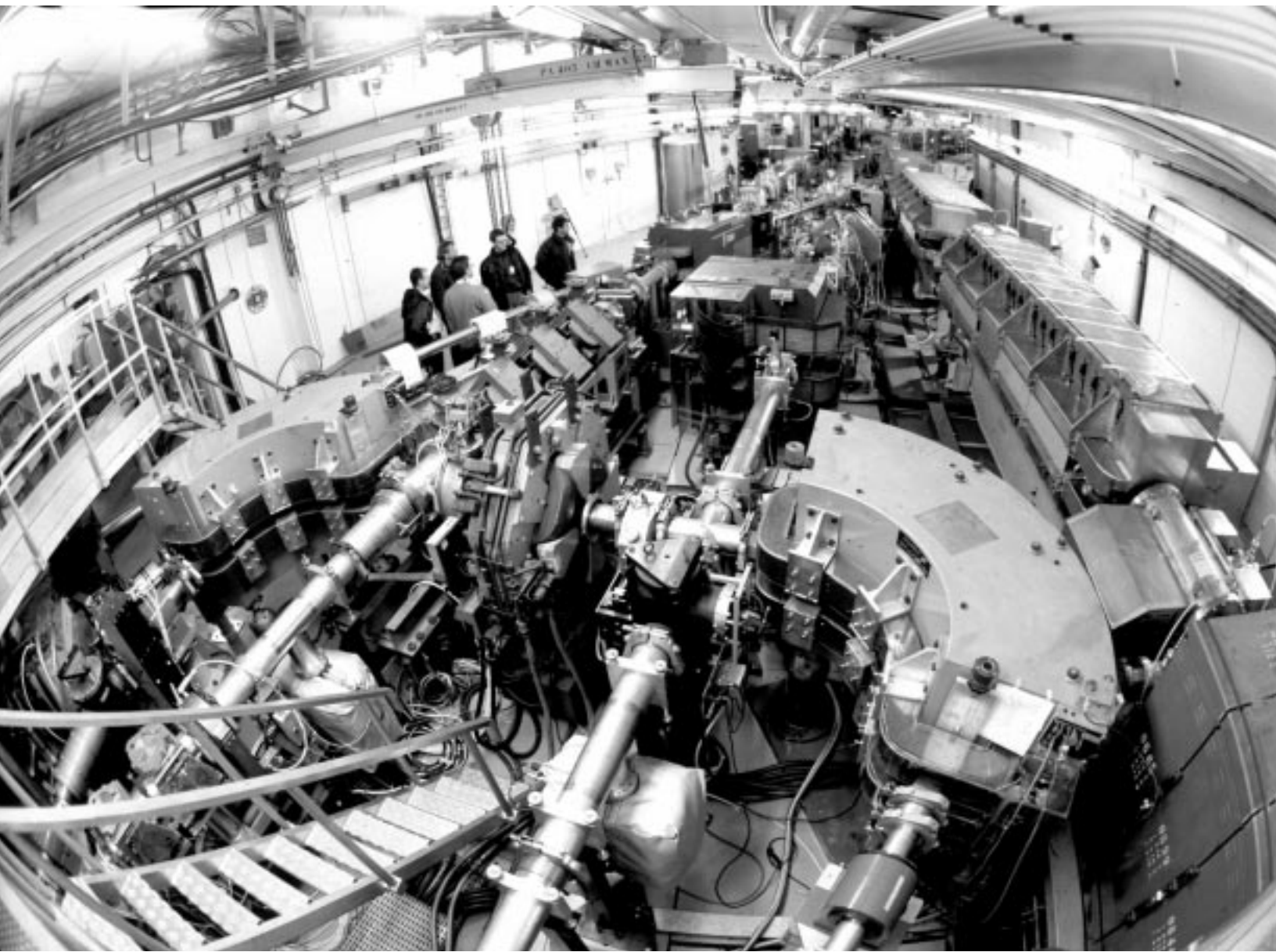


CERN's Low Energy Antiproton Ring

L • E • A • R

by GORDON FRASER



Beam transfer line ganglion at CERN. On the left are feeds from linacs towards the booster, and center, the antiproton ejection line from the PS proton synchrotron

to LEAR. Across these is the bulky U-turn to steer linac particles directly towards LEAR. On the right is a section of the PS.

