Fermilab Tests Its Antiproton Factory

Physics experiments with the world's highest energy proton antiproton collider will begin a year from now

Physicists at the Fermi National Accelerator Laboratory have begun testing the antiproton source that is a key part of a $137 million project to turn the laboratory's proton synchrotron, the Tevatron, into the world's highest energy colliding beam machine. When experiments begin a year from now, each collision between protons and antiprotons circulating in opposite directions in the Tevatron will release up to 2 trillion electron volts (TeV), more than three times the 0.63 TeV available from the proton-antiproton collider at the European Laboratory for Particle Physics (CERN), which has produced most of the elementary particle news in the last 3 years.

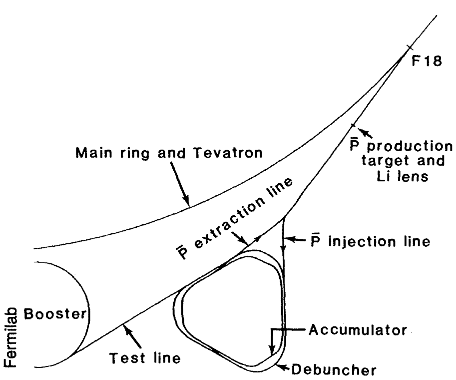
Energy is definitely the name of the game in elementary particle physics. CERN's collider represented a big breakthrough when it came on line at the end of 1981 and demonstrated that colliding beam operation with protons and antiprotons was feasible. Its initial collision energy of 0.54 TeV was about nine times that of the previous record holder, an older CERN machine called the Intersecting Storage Rings (ISR), which has now been dismantled.

This collision energy was the first one high enough to permit physicists to detect and measure some properties of the massive intermediate vector bosons (*W* and *Z* particles), key ingredients in the so-called Standard Model of the elementary particle world. It was also enough for two CERN physicists, Carlo Rubbia and Simon van der Meer, to garner last year's Nobel Prize in Physics.

Now flowing from theorists' heads is a plethora of still more massive particles, some of which may be needed to make a more complete model of the most elementary constituents of matter and the forces that act between them than the Standard Model, which so far has correctly explained everything it covers but is not so all-encompassing that it treats everything. As the mass goes up, so does the required energy of the accelerator that makes them.

The current thinking, according to Fermilab theorist, James Bjorken, is that the Superconducting Super Collider (SSC), a 40-TeV behemoth that is in the early R&D stage, will probably be necessary to sort fully through the numerous alternatives for extending the Standard Model (*1*). Whether Fermilab's Tevatron collider will be energetic enough to take a peek at any of the conjectured new particles, it is not possible to say, but for a decade it will be the best accelerator available to explore the low end of this new energy range.

In any case, the physics associated with the *W* and *Z* has just begun to be explored. Because of its higher energy and its improved antiproton source, the Tevatron collider will produce these particles at a higher rate than the CERN machine, even after an upgrading now in progress there is completed.* Also on the agenda are confirmation of the top quark, the long-missing sixth member of the quark family for which CERN physicists presented preliminary evidence last year, and a search for still more massive quarks. And a warrant remains out for the Higgs, the only particle predicted to exist by the Standard Model for which there is no experimental evidence.



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Making antiprotons

Protons circulating clockwise from the main accelerator strike the tungsten target to make antiprotons, which are cooled and collected in the debuncher and accumulator rings, and which feed back into the main ring in a counterclockwise direction. The test line from the booster synchrotron permits testing the system with protons.

Finally, while new particles get most of the attention, they are not the only phenomena of interest. An unanticipated finding from the CERN collider has been the increasing "cleanness" of events in which quarks within the protons and antiprotons scatter one another at large angles (jet events) as the collision energy increases. Clean, high-energy jets tower above otherwise obscuring, low-energy debris and allow physicists to study in ever closer detail the nature of the strong nuclear force that binds the quarks together to make the conventional elementary particles called hadrons, including the proton, the neutron, and the many mesons. The theory of the strong force, quantum chromodynamics or QCD, is part of the Standard Model.

