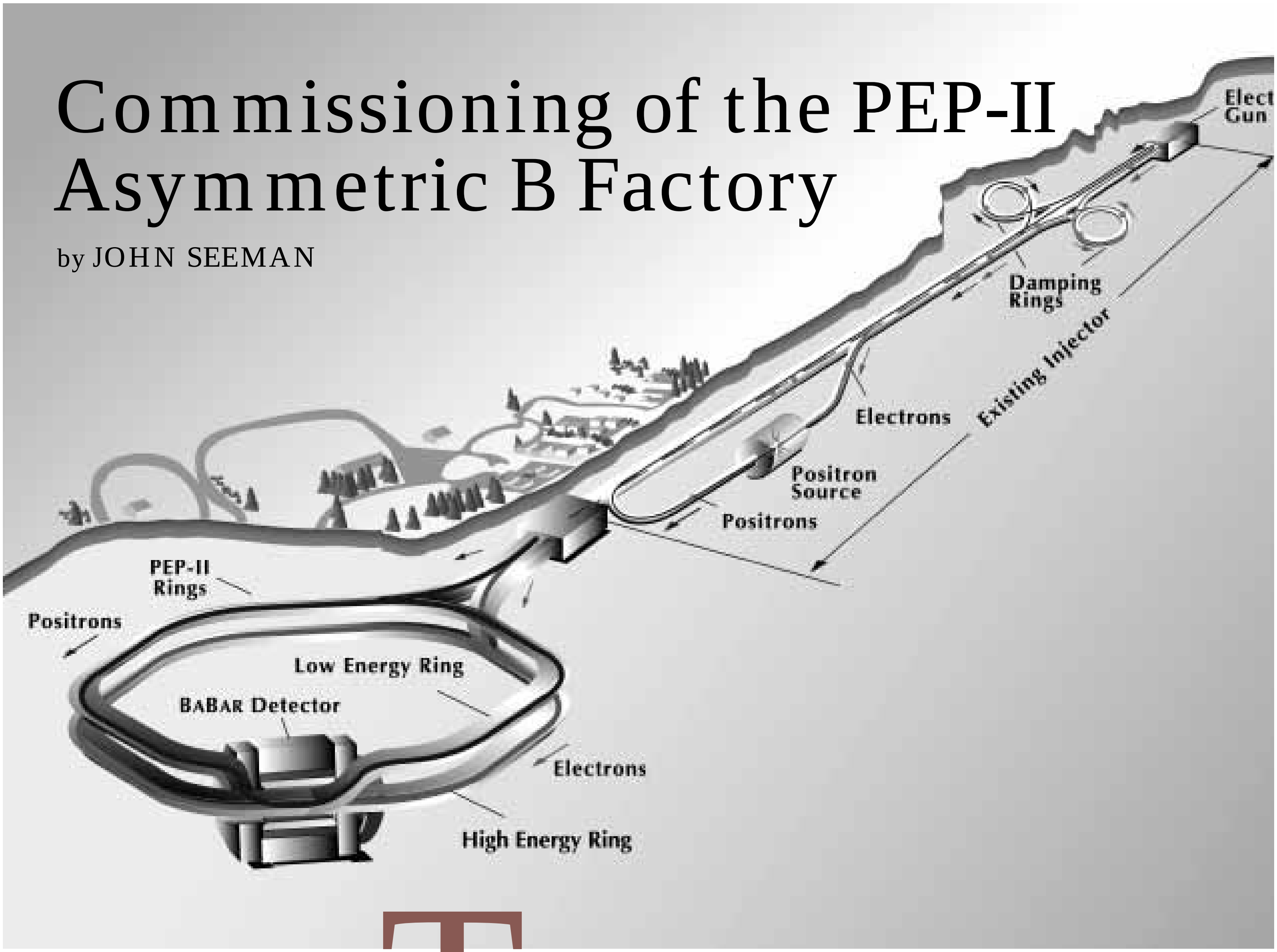
Commissioning of the PEP-II Asymmetric B Factory

by JOHN SEEMAN



The PEP-II collider, one of two asymmetric B factories in the world, is producing initial data aimed at understanding the matter-antimatter puzzle in the early Universe.