IN SHAKESPEARE'S TRAGEDY, King Lear falls victim to his own misjudgment and dies from grief after a series of Job-like misfortunes. Another LEAR, CERN's Low Energy Antiproton Ring, was also buffeted by the stormy waves of destiny. Coming in the wake of CERN's push for a high energy proton-antiproton collider, LEAR, a machine physicists' concert platform, eventually fell victim to an even larger scheme—the Large Hadron Collider.

Andy Warhol said that anyone can be famous for fifteen minutes. For LEAR, this fame came in January 1996, when newspapers and media all over the world carried the news that an experiment had synthesized the first atoms of chemical antimatter. But LEAR will also go down in science history as a stage which saw remarkable machine physics performances.

In the mid-1970s, antiprotons were just another item on a long menu of secondary beams. But the idea was taking root that new techniques using antiprotons could open up another route to physics. The demonstration of electron cooling, by Gersh Budker's team at Novosibirsk, and the invention of stochastic cooling, by Simon van der Meer at CERN, promised that high fluxes of antiprotons could be produced. In addition, the antiparticles would be free of contamination by other particles, and extremely "cold"—well collimated in momentum and energy. At the time, the first electron-positron colliders were making their mark on the world physics stage. Budker suggested doing annihilation physics with protons and antiprotons. But antiprotons are more difficult to produce than positrons, and to feed them into a collider needed additional control via cooling. With the demonstration of cooling, the door to proton-antiproton collider physics was unlocked. The key was turned by Carlo Rubbia, and at CERN a working group was established to look into the possibility of using the new SPS proton synchrotron as a proton-antiproton storage ring.

Still untouched by these collider ideas, Kurt Kilian, then at Heidelberg, was doing experiments using secondary beams of antiprotons from CERN's 11 GeV PS proton synchrotron. A mere five antiprotons per PS cycle were available at low momentum, but the special conditions of particle-antiparticle annihilation are always a fruitful source of physics. Kilian was impressed when his machine physics colleague Dieter Möhl at the PS told him that in principle the new cooling techniques could open up the antiproton sluice

gates and provide a million antiprotons per second.

Rubbia and his colleagues were looking at how to produce antiprotons and accelerate them to high energies. For this, one initial idea was to use a small ring to decelerate the antiprotons so that electron cooling could be applied. This scheme was subsequently abandoned in favor of stochastic cooling at higher energies, but the possibility of decelerating antiprotons had been discussed.

Looking at the dynamics of antiproton production, Kilian soon realized that if secondary antiprotons produced by the PS could be decelerated, several orders of magnitude more antiparticles could be made available than via a standard secondary beam.

The 1977 International Accelerator Conference at Serpukhov heard a paper by Kilian, Möhl, and Ugo Gastaldi of CERN for the deceleration of antiprotons for physics experiments at a low energy antiproton factory. From the outset, the idea was very much overshadowed by the imaginative schemes pushed by Rubbia for high energy proton-antiproton reactions. Rubbia's aim was to use the proton-antiproton route to obtain sufficient energy to synthesize the long-sought *W* and *Z* carriers.

In contrast, the objective of the low energy scheme was to explore in depth the annihilation process, where many kinds of particles could be created. This would greatly extend the exploration of hadron spectroscopy. In addition, low energy antiprotons on tap would open up the study of antiprotonic atoms and even the possibility of synthesizing

chemical antimatter, atoms containing nuclear antiprotons and orbital positrons.

While the big push at CERN continued for a high energy proton-antiproton collider, the low energy splinter group was joined by Pierro Dalpiaz, then at Ferrara, and many other enthusiastic antiproton physicists. The machine side was joined by Pierre Lefevre (later to become project and eventually group leader) and Werner Hardt of CERN.

To extract particles slowly from a circulating beam, the classic method is to excite a beam resonance and use a magnet to remove a thick layer of beam. With expensive antiprotons, such brutal treatment would be wasteful. However a new technique of ultra slow extraction developed at CERN enabled particles to be delicately scraped off the surface of the stored antiproton beam. This made it feasible to propose an additional ring, grafted onto the low energy side of the new CERN antiproton complex.

This ring was initially called by the unimaginative name of APR (Anti-Proton Ring), before Helmut Poth of Karlsruhe suggested the LEAR low energy antiproton ring acronym. The scheme had the strong backing of CERN's PS Division under Gordon Munday and Gunther Plass, and the enthusiastic support of a wide physics community.

