

From AA to Z

was possible. In theorist Sidney Coleman's words, 't Hooft's work turned the Weinberg-Salam frog into an enchanted prince.'

In 1979, Sheldon Glashow, Abdus Salam and Steven Weinberg shared the Nobel Prize for Physics, a courageous move by Stockholm in view of the fact that the W and Z particles predicted by the electroweak theory had not yet been discovered. As one notable experimenter was heard to remark on learning the news, 'does this mean they'll have to give the prize back if we don't find the Z?' The question was to remain a hypothetical one.

(Most of the quotes used in this article come from the Nobel laureates' lectures. Extracts were published in the CERN Courier, November 1980, pages 350-7, and the full versions are to be found in Reviews of Modern Physics, July 1980 issue, vol. 52 No. 3).

The conditions for proton-antiproton physics were attained thanks to a remarkable sequence of developments in accelerator physics.

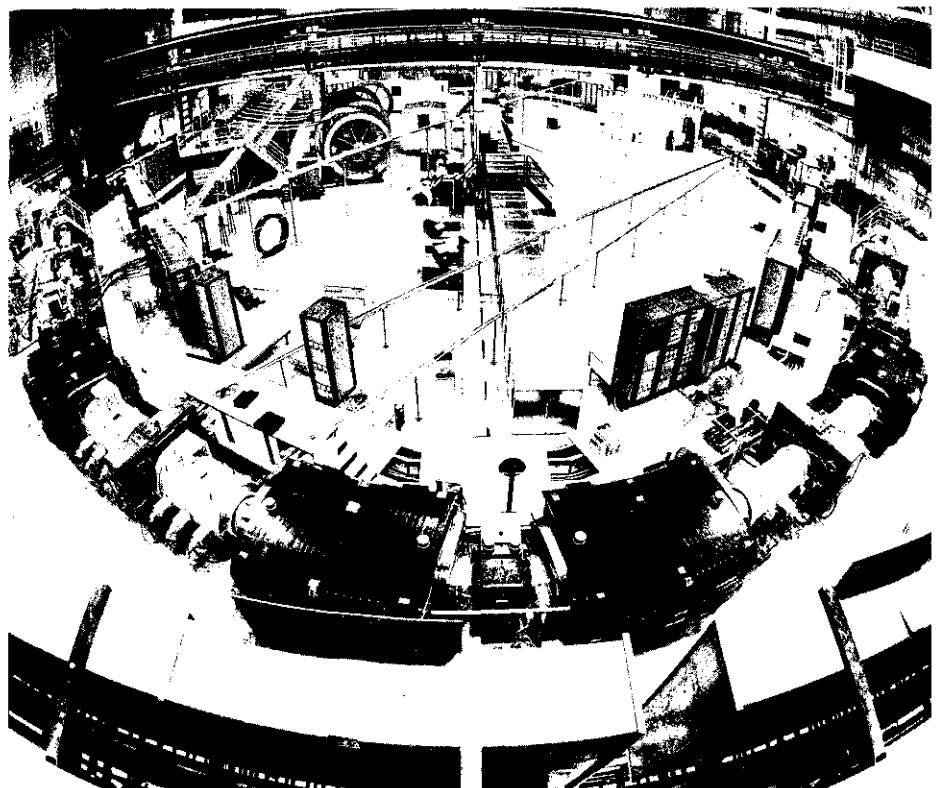
The first ideas about beam cooling (though not, in the end, the ideas used in the CERN project) came in 1966 from the imaginative Gersh Budker and his colleagues at Novosibirsk. They were then launching a 25 GeV proton-antiproton storage ring named VAPP-NAP and obviously needed some scheme to produce intense antiproton beams.

They termed their technique 'electron cooling'. The idea was to run an electron beam along with the antiproton beam at the same velocity and to continually refresh the electron beam. The electrons have precisely the desired momentum and, in their collisions with the antiprotons, energy is transferred in such a way that the continually refreshed electron beam conditions gradually pre-

dominate. The antiproton beam settles around the desired momentum.