THIS SUMMER has been an exciting time for high energy physicists. In California and Japan, two new electron-positron colliders known as asymmetric *B* factories have begun producing events. Both are relatively low-energy devices, operating at center-of-mass energies just over 10 billion electron volts (10 GeV). They are the first of an imaginative new breed of particle colliders in which the electron and positron beams meet at *different* energies, producing many millions of short-lived subatomic particles known as *B* mesons. The associated particle detectors have begun recording data that physicists will employ to examine the mysterious phenomenon of CP violation—a small but fundamental difference between matter and antimatter expected to occur in these particles.

In late May the two *B* factories—PEP-II and its detector BABAR at SLAC, and KEKB and its detector BELLE at the Japanese KEK Laboratory in Tsukuba—independently began operations less than a week apart. They are now locked in a head-to-head competition to determine the nature and extent of CP violation in the B meson system. Here I discuss the PEP-II collider and our experience in commissioning this state-of-the-art machine; Shin-ichi Kurokawa and Steven Olsen describe KEKB and BELLE in a companion article on page 23.

THE DESIGN of asymmetric B factories began in 1987 when physicists recognized that neutral B mesons offer a powerful means to study CP violation. These particles have relatively long lifetimes and exhibit strong mixing between states. Pier Oddone of Lawrence Berkeley Laboratory had the revolutionary idea to collide electron and positron beams of different energies and create the $Y(4S)$ resonance in motion.

The $B\bar{B}$ system resulting from its disintegration allows separation of the two decay vertices, greatly enhancing experimenters' abilities to search for anticipated CP-violating effects. This idea soon made an asymmetric electron-positron collider the machine of choice for such research. At a center-of-mass energy of 10.58 GeV, with beam energies in the ratio of three to one, the B and $\bar{B}$ decay at a mean separation of about 250 microns—easily resolvable with a good vertex detector. A surrounding particle detector can then determine the decay parameters of the two particles independently, giving experimenters a more direct look at the underlying CP-violation mechanism.

But even with this bold new approach, the total number of events needed is enormous (due to the small probabilities of the most interesting decay modes), making necessary a very high-luminosity collider—over an order of magnitude higher than what was previously attainable. A luminosity of 3×10^{33} per square centimeter per second is needed to produce the desired 30 million pairs of B mesons per year.

Although an asymmetric collider makes it much easier for physicists to study CP violation, the need for two fairly different energies and high luminosity makes its design decidedly more difficult. Many issues constrain the design—from stored beams with amperes of circulating current to high-power microwave accelerating cavities to the intricate details of the interaction region.

Three Department of Energy laboratories built the PEP-II collider at a cost of $177 million, provided by the U.S. government: SLAC, Lawrence Berkeley National Laboratory, and Lawrence Livermore National Laboratory. Additional contributions came from the High Energy Physics Laboratory in Beijing, China, and the Budker Institute for Nuclear Physics in Novosibirsk, Russia. This work began in January 1994 with the dismantling of the existing PEP electron ring and ended in July 1998 with the completion of the new positron ring.

PEP-II has two separate rings located in an existing tunnel roughly 10 m below the rolling hills on the Stanford University campus. The positron beam energy is 3.1 GeV, while electrons circulate at 9.0 GeV. The design currents are 2.1 amperes for positrons and 0.75 amperes for electrons, distributed over 1658 bunches that are spaced 1.2 m apart, which results in the design luminosity of 3×10^{33} cm^{-2}sec^{-1}. The

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The author struggles to indicate just how narrow the two beams are at the collision point of the PEP-II collider.

STARTING TO COMMISSION a particle collider is an exhilarating moment. The construction team, which has struggled to build the most perfect machine it can, is ending its job constantly pressed for time and money. Technical decisions must be made right up to the end; often several components are temporary. Every part of the collider has to work, or the machine won't perform.