Coming on line almost 5 years behind CERN's proton-antiproton collider, Fermilab's counterpart has, in addition to the higher energy, a second generation antiproton source. The basic problem is to produce in a reasonable time about 2×10^{11} antiprotons and inject them into the Tevatron. In the end, the antiproton beam has an energy of 1 TeV and comprises three "bunches" of particles, each about 1 meter in length and 0.024 square millimeters in cross section, which will collide at six evenly spaced locations around the Tevatron ring with a proton beam of the same energy and structure. Two large, general-purpose and three small, more specialized detectors at five of these locations will record the outcomes of the 2-TeV collisions.

At the time the proton-antiproton collider idea was first seriously proposed in the mid-1970's, physicists did not know for sure that it was possible to make beams of antiprotons that were dense enough to produce a usefully large number of collisions. The difficulty relates to a property of particle beams in accelerators called the emittance. In a frame of reference at rest with respect to the center of mass of the beam, the particles look like a gas with a distribution of positions and momenta. A large emittance corresponds to a wide distribution, while a small emittance characterizes a narrow one, so that emittance is somewhat analogous to temperature.

In other ways, emittance is more like the brightness of a light beam. For example, one of the properties of the emittance is that it is invariant. With magnetic lenses, for example, one can narrow the position distribution normal to the

*Two electron-positron colliders, the SLC at the Stanford Linear Accelerator Center and LEP at CERN, which will come on line in 1986 and 1988 respectively, will be *Z* factories and will be best suited for studying this particle and phenomena related to it.

beam only at the expense of widening the transverse momentum distribution; that is, squeezing the beam increases its divergence. Similarly, by manipulation of the radio-frequency system that powers the accelerator, one can narrow the longitudinal position distribution only at the expense of widening the momentum distribution in the direction of the beam; that is, shortening the bunch length makes the beam less monochromatic.

The tie-in with antiprotons is that the large emittance associated with the manner of producing these particles must somehow be reduced to a smaller value suitable for a collider. Since antiprotons do not naturally exist in large quantities in our part of the universe, physicists must make them. The usual way is to smash a high-energy beam of protons into a metal or other target. At Fermilab, the protons are accelerated to 120 billion electron volts (GeV) in the old synchrotron, extracted, and directed to a tungsten target. Among the products of the proton collisions with tungsten nuclei are antiprotons, which emerge in the beam direction, but at a much lower energy and diverging along paths distributed in a narrow cone centered on the beam axis. It is this divergence that accounts for the large emittance.

One way of reducing the emittance of a particle beam (or, equivalently, cooling the beam) was invented by the late Gersh Budker of the Soviet Union's Institute for Nuclear Physics in Novosibirsk. A low-emittance beam of electrons runs parallel to the beam to be cooled. Just as in a mixture of hot and cold gases, collisions transfer momentum from the high- to the low-emittance beam, thereby cooling the former. Unfortunately, the method is increasingly inefficient as the beam energy climbs into GeV range.

The second method was pioneered by van der Meer at CERN. Called stochastic cooling, it involves electronic sensors that measure the departure of the particles in a beam from the ideal orbit. A correcting signal races across the ring, reaching the other side in time to activate a "kicker" device that generates a voltage to nudge the particles more into line. Tests at CERN showed that both transverse and longitudinal beam cooling was possible by this means. Accordingly, the laboratory built an antiproton source based upon an accumulator storage ring, which served both to cool and accumulate antiprotons for the collider (2). The process was slow, however, taking about 24 hours.

Fermilab took a different tack in several ways. Partly because it could not convert its existing proton synchrotron into a collider as CERN was able to do with its machine, the laboratory, under its founder and first director, Robert Wilson (now at Columbia University), concentrated first on developing the superconducing magnet technology necessary for the Tevatron, a 1-TeV synchrotron that sits just below the first one in the same tunnel (*3*).

Fermilab physicists also had different ideas about an antiproton source and initially designed one comprising two storage rings. The first would accept antiprotons from the target, do some stochastic cooling, and then decelerate the beam to 0.2 GeV for injection into the second ring, where the bulk of the cooling would be done very efficiently by electron cooling.

