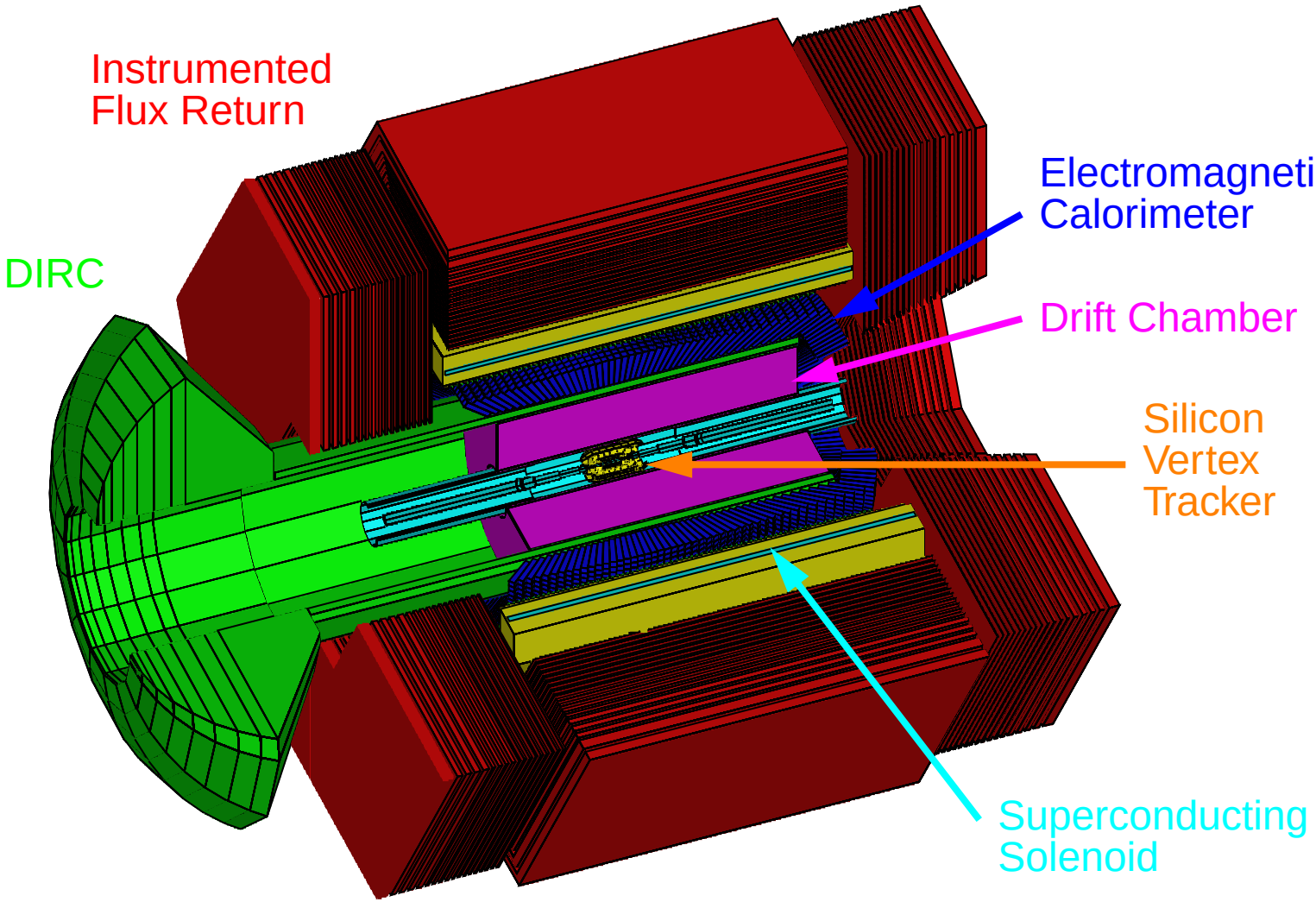
BABAR Collaboration

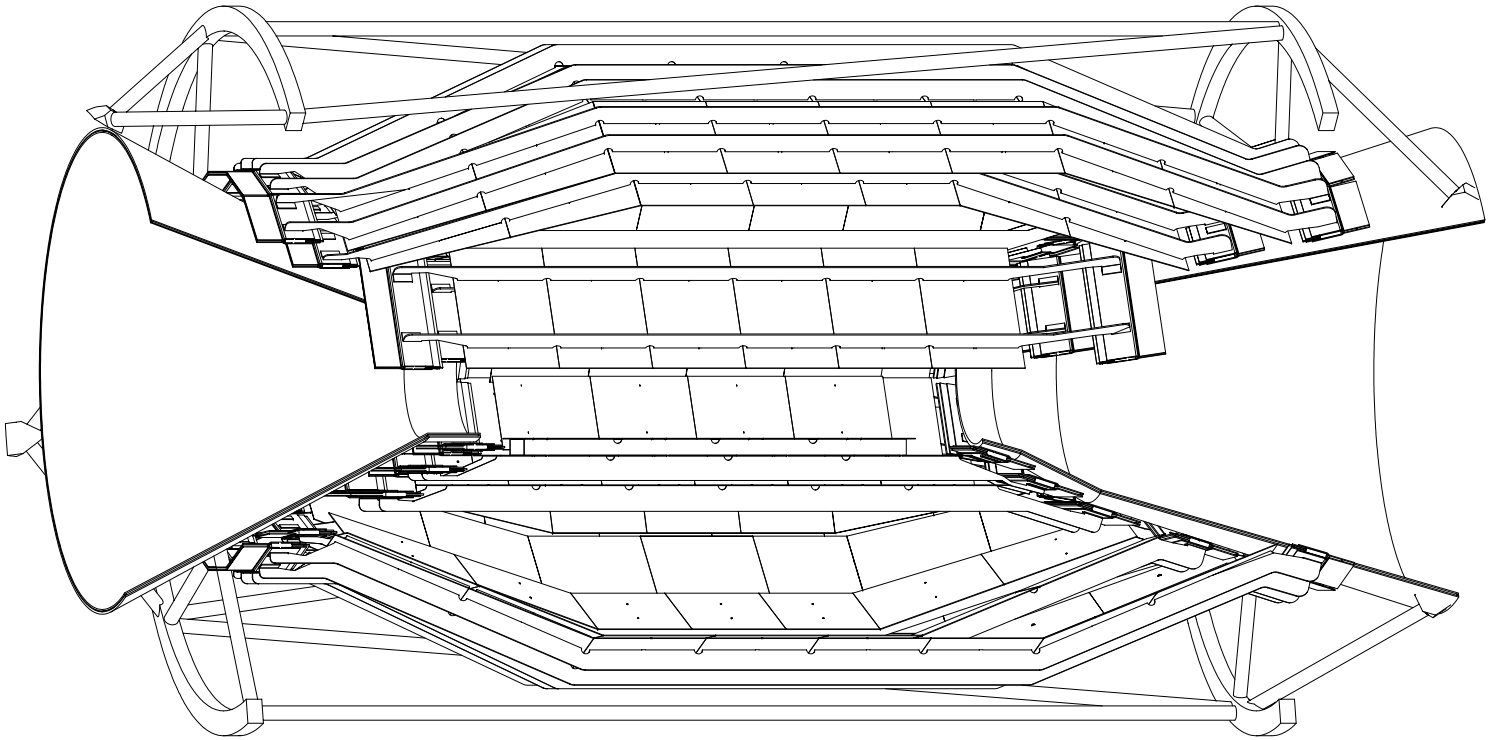
Brunel Univ.
Budker Inst., Novosibirsk
California Inst. Tech.
Carleton Univ.
Colorado State Univ.
Ecole Polytechnique
Florida A & M Univ.
IHEP, Beijing
INFN, Lab. Nazionali di Frascati
INFN, Bari
INFN, Ferrara
INFN, Genova
INFN, Milano
INFN, Napoli
INFN, Padova
INFN, Pavia
INFN, Pisa
INFN, Roma & Univ. “La Sapienza”
INFN, Torino
INFN, Trieste
Imperial College
Iowa State Univ.
LAL, Orsay
LAPP, Annecy
LBNL
LLNL
Massachusetts Inst. Tech.
McGill Univ.
Mount Holyoke College
Northern Kentucky Univ.
ORNL
Prairie View A & M Univ.
Princeton Univ.
Queen Mary & Westfield College
Royal Holloway, U. of London
Ruhr Univ. Bochum
Rutgers Univ.
Rutherford Appleton Lab.
SLAC
Saclay
Stanford University
TRIUMF
Tech. Univ. Dresden
UC, Irvine
UC, Los Angeles
UC, San Diego
UC, Santa Barbara
UC, Santa Cruz
U. Paris VI et VII
U. of Bergen
U. of Birmingham
U. of Bristol
U. of British Columbia
U. of Cincinnati
U. of Colorado
U. of Edinburgh
U. of Iowa
U. of Liverpool
U. of Louisville
U. of Manchester
U. of Maryland
U. of Mass., Amherst
U. of Mississippi
U. of Montreal
U. of Notre Dame
U. of Pennsylvania
U. of Tennessee, Knoxville
U. of South Carolina
U. of Texas, Dallas
U. of Victoria
U. of Wisconsin, Madison
Vanderbilt