The commissioning team (many of the same people) is anxious to begin. Questions abound. Is our design good enough? What mistakes have we made? What surprises has Nature in store for us? How is the competition doing? It's a great time—no known problems, but everything to make work. There's excitement about what will happen. Consisting of about three dozen hardy souls, the team is ready to work 24 hours a day, seven days a week.

The day finally arrives when the ring and injection line are completed. Vacuum systems, temperature interlocks, magnets and their power

Tao of Commissioning

supplies, personnel protection systems, microwave cavities and their klystrons, feedback systems, controls, staff training and safety reviews—all are ready at last.

Let's push the button! But where's the beam? Now the real commissioning starts.

Work the beam down the injection line. Why has it stopped part way? Check the magnets, check that the vacuum valves are open, check that the beam instrumentation is working. Tweak all the knobs and look for a small signal. Now make the signal bigger! A diagnostic device is not working, so move on to the next. Keep pushing. Days go by.

Small victories start to occur: The beam makes it around one turn. We know the ring is complete!! Then two turns, then ten. Now adjust the injection energy, position, and angles. A few correctors have been wired backwards! We turn on and phase the microwave cavities. The beam goes around 100 turns, then 500, then 2000, and finally lasts a full second. Theorists do studies to explain why the beam acts as it does, not as it should. Try the corrections they suggest. Try steering the orbit, turning on the sextupole magnets, and activating the last few vacuum pumps. Finally, the beam stays in the ring for 30 minutes! It stores!!

Keep pushing. Reschedule experiments to match the expertise of the people on shift. Broken hardware alters the schedule. A day is lost. Start the studies again. Look for an image of the beam in the synchrotron-light monitor. On the side, get the needed hardware upgrades going in the machine shops. Meanwhile, learn to accumulate multiple injection charges in a single bunch, then multiple bunches. Why does good injection keep getting lost? Push the beam lifetime with lattice adjustments and x-ray processing. (And take time off to see the family.)

Around this time new accelerator-physics effects start to appear. Take some data, followed by computer simulations, then more data, and further simulations. A publication takes form, and off it goes to a conference.

After several months, a down time finally allows us to replace temporary accelerator components. Then we restart the machine and push forward for several more months. At higher currents, we turn on and debug the feedback systems. In the end, we manage to store a respectable current for a respectable lifetime and with respectable parameters. The electron ring has officially been commissioned, except for half a dozen “minor” issues.

Now it's time to start the process all over again for the positron ring. And let's do both rings at the same time! Many common problems have been solved, but each ring has it's own unique issues. Push the tests. Push the beams.

After a month of rapid progress, it's time to collide beams. We start with a single bunch in each ring, timing them with a position monitor near the collision point. Next move the beams up and down, back and forth, looking for the beams to interact. First the electron beam drastically reduces the positron beam lifetime, thus locating the collision point. After careful centering and size adjustments, the two beam lifetimes are acceptable. The luminosity signal is sought and found. We have measured luminosity! Time to celebrate!

But the luminosity is still much too low. Try to increase the charge per bunch. Squeeze the beams at the collision point by reducing the beta function, beam emittances, energy dispersion and relative tilt of the two beams. Try to collide many bunches at once. Every few days, we achieve a new luminosity record. Sometimes, a problem stalls us for a week. With every new advance, the luminosity reaches a new plateau which requires us to take a fresh look at all the variables and knobs that didn't work before, but may now. Our understanding of the machine's subtleties grows daily. We soon find that raising all parameters to their present limit maximizes the luminosity. We must work on all frontiers at once.

At last, the luminosity is high enough that the experimenters want to collect data. The big detector rolls into position. Issues of sustained production now surface. Beam glitches cause backgrounds in the detector, which abort the beams. Higher currents mean higher backgrounds and trigger rates. The 100 Hz trigger rate must be reduced. The detector takes too long to ramp its voltages, and we lose a fill. The data-logging computers hang up. Interlocks cannot be cleared. These issues get solved one by one. Finally, the collider is producing actual physics events. The experimenters are happy with their data, while accelerator physicists take a brief pause to recharge. There is great sense of accomplishment.

