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Livermore constructs Mirror Fusion Test Facility

The Lawrence Livermore Laboratory has begun construction of its Mirror Fusion Test Facility, which is designed to investigate whether the plasma stability demonstrated in current experiments will continue (or even improve as predicted) on a larger scale. The $94-million effort reflects new confidence in the confinement of plasmas by magnetic mirrors, which is the primary alternative in the US magnetic-confinement program to the toroidal approach embodied by tokomaks. The confidence in mirrors stems partly from Livermore's success in controlling the growth of microinstabilities in their current 2XIIB device (see PHYSICS TODAY, November 1976, page 17). Hopes for the new machine are also based on the promising concepts of tandem mirrors and field reversal, either of which could further enhance the performance of the mirror fusion facility for the generation of power.

The new mirror facility, which is under the direction of T. Kenneth Fowler, will be similar in design but larger in scale than the existing 2XIIB device. One prime difference will be the steady-state operation with superconducting magnets. A giant coil winder is already at work laying the more than 15 miles of niobium–titanium wire that will comprise the world's most massive magnet (see photo). This pair of so-called "Yin-Yang" magnets will create a field whose central value is 2 teslas and whose shape is similar to that made by coils that follow the lines of stitching on a baseball. The intensity of the resulting field increases outward from the center in every direction, thus forming a magnetic well that traps the plasma. The major radius of the magnet pairs will be 2.5 m, allowing a length of 3.6 m be-

Construction of superconducting coils for MFTF at Livermore. Initial lengths of superconductor are being wound on coil form, which has been prepared with Kapton and perforated G-11 sheet. Also visible is the interturn spacer strip attached to the superconductor to insulate its layers.

continued on page 20

CERN builds proton–antiproton ring; Fermilab plans one

Although some high-energy experimenters have been talking about proton–antiproton colliding-beam devices for over a decade, the financial commitment to build such a high-energy storage ring had not been made. Now CERN is indeed building such a device, in which 270-GeV protons will collide with 270-GeV antiprotons. Built out of the CERN operating budget, the project is expected to cost about 91 million Swiss francs ($50 million) and to be completed by the end of 1980. Two interaction regions have been approved, each requiring a complex detector whose cost is in addition to the 91 million Swiss francs. Besides the two large detectors, three other experiments have been approved.

Meanwhile a smaller proton–antiproton effort is underway at Fermilab, partially supported by outside funds (other than Fermilab's). The group at Fermilab hopes to use the Energy Doubler now being built at Fermilab, which will product 1000-GeV protons. The Doubler itself would serve as the storage ring for 1000-GeV protons and 1000-GeV antiprotons.

And the Nuclear Physics Institute in Novosbirsk, where the electron-cooling method for colliding beams has been pioneered, has proposed using the new Serpukhov accelerator, UNK, expected to produce 2–3 TeV in 1988–90, to make a colliding-beam device with 1000-GeV protons and 1000-GeV antiprotons.

Proponents of the high-energy $p\,\bar{p}$ devices argue that they are ideal for looking for the charged and neutral intermediate vector bosons (expected to have a mass of less than 100 GeV/c^2), W and Z, and the Higgs boson, which is required by the

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Weinberg–Salam model.

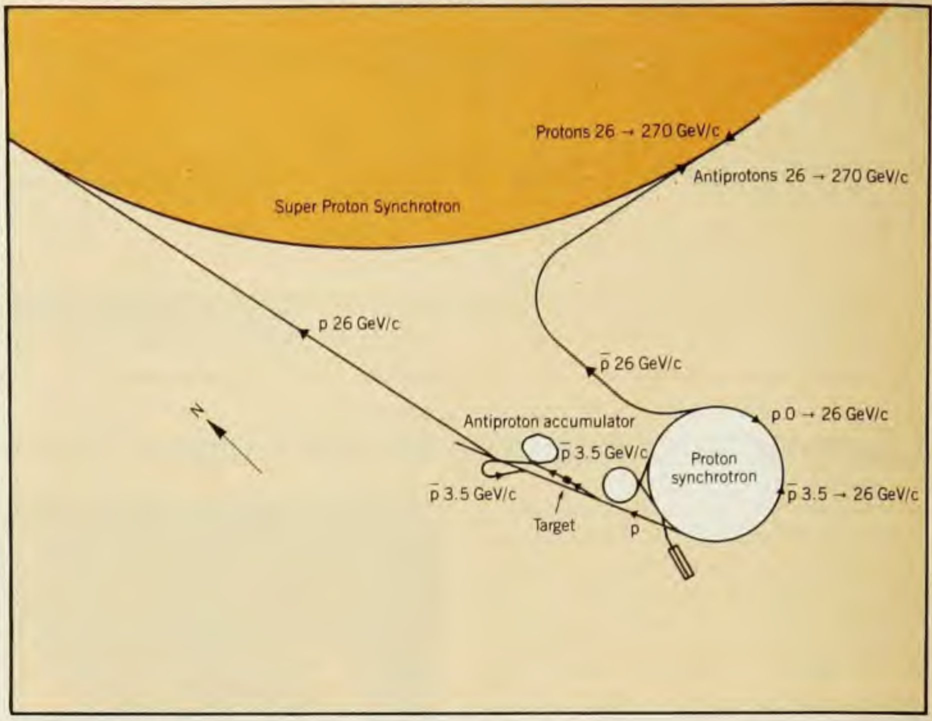
Phase-space cooling. For electron–positron storage rings, the proposed Large Electron–Positron device recommended by the European Committee for Future Accelerators (in the range of 70 GeV in each beam) is close to the top energy that is likely to be built in such a traditional e^+e^- storage ring. Beyond that energy, it may become too expensive to replace the energy lost by synchrotron radiation.