The project was finally approved in June 1980, two years after CERN's major high energy proton-antiproton scheme had been given the green light. By this time a substantial low energy antiproton physics program had begun to crystallize, leading to 16 experiments involving 240 physicists from 44 research centers.

CERN, however, was justifiably very protective of its high energy proton-antiproton scheme. LEAR was only approved subject to the conditions that it should not interfere with the PS commitment to the high energy antiproton scheme, that it could use only six percent of CERN's antiproton production, and that it should have overall "low priority."

It was a deprived childhood, but nevertheless introduced a completely new way of life for the low energy antiproton physics community. Very nice results emerged—meson spectroscopy, antiprotonic atoms, low energy annihilation, reaction mechanisms on protons and nuclei, and strangeness production.

It was also a lengthy childhood, extended by the drama of the last experiment at CERN's Intersecting Storage Rings (ISR) before this machine was closed in 1984. This study, which used a gas jet target, clamored for a stored beam of antiprotons in just one of the two ISR rings.

AT THE RINGSIDE

Before injection, LEAR's meager ration (typically 10^9 antiprotons) would be skimmed off from the Antiproton Accumulator once every 15 minutes or longer, and first be decelerated in the parent PS from 3.5 GeV/c to 600 MeV/c to benefit from phase space optimization. For this, the PS had to learn some new tricks, in addition to the repertoire needed to handle all CERN's different beams on complicated "super-cycles."

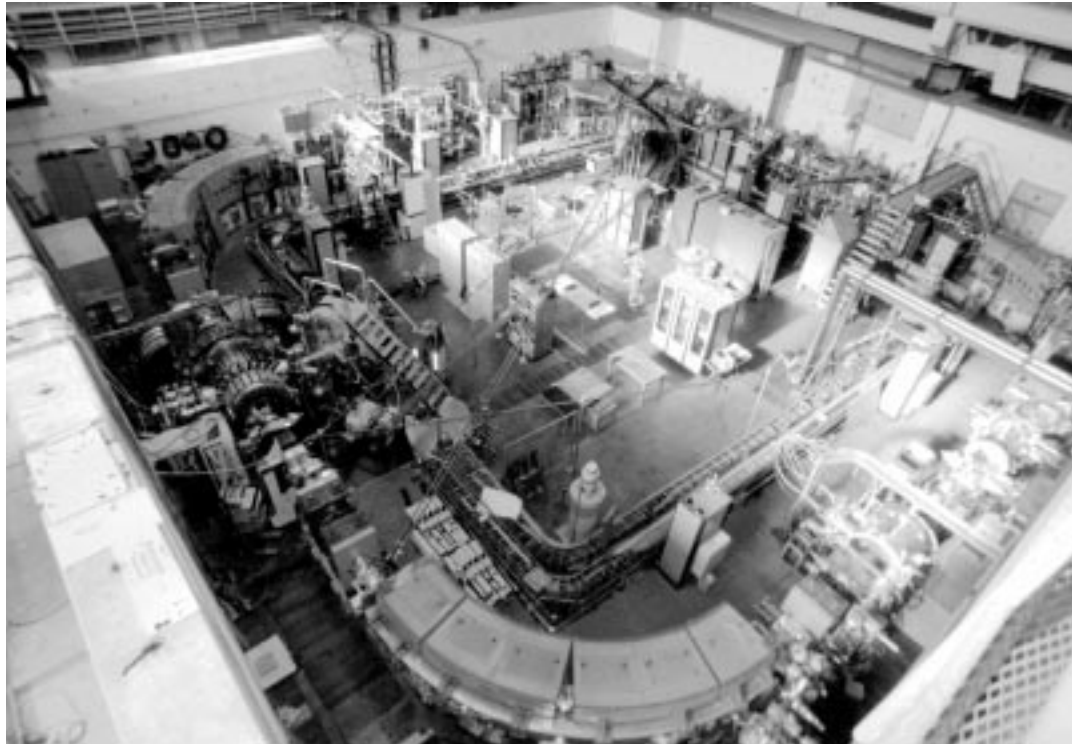
Although LEAR's *R* stands for ring, it is in fact four 10-meter straight sections joined by 90 degree bends. It

was built inside the existing South Hall of the PS in just 16 months.