→ 72 Institutions, 652 members from 9 countries.

Detector Subsystems



Silicon Vertex Tracker (SVT)



- 5-layer double-sided Si detector — 0.94 m^2 of wafers.
- 143k channels read out by custom CMOS ICs.
- Radiation-hard up to 2 Mrad.
- Target resolution $\sigma_{xy} = \sigma_z = [50/p_t\ (\mathrm{GeV}) \oplus 15]\ \mu\mathrm{m}$.

SVT Design

Mechanical design

- 5 layers between r = 3.3 cm and 14.4 cm. Layers 4 and 5 “arched.”
- CFRP support structure clam-shells on the B1 magnets.

Silicon wafers

- 300 μm-thick, double-sided silicon.
- Readout pitch 50 to 210 μm.

Readout electronics — AToM IC (LBNL, INFN-Pavia, UCSC)

- 128-ch readout IC using 0.8 μm radiation-hard CMOS process.
- Contains amplifier, shaper, discriminator, latency buffer, sparsification, serial readout and control logic.
- Time-over-threshold information for signal amplitude.

SVT Status

Completed in January 1999.

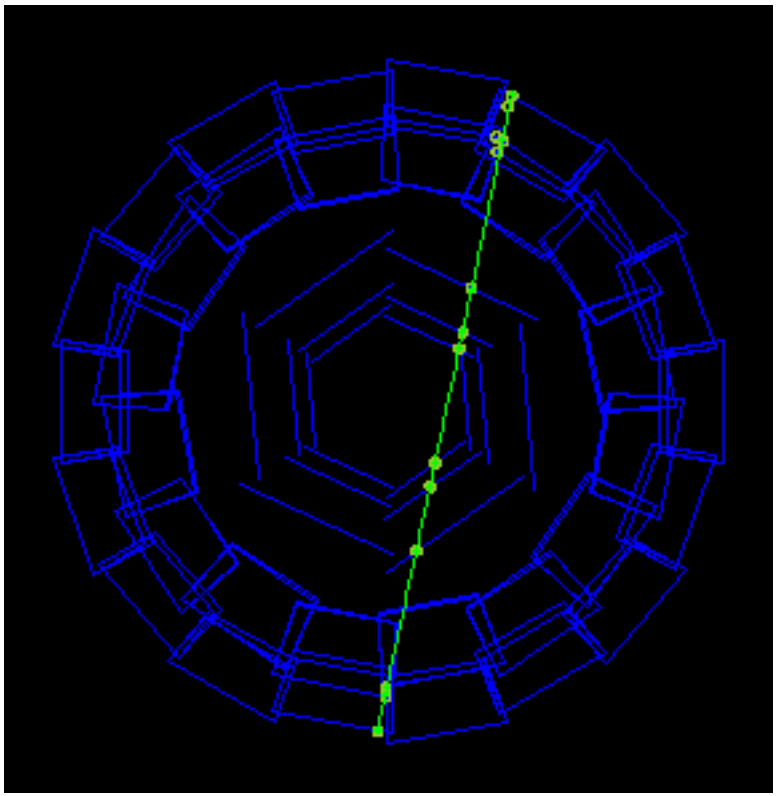
- Delay due to wafer production and AToM chip problems.
- All problems solved.
- Final assembly and survey in LBNL.

Cosmic-ray test in February.

- 98% hit efficiency at 0.2% noise occupancy.

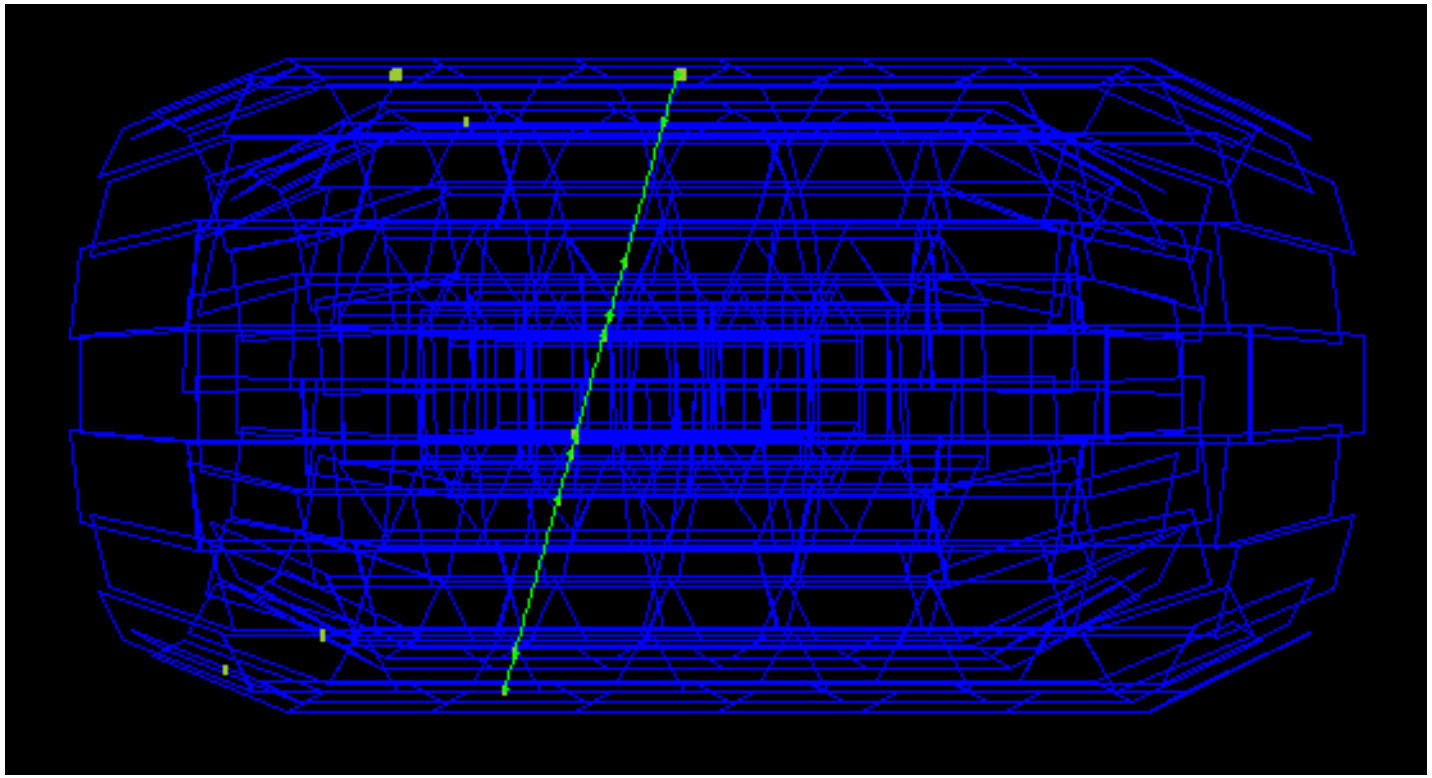
Arrived SLAC in March 1999.