But the experimenters find they need higher luminosity and want to do an energy scan. The push starts again. Our plan to adjust the energy will finally be put to the test. But accelerator physicists smile: “This is as good as it gets.”

positron ring is mounted about a meter above the electron ring except at the interaction region, where they merge. There are six curving arcs each 250 m long and six straight sections each 120 m long for a total circumference of 2200 m. The BaBar detector sits in one straight section, while the others contain the microwave cavities, feedback systems, electron and positron injection lines from the SLAC linac, and other beam-monitoring and control systems.

At the interaction region where BaBar sits, the positron beam bends down to the same plane as the electron beam, then approaches it horizontally. Using two strong permanent magnets just before and after the collision point, we steer the beams into a head-on collision (they have distinct orbits in the rest of the ring). We determine beam parameters using a luminosity monitor while scanning the beams across each other transversely to measure their heights and widths.

Injection of ampere-scale beams in a few minutes requires a good injector. Using the SLAC linac as modified for PEP-II, we inject beams swiftly, taking only three minutes to fill each ring. During normal operations we "top off" the beams by adding electrons and positrons after the luminosity has fallen by about 30 percent; such a top-off cycle lasts about 4 minutes. Any major beam loss during operations must be handled with great care because of the vast energy (up to 50 kilojoules) stored in these intense beams. Abort systems can extract the entire charge from either ring during one turn if any of several abort signals—excessive detector backgrounds, a microwave cavity trip, a high vacuum-chamber temperature, an erratic beam orbit, or a large beam loss—occurs.

THE PEP-II electron ring was finished in June 1997 and the commissioning process began that month. After several brief periods of commissioning spread over two years, it has reached its full design current of 750 mA distributed

PEP-II In Review

Milestones Achieved

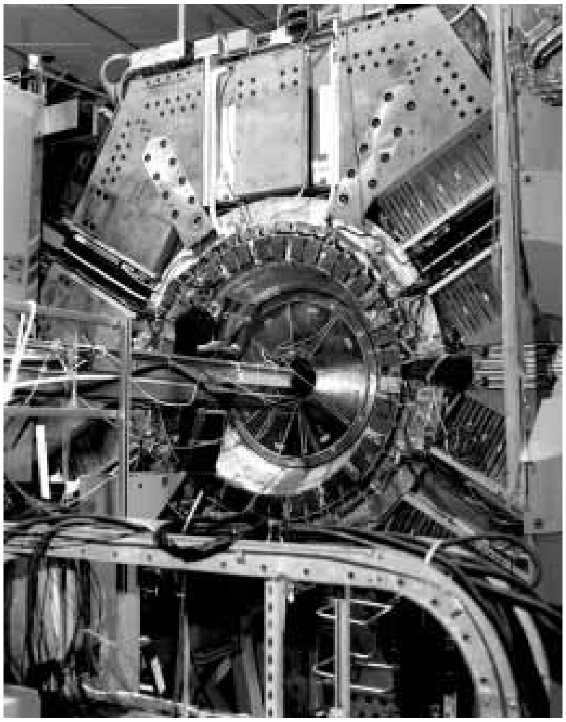
January 1994	Start of PEP-II construction
June 1997	Electron ring installation completed
June 16, 1997	First electron beam stored
Jan 31, 1998	750 mA electron beam attained
July 10, 1998	Positron ring installation completed
July 16, 1998	First positron beam stored
July 23, 1998	First electron-positron collisions
February 8, 1999	Luminosity reached 5.2×10^{32} cm^{-2}sec^{-1}
February 22, 1999	1171 mA positron beam attained
March–April 1999	BaBar installed on beam line
May 15, 1999	Two beams stored with BaBar in place
May 26, 1999	First events recorded by BaBar
July 12, 1999	Luminosity reached 5.6×10^{32} cm^{-2}sec^{-1}

Parameters

	Present	Design
Electron beam energy (GeV)	9.1	9.1
Positron beam energy (GeV)	3.0	3.0
Maximum electron current (mA)	750	750
Maximum positron current (mA)	1171	2140
Maximum luminosity (cm^{-2}sec^{-1})	5.6×10^{32}	3×10^{33}
Maximum number of bunches	1658	1658
Typical electron beam lifetime (h)	5	4
Typical positron beam lifetime (h)	2	4

A view down the tunnel of the PEP-II B Factory. The positron ring sits just above the electron ring.