Protons and antiprotons do not have this mechanism for quenching particle oscillations (synchrotron radiation); so one must start with high-intensity beams. For proton–proton storage rings, making intense proton beams is a relatively simple problem. The CERN Intersecting Storage Rings have been producing 25-GeV protons to collide with 25-GeV protons since 1971 and now have a luminosity of 4×10^{31} cm^{-2} sec^{-1}. And Brookhaven's Isabelle, scheduled to operate about six years hence, is to have 400-GeV protons striking 400-GeV protons; it is expected to have a luminosity of 10^{32}–10^{33} cm^{-2} sec^{-1}.

To make antiproton–proton devices, however, is a lot more difficult because antiprotons are generated with a low density in phase space. A practical storage ring requires a large increase in this density; that is, one needs a mechanism to reduce the oscillation amplitude and momentum spread of the antiprotons.

The idea of electron cooling to reduce phase space was announced in 1966 at a storage-ring conference in Saclay by Gersh I. Budker, then director of the Novosibirsk Institute. At that time he and Alexander Skrinsky proposed building a $p\bar{p}$ device (25 GeV on 25 GeV) for the Institute. The idea was not very actively pursued elsewhere until Skrinsky and his colleagues obtained surprisingly good results in experiments that began in 1974. In electron cooling, the idea is to have two parallel beams, one of electrons, the other of antiprotons (or protons). The electron beam is given the same mean velocity as the antiprotons. The two kinds of particles can exchange energy and because the electron beam is continually supplied with more electrons at the same energy, the beam cools the antiproton beam to the same energy. As N. S. Dikansky, I. N. Meshkov and Skrinsky (all of Novosibirsk) recently pointed out,[1] the permissible energy spread for antiprotons in a storage ring is a fraction of a percent of the mean energy. The Novosibirsk workers have shown that they can cool an 85-MeV proton beam with a 45-keV electron beam so that the energy and momentum spreads are about 10^{-5} and the angular spread less than 5×10^{-5} radians. The cooling time was 50 millisec.

One reason the Novosibirsk group achieved such short cooling times was that they used a strong solenoidal magnetic field, which reduced the space charge



CERN $p\bar{p}$ colliding-beam device. 26-GeV protons, produced in the PS, strike a target and produce antiprotons, which are cooled and stored in the accumulator ring. Then they loop back to the PS, are accelerated to 26 GeV and then enter the SPS. Meanwhile protons are injected in the SPS, moving in the other direction. Each beam is accelerated to 270 GeV and allowed to collide.

tending to make the beam diverge in a long straight section.

Meanwhile, in 1972, at CERN, Simon Van Der Meer proposed the idea of stochastic cooling. In this approach, the fluctuations in particle density are detected in a piece of the beam by appropriate pick-ups. The fast electronic feedback system then applies an electric field to push the center of gravity of the piece closer to the desired orbit. Because the method is statistical, some particles are unfavorably affected, but most behave as ordered. To achieve significant cooling, the process has to be repeated many times.