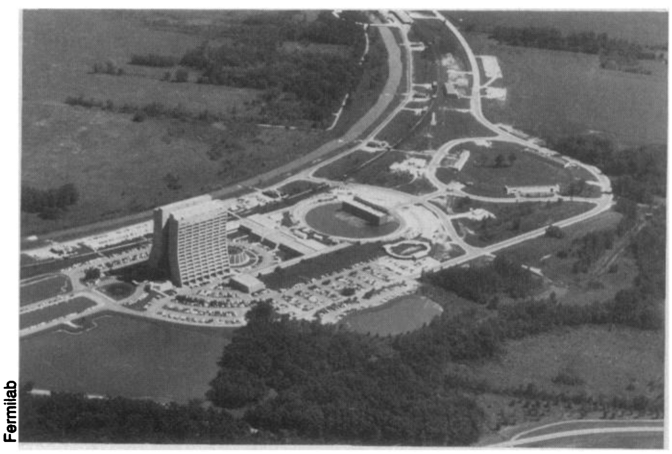
Several factors conspired against the implementation of this scheme, however. For one thing, it was discovered that comparatively few particles would successfully make the transfer between the two storage rings because the beam would blow up as it decelerated. As a result, the antiproton source would be no faster than that at CERN, though more complex and expensive. A negative review of the original design by an outside committee sealed its fate, and, under orders from current Fermilab director Leon Lederman, work on a new source began in 1981.

By early the next year, the collider group headed by John Peoples turned in a revamped plan for an antiproton source. The plan retained the two-ring concept, but switched to stochastic cooling in the second ring with no deceleration required. Projected performance was dramatically improved, reducing the time to generate an antiproton beam of the required density from 24 to 2 hours. One other difference was that the new source was budgeted at $40 million more than the preceding one. At the time, the first priority was finishing the Tevatron. The laboratory also needed to upgrade substantially the fixed target experimental areas to accomodate the higher beam energy.

But everything is in place now and testing of the antiproton source has begun. At the time this is being written, Fermilab scientists have just started storing antiprotons in the accumulator ring. Prior to that most everything that could be tested using protons (either by reversing the polarity of the magnets, so that protons follow the same course as the antiprotons would, or by running the protons through in the reverse direction) had been with generally favorable results.

When the antiproton source is fully working, the sequence of events will be as follows. Antiprotons emerging from the tungsten target in an energy range around 8 GeV will be collected by a lithium lens. The lens, which was originally developed in Novosibirsk, is one wrinkle that the CERN source does not have, although its upgraded one will. The lens comprises a rod of lithium through which a large current is passed to generate a focusing magnetic field. It allows the capture of a wider cone of antiprotons, thereby enhancing the efficiency of antiproton production. Even so, only one antiproton will be collected for every 30,000 protons bombarding the target.

The antiproton beam, which, like the proton beam that created it, comes in the form of a pulse comprising 84 bunches. It proceeds to the first of the two storage rings, the debuncher. The debuncher, which is shaped like a triangle with rounded corners, restructures the antiproton beam so that it can be more efficiently cooled by coalescing the tiny bunches into a continuous pulse, the debunching process. It also does some



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Aerial view of antiproton complex

Fermilab's Tevatron arcs across the upper left corner of the photograph. The debuncher and accumulator rings sit underground inside the triangular roadway on the right. The tungsten target and lithium lens are under the rectangular building to the right of the Tevatron.

pre-cooling of the beam before transferring it to the second ring, the accumulator.

The accumulator sits inside the debuncher and looks like an irregular hexagon with three long sides and three short ones where the corners of the debuncher are. Its job is to stochastically cool and store successive pulses of antiprotons arriving from the debuncher. After about two hours of running, the stored antiproton beam contains about 2×10^{11} particles. It turns out that the precooling in the debuncher is a key to reducing the cooling time in the accumulator. The reduced beam size due to precooling permits higher frequency operation and hence a shorter cooling time.

From the dense core of the stored beam, antiprotons are extracted to form one of the three bunches in the collider. This bunch is first accelerated to 150 GeV in the old synchrotron ring and then injected into the Tevatron. The process is repeated three times to obtain three antiproton bunches, which are then accelerated together with three proton bunches to the final beam energy.