The BaBar detector as it nears completion. Standing before its drift chamber is deputy spokesperson Gerard Bonneaud of École Polytechnique in Paris.



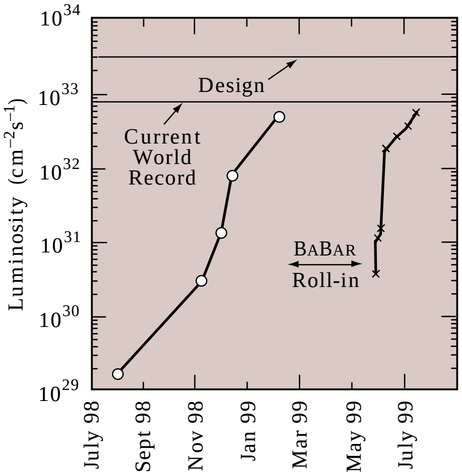
over 1658 bunches. Commissioning of the positron ring began in July 1998; by late February 1999 it had attained 1171 mA, which is 55 percent of the design current and a world record.

We brought the two beams into collision for the first time in late July 1998, shortly after storing the first positron beam, without the BaBar detector in place. At first, the principal evidence for these collisions was the observation that one beam was deflecting the other. Actual luminosity was measured in November; during the next three months the peak luminosity swelled by over three orders of magnitude, reaching 5.2×10^{32}cm^{-2}sec^{-1} on February 8, 1999 (see graph at right). This luminosity occurred with 786 bunches in each beam, amounting to currents of 680 mA in the positron ring and 354 mA in the electron ring.

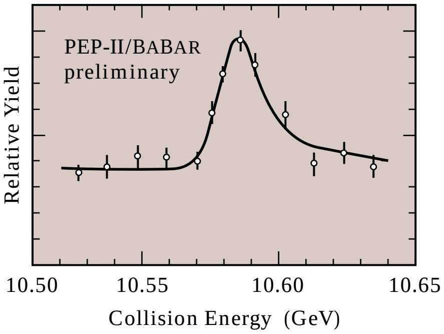
During March and April, engineers and technicians rolled BaBar into position at the interaction region while experimenters in the big collaboration made final installations and adjustments. The accelerator physicists could hardly wait to begin commissioning the collider again, this time with the detector in place and its solenoidal superconducting magnet turned on. Because this magnetic field strongly perturbs PEP-II, it took us several days of beam tuning to get the beams back into collision. We finally resolved these problems and collided beams again on May 25. At 4 o'clock the next morning, BaBar physicists observed the first events in their detector.

During the next six weeks, the luminosity of PEP-II again grew steadily, this time with BaBar in place and its magnet turned on. Sufficient events were being recorded to permit us to scan the electron beam in energy; we located the $\Upsilon(4S)$ resonance peak on June 16 at close to the expected value of 10.58 GeV (see bottom graph at right). And on July 12, just before a brief shutdown for repairs, the luminosity exceeded the previous record, reaching 5.6×10^{32}. This is almost 20 percent of the design value and 70 percent of the current world's record, set recently at Cornell's CESR collider.

As the Asymmetric *B* Factory begins operations and produces millions of *B* mesons over the coming year, our goals include reaching design luminosity by next summer and understanding the machine so thoroughly that we can try to exceed this level. Future upgrades will be required to increase the PEP-II luminosity to 10^{34}. To triple the design luminosity will probably require increasing the positron current to 3 A and squeezing the beam size vertically by an additional 30 percent. Exactly how these parameters can be improved will become clearer over the next few years. But the accelerator physicists who designed, built and commissioned this pioneering machine over the last decade can already take great pride in their work. The decade of data collection just now beginning promises to open broad new vistas on CP violation and its impact on the early Universe.



Luminosity achieved in PEP-II during commissioning.



Preliminary data for the $\Upsilon(4S)$ resonance. (Courtesy BaBar collaboration)