Last year measurements with the CERN Initial Cooling Experiment (in the old ($g - 2$) storage ring) showed[2] that stochastic cooling was behaving as predicted. In March, an injected proton beam was cooled by a factor of nine in three minutes. In July, the experimenters took 18-GeV/c protons from the PS, aimed them at a tungsten target, and then guided the resulting beam of several hundred antiprotons at 2.1 GeV/c into ICE; they were kept circulating for 85 hours. By that time about 80 antiprotons survived. Such a particle loss is consistent with antiproton scattering on residual gas molecules in the ring. Not only did the experiment show the feasibility of storing antiprotons for a long time, it also improved the limit on the antiproton lifetime by a factor of 10^9.

In 1976 David Cline (University of Wisconsin), Peter McIntyre (now at Fermilab) and Carlo Rubbia (CERN and Harvard University) suggested using existing synchrotrons to store and collide high-energy beams of protons and antiprotons circulating in opposite directions. They and Frederick Mills (at Fermilab) have been active since then in pushing $p\bar{p}$ projects at CERN and Fermilab.

The CERN $p\bar{p}$ colliding-beam project will have an antiproton accumulator using stochastic cooling, which is being built by a group headed by Van Der Meer and Roy Billinge. Its ring, with a circumference one-quarter that of the 28-GeV Proton Synchrotron, will have a very large radial aperture—70 cm, and an ultra high vacuum, about 10^{-10} torr. Antiprotons of 3.5 GeV/c energy will be produced when 26-GeV protons from the PS strike a target. To make a large number of antiprotons, the aim is to crowd as many protons as possible into one-quarter of the PS circumference. This will be done by combining protons at slightly different energies into two lots of five double bunches. Because of the differing energies, the rf system will capture both lots, each with four times normal intensity.

Inside the accumulator, a new pulse of antiprotons will undergo a rapid precooling to reduce its momentum spread from ± 7.5 to ± 1 part per thousand. Then the rf system will stack the new batch of antiprotons with those already stored, before the next burst of antiprotons is injected. The stack of antiprotons will be cooled continuously, both longitudinally and transversely. After 24 hours, it is expected that 6×10^{11} antiprotons will be circulating.

The antiprotons then enter the PS for acceleration to 26 GeV/c (above a problem energy for the Super Proton Synchrotron). In the PS, the antiproton bunch gets reduced in length to less than 1.5 meters. Then the bunch is injected into one 200-MHz bucket of the SPS, where it is stored. Twelve such bunches are to be equally spaced around the SPS circumference.

Meanwhile twelve proton bunches will have been injected in the SPS, circulating in the opposite direction. Once both beams are orbiting, they will be accelerated to 270 GeV each. This will be done with four traveling-wave rf cavities. To enhance the luminosity, the bunches of protons and antiprotons will be combined into six pairs. The CERN workers expect to obtain a luminosity of 1×10^{30} cm^{-2} sec^{-1}. The vacuum in the SPS will have to be improved, to at least 10^{-9} torr, so that good luminosity can be maintained over a 24-hour storage period.

Of the 91 million Swiss francs to be spent by CERN for the $p\bar{p}$ project, 54.5 million will go for the $\bar{p}$ accumulator, 6.6 million for the modification of the Super Proton Synchrotron and 30.8 million for beam transfers and target. The cost of the experiments described below is in addition to the 91 million Swiss francs for the project.

The first interaction region expected to be in operation will house a large magnetic dipole detector, the UA 1 (Underground Area 1), whose field is perpendicular to the beams. The UA 1 detector is being built by a collaboration among Aachen, Annecy, Birmingham, CERN, Queen Mary College (London), College de France, Riverside, Rome, Rutherford, Saclay and Vienna, headed by Rubbia. This huge apparatus, 10 m long by 5 m wide, is expected to cover almost 4 π in solid angle. It will have an electromagnetic shower counter, hadron calorimeter, forward-arm spectrometer to see down to 5 millirad, and a central tracking device (a series of chambers to follow the detector).

In December a second interaction region was approved, which will house a second large detector, UA 2, to be built by a collaboration among CERN, Saclay, Orsay and Pavia, headed by Pierre Darriulat. UA 2 will have a toroidal magnetic field that covers a smaller solid angle than UA 1. It is designed primarily to search for electrons. But both UA 1 and UA 2 should be capable of detecting the W if it is there.

A second experiment, UA 3, has been approved for the first interaction region; it is designed to search for monopoles and other new particles. A second experiment for the second interaction region, UA 4, has also been approved; it will measure total cross sections and do small-angle elastic scattering. A fifth experiment, UA 5, a streamer chamber, has just been approved.