Although a modest machine, LEAR had some interesting technical curiosities. Strong focusing proton rings have to face up to the problem of transition. When accelerated particles attain a certain energy, relativity effects come into play, and the radiofrequency accelerating field has to be adjusted to maintain the vital phase stability of the circulating particle bunches.

With conventional magnetic optics, LEAR's transition energy would have occurred right in the middle of its physics range. However, the design ensured that high momentum particles follow a shorter orbit rather than the larger one normally encountered. Transition was thereby totally side-stepped, a feature which has been adopted in the design of the proposed Japanese Hadron Facility.

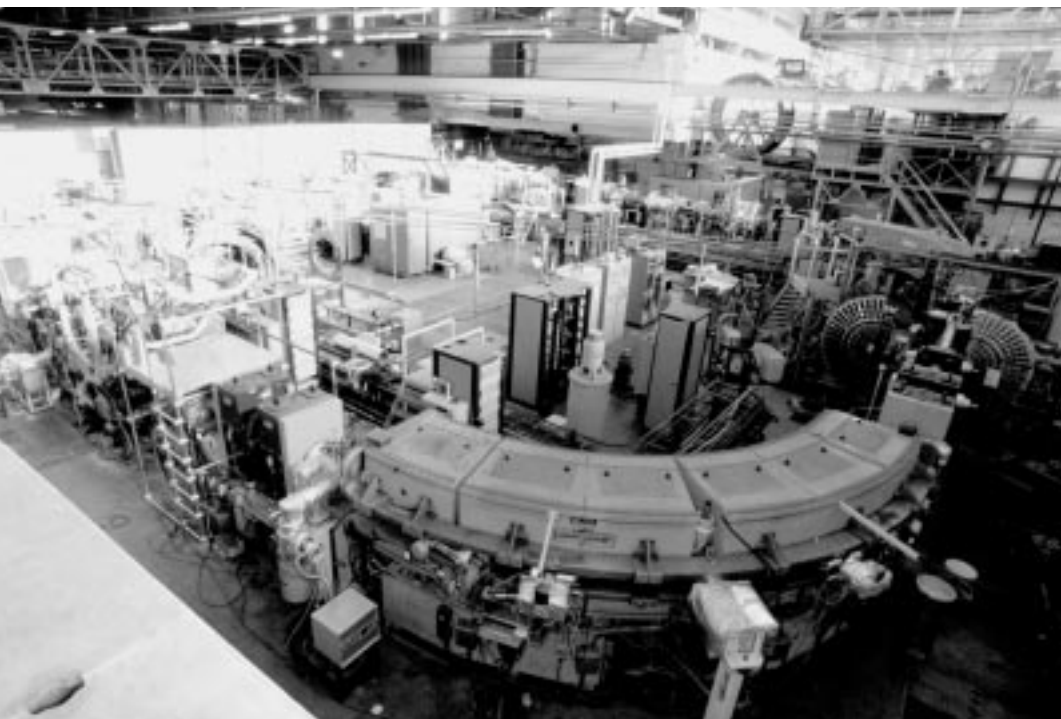
Having to contend for the crumbs of CERN's antiproton supply had a major influence on LEAR's design and operation. But there was not only bad news. With the PS warranting a new linac injector, LEAR inherited the old one and was thus able to extend its range of beams. LEAR was tested and later routinely set up for physics using expendable test particles (protons and negative hydrogen ions) and in principle could even store antiprotons and other particles at the same time, using colliding or overlapped co-rotating beams. However the linac was pointing the wrong way and this unexpected legacy required construction of a violent 210 degree U-turn to steer the linac particles towards LEAR.



To shape LEAR's beams at injection and at higher energy required stochastic cooling. Assuring synchronization of the cooling signals over a range of energies called for special solutions, and this variable energy stochastic cooling became another LEAR trademark. Once cooled, the low energy beam was "frozen" by electron cooling. Taking the beam down to 100 MeV/c required just one minute, with intermediate cooling at 600 (stochastic), 300 and 200 MeV/c (electron cooling). LEAR was the first machine to use electron cooling as an integral part of its operations, using the electron cooler inherited from CERN's Initial Cooling Experiment and refurbished in collaboration with a group headed by Helmut Poth from KfK Karlsruhe.