- Installation on the beampipe completed.



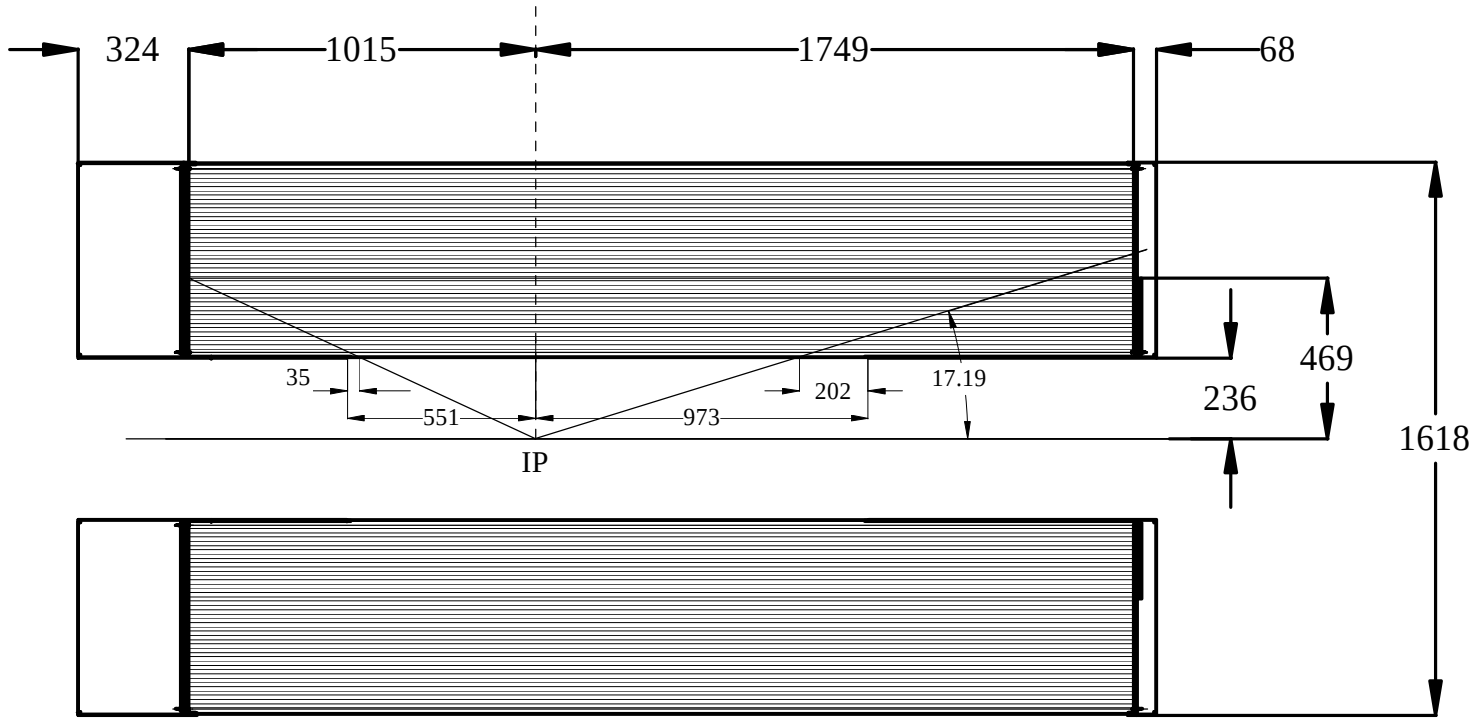
$\rightarrow$ Waiting to be installed in BABAR.

SVT Event



- Hits on all 5 layers. Very few noise hits.

Drift Chamber (DCH)



- Minimize material, esp. in the forward direction.
- 12mm/24mm Al end-plates. Be inner cylinder. CFRP outer cylinder.
- He-iC_4H_{10} (80:20) as the drift gas.
- Target resolution $\sigma p_t/p_t$ = [0.21 + 0.14 p_t (GeV)]%.

DCH Design

Wire layout

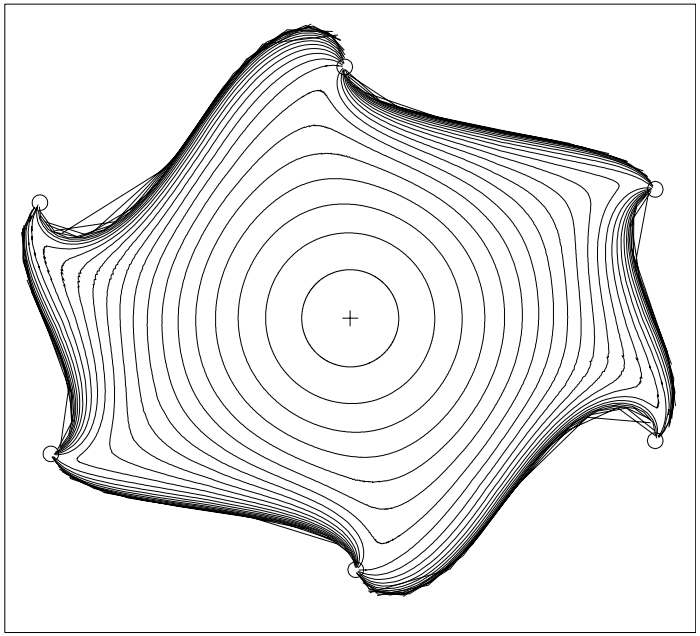
- 7104 hexagonal cells in 40 layers.
- 10 axial and stereo superlayers.

Construction

- Al end-plates supported by Be inner and CFRP outer cylinders.
- Wires held by crimping feedthroughs.

Electronics (SLAC/LBNL/UCSC)

- 4-ch amplifier/shaper/discriminator IC.
- 8-ch TDC/FADC IC. Built-in 12μs latency and 4 event buffers.
- Packaged in Al boxes plugged on to the rear end-plate.
- Output sent via optical fibers.