In 1974, tests led by A. N. Skrinsky in a small storage ring, NAP-M, at Novosibirsk demonstrated that cooling was being achieved. These results were confirmed later at CERN and at Fermilab. However the alternative idea of stochastic cooling (described in our opening article) from Simon van der Meer proved so successful that in the final schemes for proton-antiproton colliding beams at both CERN and Fermilab, electron cooling was dropped.

The first successful tests on stochastic cooling took place on 21 October 1974 on proton beams in the Intersecting Storage Rings. This followed the development of electronics sufficiently fast (GHz range) to allow the beam to be monitored in an intersection region on the machine (using two directional loop pick-ups connected to a differ-



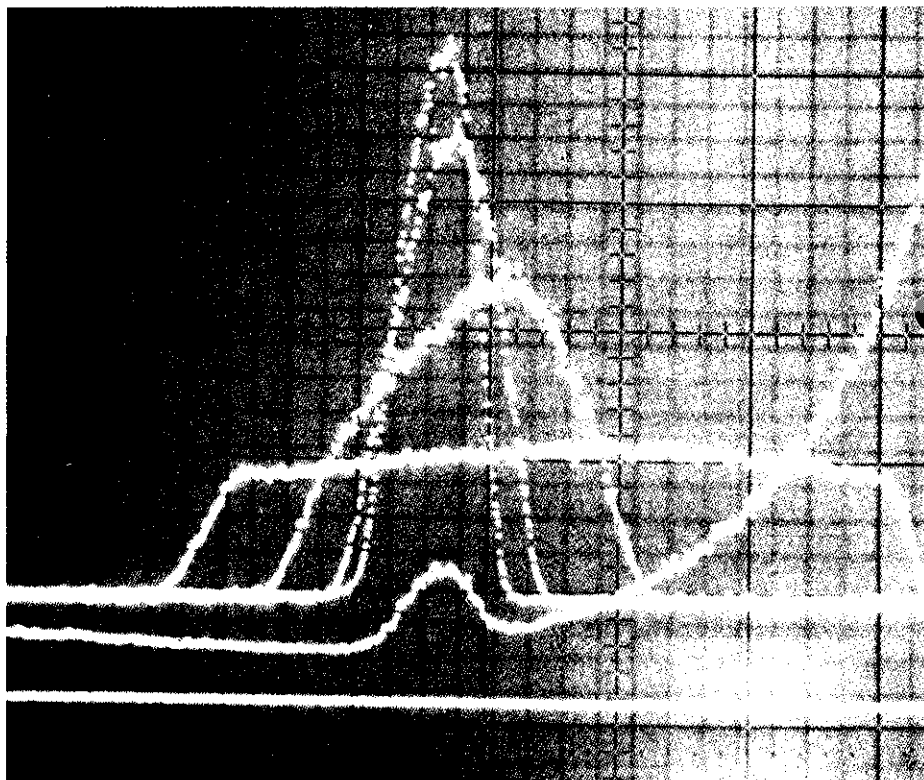
The Antiproton Accumulator, the heart of the CERN antiproton project.

(Photo 582.10.80)

encing transformer) and to transmit the appropriately amplified signal to kicker magnets in the next intersection region. Thus the signal bypassed an arc of one eighth of the machine, racing the beam around the ring so that the same slice of beam could be acted upon. Over seven hours, a cooling rate of 2 per cent per hour was achieved.

This modest success gave encouragement to those who were working on the better understanding of the theory and on improving the hardware — people like Hugh Hereward, Dieter Möhl, Bob Palmer, Frank Sacherer, Peter Bramham, George Carron, Leo Faltin, Kurt Hübner, Wolfgang Schnell and Lars Thorndahl. The initial tests were concerned only with reducing the vertical spread of the beam. In 1976 the horizontal spread received the same treatment in the ISR and the results were again in excellent agreement with theory. With low intensity beams (around 5 mA), cooling rates went as high as 10 per cent per hour.