LEAR was foreseen from the outset as providing antiprotons for a wide range of experiments. As well as the possibilities with co-rotating beams, the straight sections were designed to accommodate internal targets. The bending magnets at the corners of the ring were C-shaped so that electrically neutral states formed in experiments using internal targets in the straight sections would not be

CERN's LEAR low energy antiproton ring, the site of remarkable accelerator physics.



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obstructed and could fly out. This was vital for the antihydrogen finale in 1995.

The machine design paid a lot of attention to internal targets; however, a large part of the experimental program used extracted beam with a network of beam lines and splitter magnets serving time-shared South Hall experiments.

After initial tests with protons in 1982, LEAR began providing antiproton beams to experiments in July 1983. However elsewhere in CERN's antiproton complex the UA1 and UA2 experiments studying high energy proton-antiproton annihilation were seeing their first Z particles and LEAR's experimental debut went relatively unnoticed.

MACHINE ACCOMPLISHMENTS

Having to live on a subsistence diet of antiprotons meant that LEAR had to learn how to make the most of its precious antiparticles. LEAR's resourceful machine specialists perfected a system of ultra slow extraction in which antiprotons were peeled off the rotating stack over

several minutes. Just a single antiproton per turn could be shaved off, giving an extracted beam that resembled a slender antiproton chain stretching from the Earth to the Sun with a single antiparticle every 100 meters! The record was providing 30,000 antiprotons per second at 310 MeV/c to two separate experiments for 14 hours.

Ultra slow extraction required the development and perfection of resonance extraction with radiofrequency noise (really carefully orchestrated music) which drives particles very gently towards the resonance. Traditionally, extraction magnets chisel particles from a stored beam. However when the beam has to be ejected over a very long spill (several minutes), unavoidable ripple in the power supplies leads to an erratic extracted flux, with big spikes alternating with no particles at all, which is unacceptable for the experiments.

With the objective of assuring quality beams, the scheme developed at LEAR instead carefully "diffuses" the beam against the resonance while the particles are still being accelerated. This gives a regular profile of the extracted flux over hours rather than seconds. Similar techniques are now proving invaluable for new machines to provide precision beams, such as those for cancer therapy.

NEW PHASE

In 1987, CERN's antiproton supply was augmented by the new Antiproton Collector ring and LEAR began a new phase of experiments with considerably boosted performance.

By this time, CERN's high energy proton-antiproton collider physics was nearing the end of its career, and LEAR was no longer the poor relation. In 1988, the first full year of operations using the new scheme, LEAR had six times more antiprotons than before. The antiproton supply gradually increased over the machine's lifetime, providing a total of 1.3×10^{14} antiprotons (0.2 nanograms).

In cost-conscious times, even masterpieces of physics have to be sacrificed on the altar of economy. At CERN, the Intersecting Storage Rings, the world's first proton-proton collider, had to be axed in 1984 to release money and resources for CERN's LEP electron-positron collider, then under construction. Twelve years later, LEAR in turn was a victim to CERN's next major project, the LHC proton collider. As if to underline the irony of its premature demise, the condemned LEAR was enjoying ten times more antiprotons than it had a decade earlier.

LEAR is not totally dead however. The LHC is designed to handle heavy ions as well as protons, and CERN's existing ion source and booster cannot deliver the ion beam intensity required for the LHC. LEAR (rechristened LEIR for Low Energy Ion Ring) joins the LHC injector chain. This time the emphasis is on injection and accumulation of ions from the linac rather than ejection to experiments, but the idea is similar. LEIR will keep pace with particle energy in the linac as it is increased, accepting particles over many LEIR turns rather than a single turn. Trials showed that doing this at the same time as applying electron cooling was initially difficult

as ions recombined with the cooling electrons, but subsequent work showed how this could be overcome and big gains in intensity via stacking become possible.

The destiny of Shakespeare's King Lear was largely shaped by his three daughters. Apart from its physics discoveries and machine physics achievements, LEAR too was the father of a progeny of daughter rings which all use beam cooling techniques—ASTRID (Aarhus), CELSIUS (Uppsala), COSY (Jülich), CRYRING (Stockholm), ERS/SIS (Darmstadt), IUCF cooler (Bloomington, Indiana), TARN (Tokyo), and TSR (Heidelberg).

At CERN, the recently completed antiproton decelerator, a simpler machine than LEAR, will continue CERN's antiproton traditions.