+ Sense, 20μm Au-W

❍ Field, 120μm Au-Al

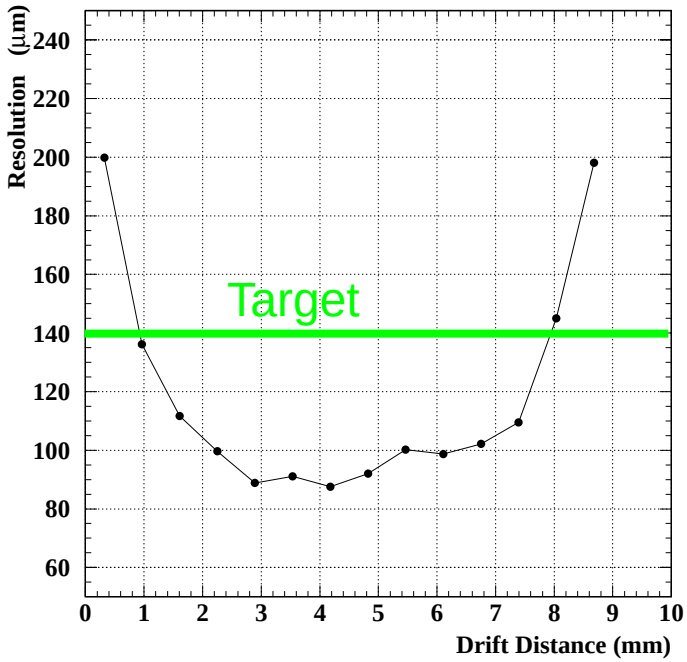
DCH Status

Construction and stringing in TRIUMF.

- Stringing finished in 4 months.
- Delivered to SLAC in March 1998.

First cosmic-ray recorded in August 1998.

- Spatial resolution 130 μm (target value: 140 μm) achieved.
- dE/dx resolution 6.8% (target value: 7%) for 40 hits.



Installed in BABAR in September 1998.

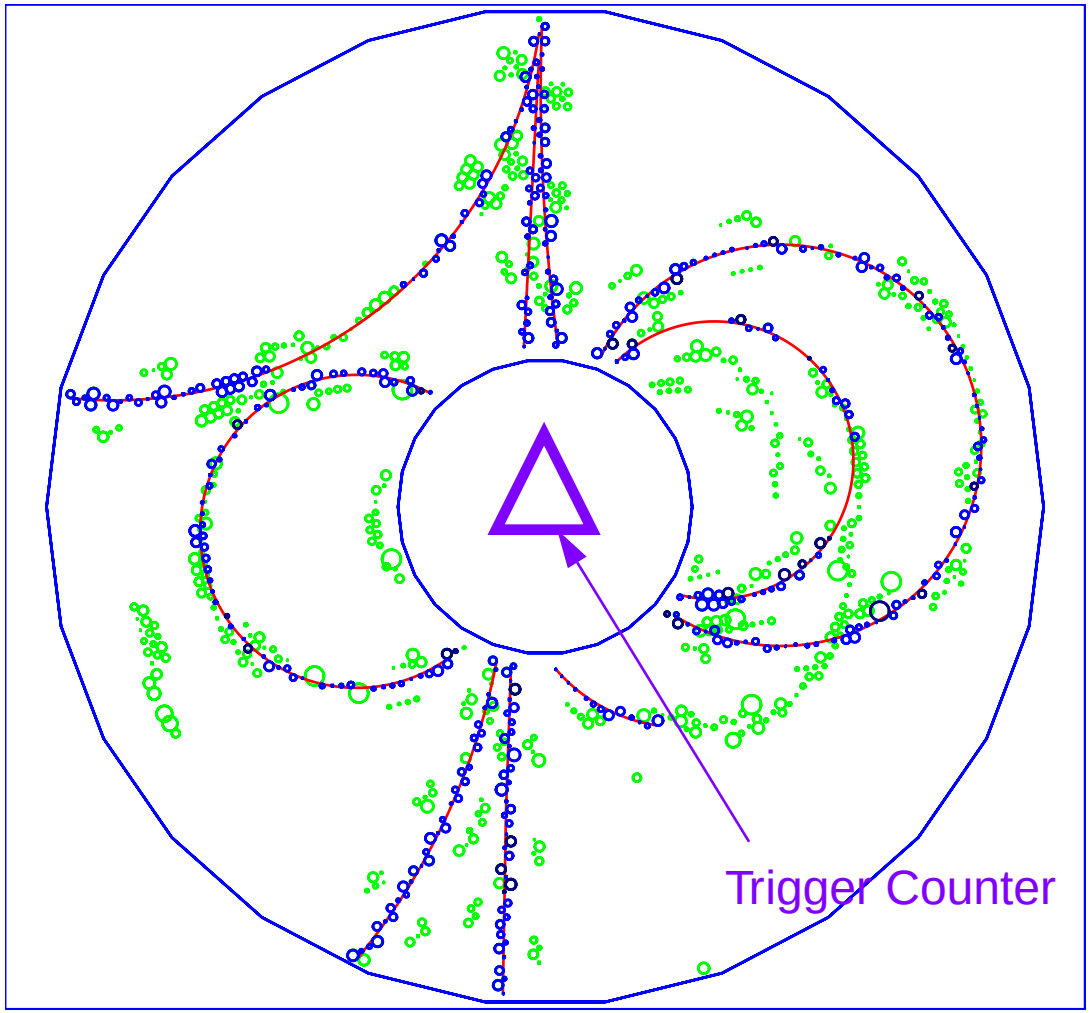
- Stable operation throughout the cosmic run (Oct.1998 → Jan. 1999).

→ Ready for data taking since October 1998.

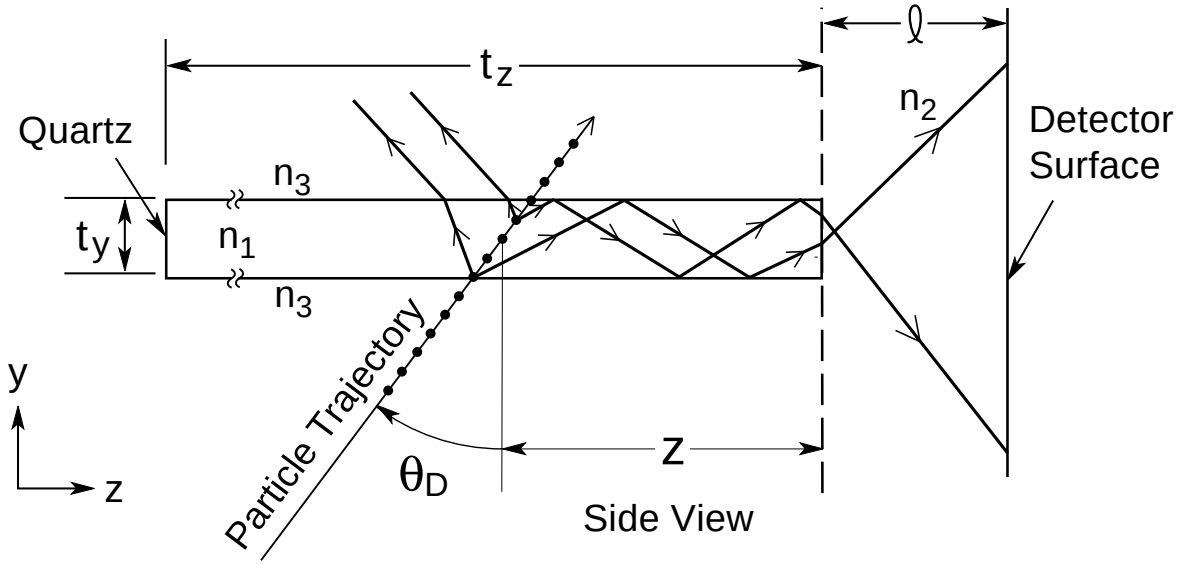
DCH Event

Cosmic ray event

- Offline event display.
- Showered in the calo-rimeter and the trigger counter.
- Tracking software picked up most of the “loopers” successfully.
- Blue circles = Hits on tracks.
- Green circles = Noise, crosstalk, missed hits.