A huge hole has already been dug at CERN for the antiproton source. So hopes are high for meeting the target date of late 1980. Rubbia told us that even though Isabelle will have a much greater luminosity than the CERN $p\bar{p}$ project, the CERN device will be operating at least five years earlier. So it will presumably get the first crack at any new physics to be learned.

At Fermilab, a small storage ring for cooling has been built. Initially electron cooling of protons is being done. By summer, stochastic cooling of protons will be started, using a system being constructed by a Berkeley group. The same ring can then be used for the antiproton source.

A target station is being built by a Fermilab–Wisconsin group (including Cline, Mills and McIntyre) to produce antiprotons. Protons will be extracted from the Fermilab accelerator at 80 GeV. These will strike a target and yield 6-GeV/c antiprotons. Those antiprotons will enter the Booster and be decelerated to 200 MeV (while the Booster also continues to accelerate protons to be accelerated further in the main ring). The 200-MeV antiprotons enter the cooling ring, are cooled and put into a parking orbit. Then more hot antiprotons are injected for cooling. The team expects to get 10^{10}–10^{11} antiprotons. Then the 200-MeV antiprotons are to be accelerated in the main ring to say 150 GeV, then transferred into the Energy Doubler to be accelerated to 1000 GeV. The same procedure would be used for protons. Then the two beams, circulating in opposite directions, would interact. The resultant center-of-mass energy (2 TeV) would be the highest energy contemplated by any of the next generation of accelerators.

If these plans reach fruition, Cline believes that the Fermilab project could eventually have a luminosity a factor of 20 higher than CERN. He told us that the cross section for making antiprotons at 80 GeV is five times higher than at 26 GeV. Furthermore, having 1000-GeV protons and antiprotons instead of 270 GeV each gains another factor of four because high-energy beams are damped adiabatically.

Experimental prospects. Burton Richter of SLAC, who has SPEAR-headed electron–positron storage rings, believes that the way the Fermilab project is going, a luminosity of only 10^{28} cm^{-2} sec^{-1} appears likely, while CERN can expect a luminosity of 10^{30}. But for e^+e^- storage rings, he said, luminosities of 10^{32} are typical. Although, he says, the CERN project may in fact discover the Z or W, "$p\bar{p}$ devices are not the way to find out the properties of such particles." He went on, "to me most of the interest in $p\bar{p}$ rings is in the possibility of reaching enormous effective energy, where cosmic-ray studies give faint clues to new things that may be happening. The Fermilab project can give 2×10^{15} eV equivalent lab energy, and if they reach that with improved luminosity, they have their own voyage of discovery to make, independent of who wins the race to the Z."

Rubbia notes that event rates are expected to be 1000 times lower in the $p\bar{p}$ devices than in e^+e^- devices. But he and Cline feel that $p\bar{p}$ storage rings are the machines of the future, that these $p\bar{p}$ devices are only the first generation, and there is no *a priori* reason why the event rates need to stay so low. Leon Lederman, Fermilab's incoming director, told us that Fermilab has asked DOE for funding for a pre-cooler ring that would raise the luminosity to well above 10^{30} cm^{-2} sec^{-1}. The cost, he said, would be a fraction of the CERN expenditure.

—GBL

References

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New NMR spectrometer doubles resolving power

A new, high-resolution, 600-MHz nuclear-magnetic-resonance spectrometer at Carnegie-Mellon University will be ready for experimenters early in the spring. With a magnetic field almost twice that of previously available NMR spectrometers, the new spectrometer provides roughly a doubling of resolving power for the study of organic molecules. The Carnegie-Mellon NMR Facility for Biomedical Studies (a joint undertaking of Carnegie-Mellon and the University of Pittsburgh) has called for proposals for a first round of short experiments covering a broad spectrum of applications, to explore the capabilities of the spectrometer.

The new facility achieves a maximum precession frequency of 600 MHz for protons with a magnetic field of 14.1 tesla, provided by a driven (as distinguished from persistent) superconducting magnet developed by Intermagnetics General Corp. of Guilderland, N.Y. and Carnegie-Mellon. This is the highest NMR spectrometer field available to date. Commercially available spectrometers with persistent superconducting coils have been limited to maximum fields of 8.4 tesla, corresponding to 360 MHz. (400-MHz spectrometers are just beginning to appear on the market.) In the absence of line broadening with increased field, biochemical and biophysical investigators using the Carnegie-Mellon facility can expect approximately twice the resolution previously available for the separation of NMR peaks for hydrogen nuclei in different molecular environments.

The Carnegie-Mellon spectrometer can distinguish structures differing by 0.3 Hz