Fermilab scientists hope to demonstrate this scenario in its entirety during the current test period, which lasts to the end of this month. Peoples says there is about a 50 percent chance of accomplishing this. If it does occur, one of the two major detectors will be partially completed and in place to record the world's highest energy, man-made proton-antiproton collisions.

Obtaining collisions would be a tremendous psychological boost to carry the scientists through a long shutdown scheduled from October until next summer to accommodate two major civil construction projects related to the detectors. It would also provide useful data for tuning up the antiproton source, the collider, and the detector over the shutdown, so that everything will be ready for the first real run next year.

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Making Better Planetary Rings

Particles colliding in Saturn's rings appear to be ice balls, not snowballs, acting like molecules of a gas, a liquid, and perhaps even a solid

Saturn's rings have seemed stranger and stranger of late, as spacecraft have made revealingly close inspections. The new observations have uncovered a stunning number of variations on the few, broad rings expected by researchers and have even suggested that the rings formed only recently, a most unpalatable prospect to astronomers. However, there are new signs that theory could be catching up with the observations.

Theorists have had no trouble explaining how particles could orbit a planet in a disk so thin that, if scaled down to the size of the United States, it would be no thicker than a few centimeters. Some theorists argue that it must be even thinner. And they had little or no trouble coming up with some ways of sculpting what would otherwise be a single, featureless disk into broad rings, narrow ringlets, ripples, and spiraling waves. But Saturn's rings stayed far ahead of the theorists with their mysterious razor-sharp inner edges, narrow gaps, wavy edges, thousands of ring subdivisions, and other oddities (*1*).

One group of theorists believe that they now have a handy new tool for developing and testing explanations of the rings' bizarre appearance: a mathematical description of how ring particles orbiting a planet behave as they nudge neighboring particles. The model has passed a crucial test and has yielded some interesting initial insights.

The new model takes one of several available approaches to describing a cloud of particles in which collisions are far less frequent than those of molecules in a liquid but far more frequent than any considered in plotting the motions of planetary bodies. Accounting for collisions is crucial because they mediate the transfers of energy that shape rings. The model was developed by Frank Shu of the University of California at Berkeley and Glen Stewart, who is now at the University of Virginia (*2*). They borrowed from plasma physics the 30-year-old Krook equation, an approximate mathematical description of colliding particles, and modified it so that some of the kinetic energy of a collision could be lost to the deformation and heating of the particles. Without such inelasticity, the model's particles would be unrealistically bouncy. Put to its first test, the Krook model results compared well with other models of a ring unperturbed by external forces.

The new model has since done well on a second, more challenging test (*3*). Shu and Luke Dones of the University of California at Berkeley and Jack Lissauer, Chi Yuan, and Jeffrey Cuzzi of the National Aeronautics and Space Administration's Ames Research Center at Moffett Field, California, used the disturbance due to the periodic gravitational pull of a satellite to create a spiral density wave in the model ring. This is a wave of bunched ring particles that spirals outward from the disturbance, called a resonance, in the form of a watch spring. The Voyager spacecraft discovered dozens of them in Saturn's rings.

The model's simulation of a spiral density wave, one in the A ring due to a resonance of the satellite Mimas, bore considerable resemblance to the real thing. In a radial cross section of model and observed waves, the peaks of ring opacity are sharp, the troughs between are broad, and, most impressive, the distance between crests is inversely proportional to the distance from the resonance. The resemblance is "striking," the authors conclude, suggesting that the model's inelastic collisions are dissipating energy and damping the wave much as happens in the A ring.

The good fit to reality comes only if ring particles are assumed to be solid ice. Despite the spacecraft flybys, researchers have only been able to speculate whether ring particles are hard ice through and through, are coated with a cushioning layer of collision-produced chipped ice, or are a loose agglomeration of many particles.

The highly elastic particles required by the model bear a strong resemblance to the clean, hard ice balls studied by Frank Bridges, A. Hatzes, and Douglas Lin of the University of California at Santa Cruz (*4*). In the lab they collided two ice balls chilled to 165 K at speeds between 1.5 centimeters per second and a few tenths of a millimeter per second. Like cars racing around a track, ring particles