Particle ID (DIRC)



Measure Cerenkov angle in quartz.

- Light transmitted by internal reflection, preserving the angle.
- Detection by 1-1/8" PMTs. 120cm from the end of quartz bars.
- Location of PMT hits $\rightarrow$ Light exit angle $\rightarrow$ Cerenkov angle.
- Parallelism and surface of quartz bars are crucial.
- Target K/π separation >4σ within B-decay kinematic limits (<4GeV).

DIRC Design

Quartz bars

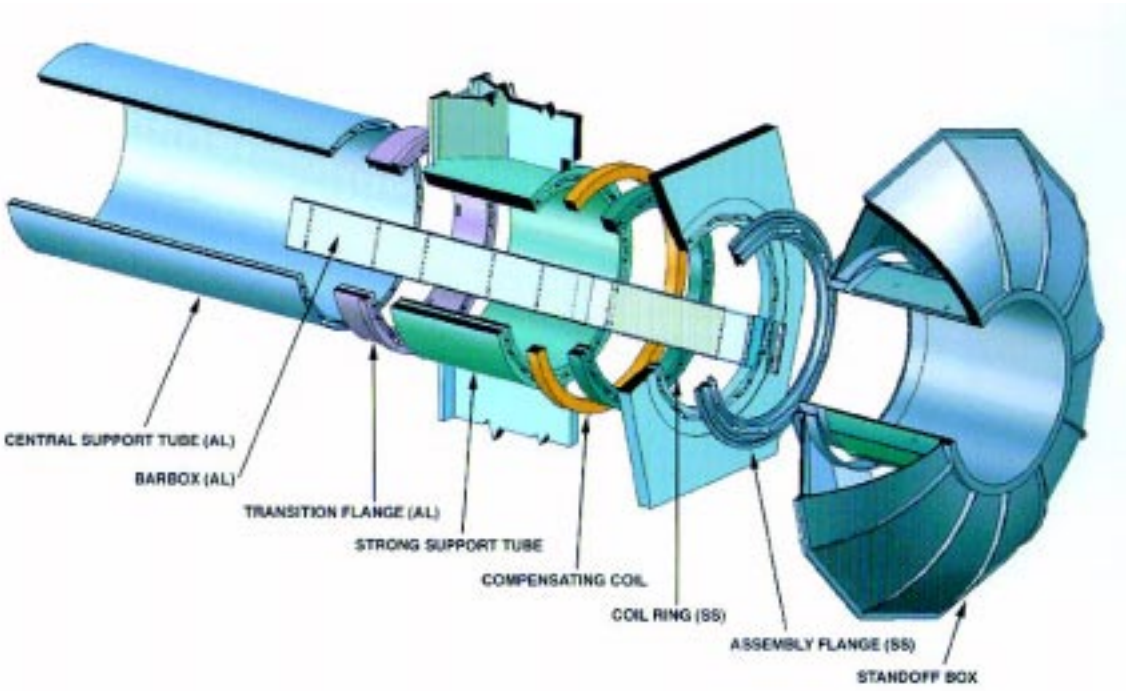
- 1.7cm x 3.5cm x 490cm. Made by gluing 4 short bars.

Bar boxes

- 12 boxes containing 12 quartz bars each.

Stand-Off Box

- Holds 10752 PMTs.
- Protected by magnetic shield.



Electronics

- 8-ch amplifier/shaper/discriminator IC.
- 16-ch digital TDC IC.
- Housed in 12 front-end crates mounted around the SOB.

DIRC Status

Mechanical structure + PMTs complete.

- Installed in BABAR in August 1998.

Electronics and DAQ complete.

- Installed and tested during the cosmic-ray run.

Quartz bars delayed due to production problems.

- Only 1 out of 12 bar-boxes installed before cosmic-ray run in 1998.

4 bottom bar boxes (1/3) are installed in March 1999.

- Must be installed before BABAR is integrated with PEP-II.
- 3 completed. 4th box will be installed on March 30.

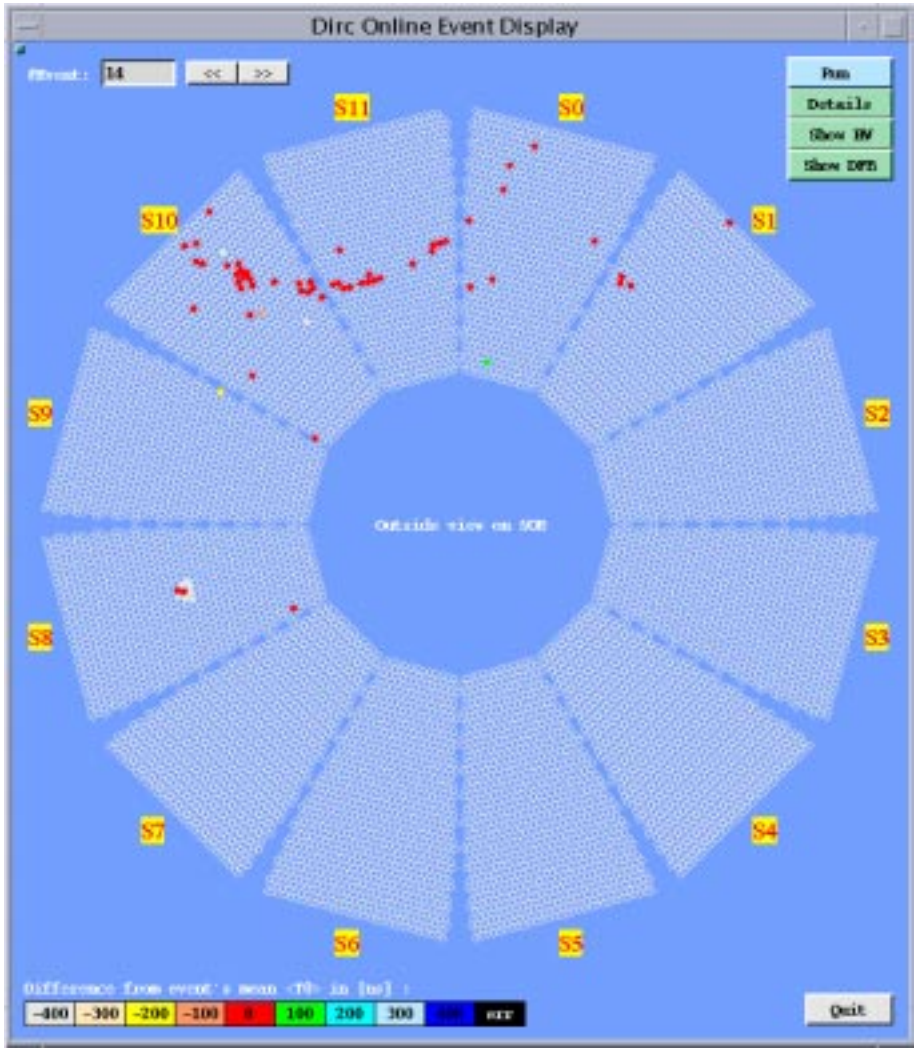
$\rightarrow$ Will take data with 4 bar boxes.