It was about this time that serious high energy proton-antiproton schemes began to emerge at CERN (spearheaded by Carlo Rubbia and studied in groups led by Franco Bonaudi) and at Fermilab (promoted by Dave Cline, Peter McIntyre, Fred Mills and Carlo Rubbia). At CERN, so as to gain more information on the potential of the two cooling techniques, it was decided rapidly to convert an existing small storage ring (the g-2 ring previously used for high precision measurements of the muon magnetic moment). The project became known as ICE, for Initial Cooling Experiment. The cooling physics was under the supervision of van der Meer, Guido Petrucci led the ring conversion, Thorndahl (who had developed a filter method for improving the effect of the cooling electronics) had responsibility for the



Experiments at the ICE ring at CERN in 1978 showed the shape of things to come. The lower trace with a broad flat plateau shows the wide spread of initial momenta in a stored proton beam. Stochastic cooling reduced the momentum spread, producing the successively sharper peaks.

stochastic cooling system and Frank Krienen for the electron cooling system.

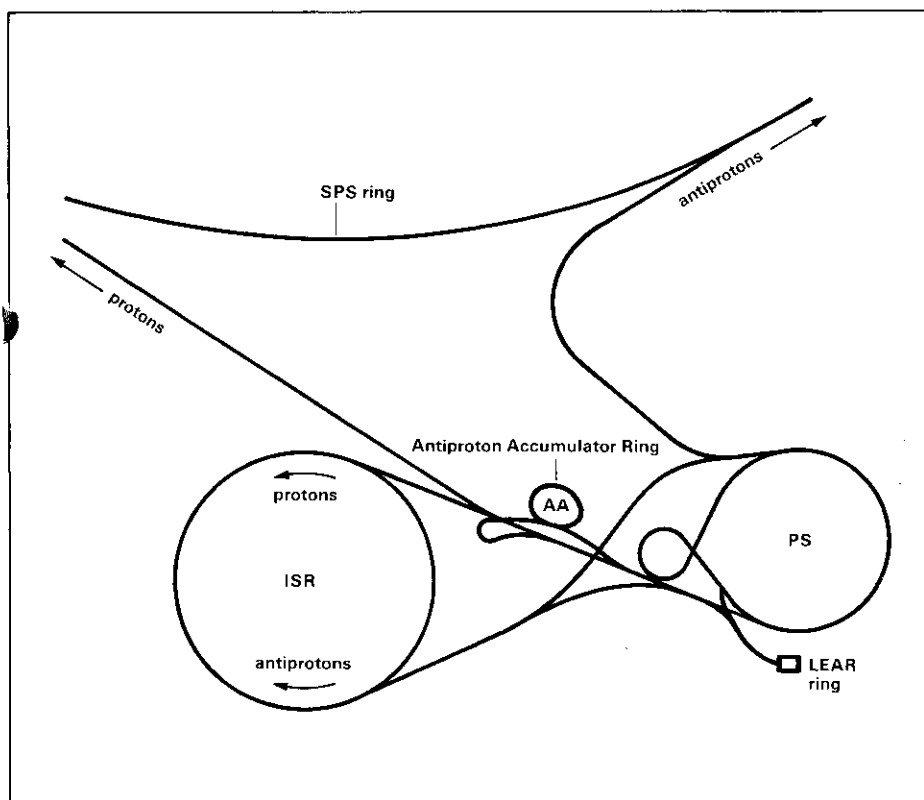
The conversion was completed in nine months and on 5 December 1977 the ICE ring received its first protons. By Christmas stochastic cooling had been achieved in two dimensions. The emphasis by then, in terms of preferred technique, was swinging steadily towards stochastic cooling. This was because, back at the ISR, further work (reported by Oswald Groebner at the Serpukhov Accelerator Conference in July) had pushed cooling rates as high as 89 per cent per hour. The results from ICE carried the preference still further. By the end of March 1978, cooling rates had reached a factor of nine in three minutes.