- Remaining 2/3 will be installed after June 1999.

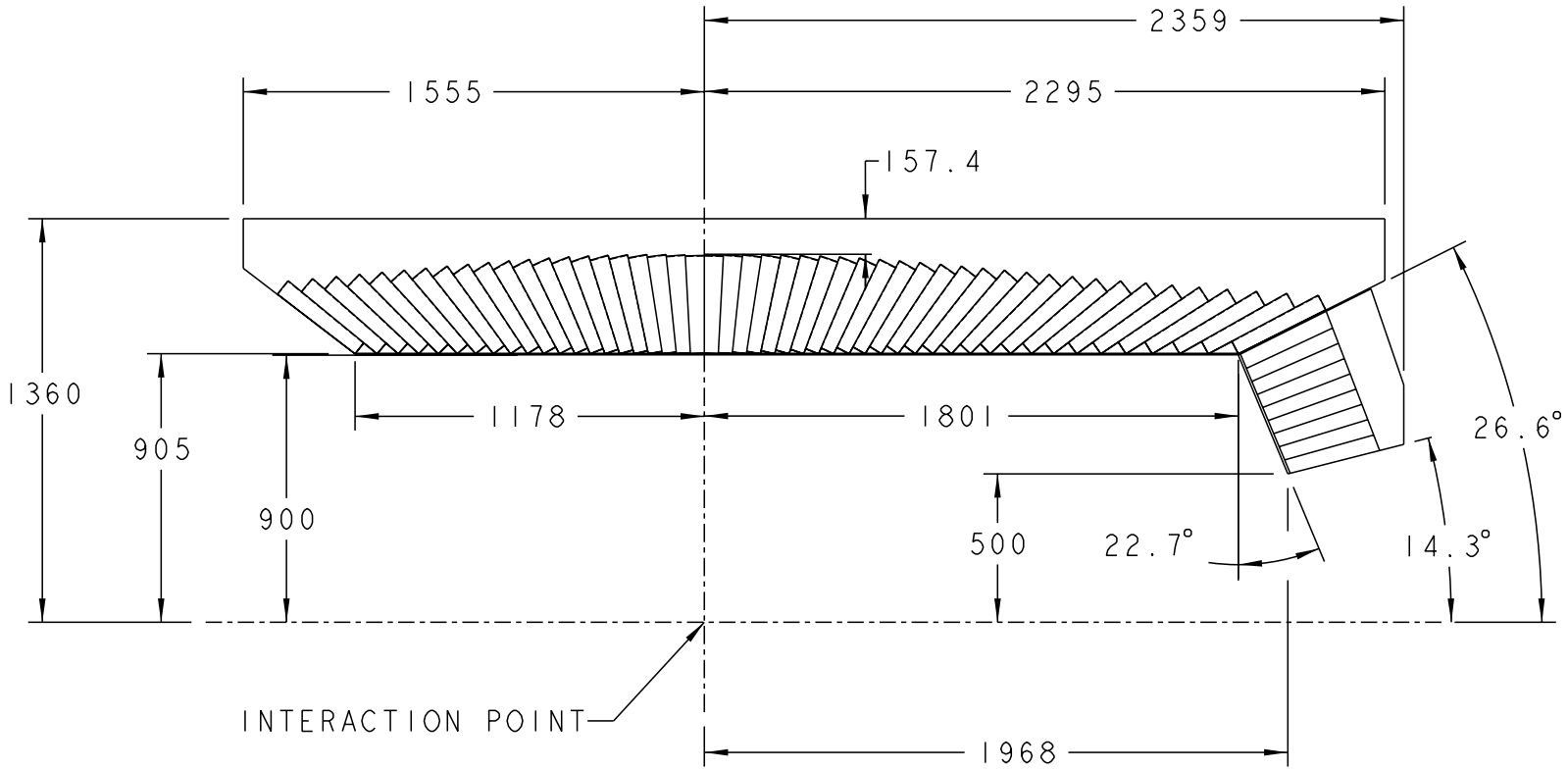
DIRC Event

Cosmic ray event

- DIRC online event display.
- Bar box was in Sector 11 (top left).
- Red dots = in-time PMT hits.
- Cerenkov ring clearly visible.
- In-time background hits from scattered photons.



Electromagnetic Calorimeter (EMC)



- CsI (Tl) crystals. 5760 in barrel and 820 in forward end-cap.
- Dual photo diode read out.
- Continuously digitized at 3.7 MHz, 18-bit effective resolution.
- Target resolution $\sigma_E/E = [1/E\ (GeV)^{1/4} \oplus 1.2]\%$.

EMC Design

Crystals

- 5760 + 820 CsI (Tl) blocks in pointing geometry. 16 to 17.5 X_0.
- Supported by CFRP compartment attached to an aluminum strongback.

Electronics

- 2 photo diodes + amplifier / crystal for redundancy.
- Special IC (CARE) to switch amplifier gain (x1, x4, x32, x256) to increase dynamic range.
- Digitization at 3.7 MHz. Resolution 10 bits + 8 bits from CARE.
- Waveform analysis and tower sum computed in real-time by purpose-built VME modules (UPC ROMs) in the Electronics House.

Calibration

- Circulate Fluorinert activated by neutron source $\rightarrow$ 6.13 MeV photon.
- 15 minutes operation yields 0.25% statistical error.

EMC Status

Crystals and mechanical structure complete.

- Crystals finished in time despite initial production delays.
- Installed in BABAR in August 1998.

Electronics and DAQ operational.

- More CPUs than all other subsystems combined.
- Barrel achieved full operation in January 1999.
- Debugging continued through and after the cosmic run.
- Entire endcap read out in February 1999.

$\rightarrow$ Ready for data taking now.

Superconducting Solenoid

Coil manufactured in Italy

- Arrived from in December 1997 by a US Air Force carrier.

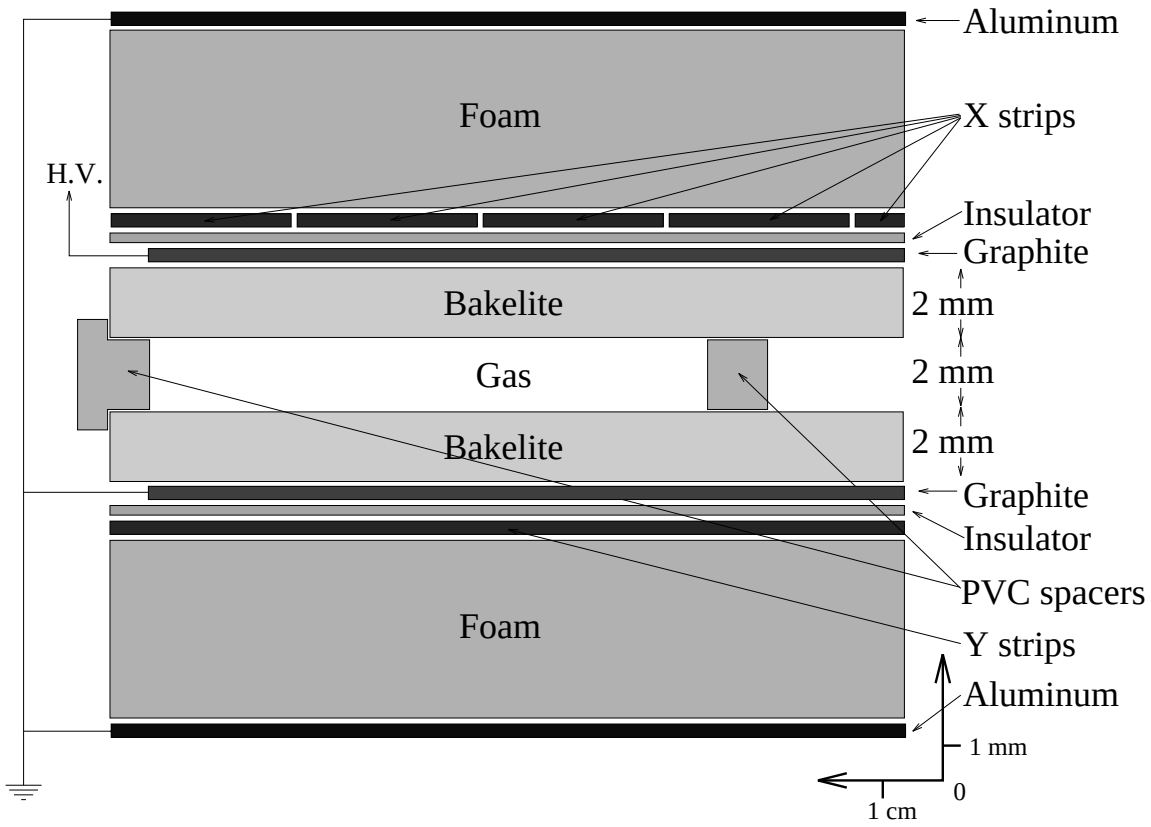
Return yoke built by Kawasaki.

Full-power (1.5T) operation in March 1998.

- Field mapping at 1.5T and 1.0T.
- Bucking coil near DIRC SOB cancels field at PMTs.

Stable operation during the cosmic-ray run.

Instrumented Flux Return (IFR)



- 18-19 layers of RPCs between flux return iron plates.
- Detects muons with p > 500 MeV.
- 2-layer Cylindrical RPC between EMC and solenoid.

IFR Design

Resistive Plate Chambers

- Made of 2 mm-thick Bakelite plates. 10^{11}-10^{12} Ωcm
- 2 mm gap filled with Ar-isobutane-Freon (59:38:3).
- Graphite coating supplies HV. 8 kV nominal.
- 3 cm-wide Al strips (X and Y) pick up induced signals.

Structure

- Barrel in sextants. Endcaps in two halves.
- 2500 m^2 sensitive area. 50000 strips.

Electronics

- Single-transistor amplifier. (200 mV raw signal)
- Records hits. TDC for OR-ed signals (1 ch/layer) planned.
- Housed in mini-crates on detector.

IFR Status

All RPCs complete and installed by January 1998.

Instrumentation continued throughout 1998.

- Gas line connection.
- Signal and HV cabling.
- Installation of mini-crates.

Last mini-crate installed in February 1999.

$\rightarrow$ Ready for data taking now.

Electronics

7 Custom ICs for improved packing and consumption.

- SVT readout (AToM).
- DCH amplifier/discriminator and digitizer (ELEFANT).
- DIRC amplifier/discriminator and digitizer.
- EMC amplifier and range-selector (CARE).

All signals digitized on detector.

Data transfer to Electronics House via optical fibers.

- E.g. DCH has only 4 pairs of fibers for control and readout.

Heavily pipelined to receive Level-1 trigger at 2kHz.

- Multi event buffers in front-end electronics.

Read-Out Modules (ROMs) receive fibers.

- Standardized across all BABAR subsystems.
- Front-end interface + VME CPU board to process data.

Trigger

Level-1 trigger using signals from DCH, EMC, IFR

- Level-1 Accept at 2 kHz with fixed latency of ~10 μs.
- DCH hit information → Track candidates.
- EMC tower energy sum → Energy clusters.
- IFR layer hits → Muon candidates.

Level-3 trigger

- Software selection running in Online Event Processor Unix farm.
- Reduces the data recording rate to 100 Hz. (10 Hz from physics events.)

Tested during the cosmic ray run.

- L-1 Trigger — Triggered the BABAR DAQ system.
- L-3 Trigger — Selected events in real-time.

→ Ready for data taking.

Data Acquisition

Data Flow

- Data transmission and synchronization: front-end $\leftrightarrow$ ROM $\leftrightarrow$ Unix.
- Configure, trigger and read data from the front-end electronics.
- Process data and transfer to Unix nodes via 100 BaseT network.

Online Event Processing

- Event building, Level-3 trigger and data logging.
- Reduces trigger from 2kHz to 100Hz. Event size 33 kbytes.
- Monitors data quality on sampled events.
- Runs on ~100-node Unix farm in IR-2.

Prompt Reconstruction

- Reconstruct events and store into Objectivity database.
- Calibration using physics events. Results applied to the next data set.
- Monitors data quality on sampled events.
- Runs on 200-node Unix farm in SCS.

Other Online Software

Run Control

- User interface for the entire online system.

Detector Control

- Monitoring the hardware conditions.
- Communicate with Run Control and PEP-II to ensure detector safety.

Online Calibration

- Calibrate electronics (e.g. pedestal) between physics runs.
- Automated system runs during PEP-II top-off (3 min.) period.

Online Database

- Configuration database: records run condition.
- Conditions database: records calibration.
- Ambient database: records hardware condition.
- All in Objectivity. Server in IR-2 to cope with network interruption.

Computing

C++ for both offline and online

- Initial learning curve was steep $\rightarrow$ People have learned.

Performance still a concern

- Speed and memory usage, esp. Reconstruction.
- Getting better lately, but still a long way to go.

Objectivity database

- Constant source of frustration for developers.
- Data have been written and read back.
- Reliability and performance is still lacking.
- Close collaboration with the software/hardware vendors.

Platform support

- Solaris and DEC currently supported.
- Linux on Intel CPUs in the future (2000?).

Cosmic Ray Run

October 1998 $\rightarrow$ January 1999

- All subdetectors but SVT participated.
- SVT had its own cosmic ray run in February 1999.

Step-by-step integration, starting from Drift Chamber.

- DCH, DIRC and IFR ran together in November 1998.
- Level-1 Trigger joined in December 1998.
- EMC joined in January 1999.

Recorded ~10^7 events

- Demonstrated essential functionalities to take data.
- All subdetectors were powered and data were read out.
- Entire DAQ chain worked.

Much development took place.

- Hardware and online software tested/debugged.
- Collected data used to exercise offline software.

Detector Roll-On

PEP-II turned off on February 22, 1999.

BABAR rolled on to the beamline on March 13-17.

- 1 week ahead of schedule.
- Reconnection of power and cooling is underway.
- Fourth DIRC bar box will be installed on March 30.
- SVT will be installed on March 31.

BABAR will be ready to take data on April 29.

$\rightarrow$ First beam will be seen on May 8, 1999.

First Physics Run: May-August 1999

First week: Beam study.

- Don't burn BABAR!

Second week: Υ_{4S} peak scan

- Background must be tolerable.
- Detector must be able to count multihadrons.

Later: Physics $\leftrightarrow$ Beam study

- Accumulate physics data at highest current BABAR can handle.
- Alternate with machine development. Sometimes at higher current.

Expect 5 fb^{-1} in 3 months.

- Proposed on- and off-peak luminosity ratio 80:20.

Followed by October 1999 Run.

- Will continue 9 months to collect 30 fb^{-1}.

Background Remediation

"June 99" background model

- Simulate detector response to the expected background.
- Can BABAR survive the radiation?

Component	First week	1999	Max dose
SVT	0.25 Mrad	0.42 Mrad	2 Mrad
EMC (crystal)	0.6 krad	0.7 krad	10 krad

- Can BABAR take data?
  - ➤ Expect 10-20% occupancy in SVT and DCH.

Monitoring and protection.

- BABAR itself: HV current, occupancy.
- Radiation monitors: PIN diodes, RadFETs $\rightarrow$ Beam abort system.

$\rightarrow$ Find balance between maximizing luminosity and minimizing the damage to BaBar.

Physics Readiness

BABAR Physics Book (SLAC-R-0504, Oct. 1998, 1056 pp.)

- Summary of 4 workshops held in Nov. 1996 through Sep. 1997.
- BABAR collaboration + 67 theorists contributed.
- Comprehensive analysis of BABAR's physics potential.

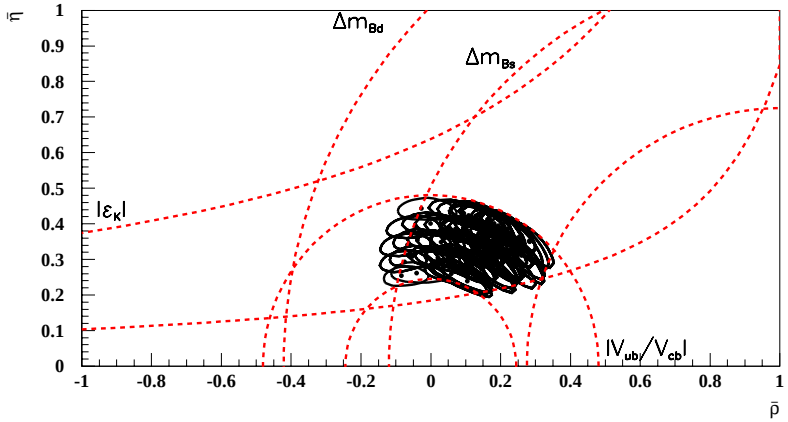
Current physics activities focus on the first-run data.

- Find interesting physics reachable with 5 fb^{-1}.
- Understand the detector systematics.
- Develop software tools for vertexing, particle ID, flavor tagging.

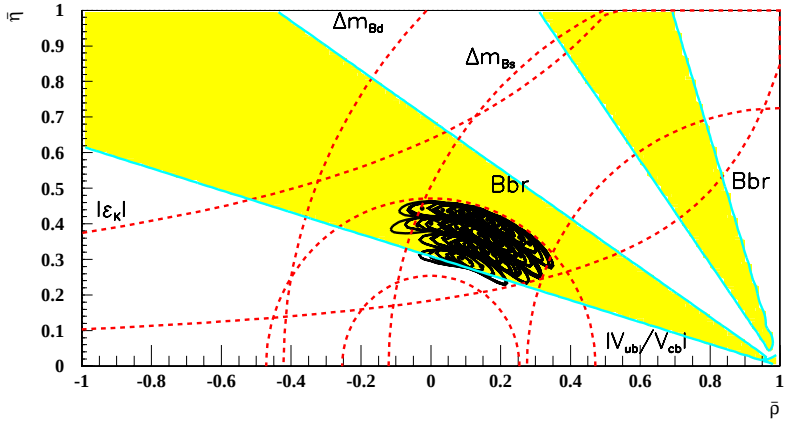
→ More people start working on physics as we complete the construction.

Unitarity Triangle

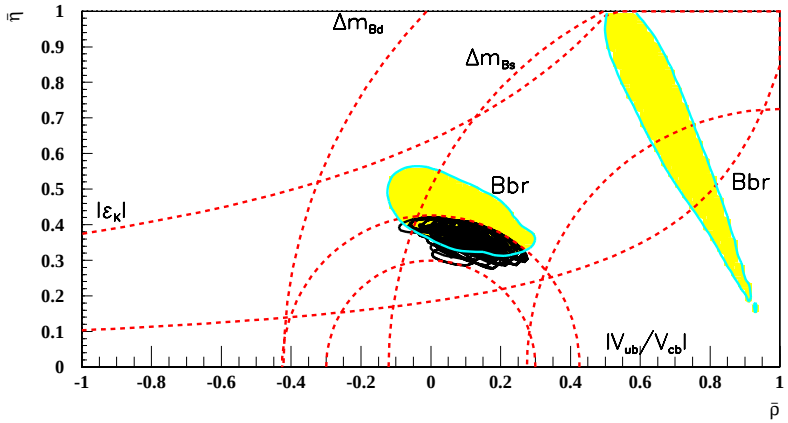
Present (1998)



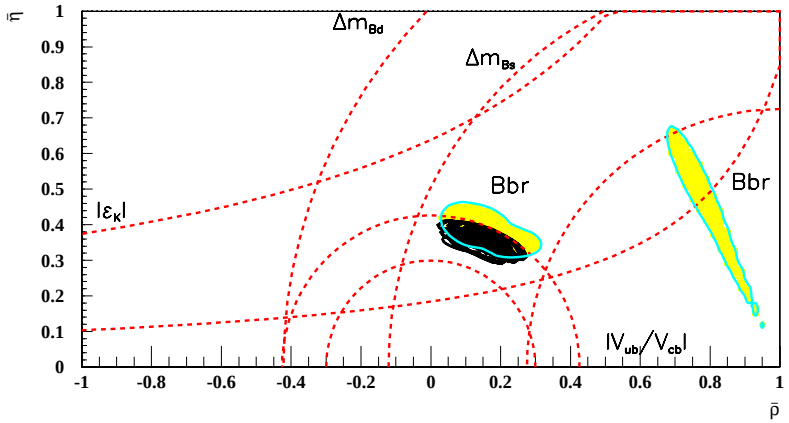
→ BABAR 30 fb^{-1}



→ BABAR 90 fb^{-1}



→ BABAR 180 fb^{-1}



Conclusion

Construction of PEP-II and BABAR is complete.

- PEP-II commissioning successful. Luminosity 5.2 x $10^{32}cm^{-2}s^{-1}$ achieved.
- BABAR recorded ~10^{7} cosmic ray events.
- BABAR has rolled to the beamline. Ready for beam by April 29.

We will see the first beam on May 8, 1999.

- Background is the biggest concern.
- Online DAQ system has a lot of work to do.

600 physicists are waiting for the first data.

- Ready to produce interesting physics in very short time.

See you at

LEPTON-PHOTON '99

Stanford University

August 9-14, 1999