In May cooling in three dimensions was achieved, demonstrating that compression in one dimension would not lead to blow up in another.

Cooling times were down to 15 s and momentum density increases were a factor of 20. The conviction that stochastic cooling could do the trick became more solid; the CERN proton-antiproton project was drawn up in detail and presented to the CERN Council for approval in June 1978.

(To conclude our story of the ICE age, in May 1979 electron cooling was tested for the first time. Good results were achieved during the year. There was also a nice bit of particle physics en route. Prior to ICE, the antiproton was known to be stable for at least 140 μ s. Every theoretician knows an antiproton lives as long as a proton, some 10^{30} years or more... but every experimenter doesn't believe all the theoreticians tell him. It was a comfort for the future of the antiproton project to observe an antiproton lifetime of at least many hours in ICE.)

The intricate layout of the CERN antiproton scheme.



How the proton-antiproton project works

The heart of the project is the Antiproton Accumulator (AA), where beam cooling is applied to build up antiproton beams containing up to 6×10^{11} particles, tens of thousands of times more than have ever been achieved before.

Protons are first accelerated in the Proton Synchrotron (PS). Instead of being evenly distributed in twenty bunches around the PS ring, as in a 'normal' acceleration cycle, they are crowded in five bunches in a quarter of the ring. This reduced 'length' of proton beam produces a length of antiproton beam, when striking a target, which fills the circumference of the AA, which is one quarter that of the PS.

The sequence in the PS is to take 150 mA of protons at 50 MeV and

150 μ s pulse length from the linac into the 800 MeV four-ring Booster. The protons are ejected two rings at a time so that bunches are combined vertically. The resulting ten bunches are combined via the r.f. in the PS to give the required five bunches.

When the protons in the PS have reached an energy of 26 GeV they are ejected towards the AA and strike a target in front of the ring. From the spray of secondary particles which emerge, a focusing system (magnetic horn) selects antiprotons of energy around 3.5 GeV for injection into the AA. It is at this energy that the maximum yield of antiprotons from the target occurs. For each pulse of ten million million (10^{13}) protons on the target, it was anticipated that some 20 million (2×10^7) antiprotons would be injected into the ring; i.e., for every million protons hitting the target, only two antiprotons are collected. (This de-

sign prediction proved to be a factor of two too high and antiproton production has been a limitation on the performance so far.) These pulses are repeated every 2.4 seconds.

Since the AA is required to provide beams containing 6×10^{11} particles, some 100 000 pulses from the PS (about three days' operation of the machine) are needed to supply all these antiprotons.

The sequence of diagrams (next page) summarizes the stacking and cooling procedure in the AA. The black outer line indicates a cross-section through the vacuum chamber of the ring. The chamber is unusually large (70 cm wide) to give space for all the necessary manoeuvres, and it is held at a high vacuum (10^{-10} torr) to minimize loss of antiprotons due to collisions with residual gas molecules.

The first pulse is injected into the ring by 'kicker magnets' so that the antiprotons orbit on the outside of the vacuum chamber. During injection this outer region is shielded from the rest of the chamber by a mechanically operated metal shutter. This shields the antiprotons, which will be stacked in the main body of the chamber, from the magnetic fields of the kickers, and makes it possible to cool the low-density injected beam without being swamped by the much stronger signals from the high-density stack. The first injected pulse of some five million antiprotons is observed at pick-up stations, and other kicker magnets act upon it to cool the antiprotons.

In two seconds the injected pulse is precooled so that the random motion of the particles is reduced by a factor of ten. The shutter is then lowered and radiofrequency fields are applied to move the precooled antiprotons into the main body of the chamber (into the stack position).

The shutter rises again and the

The technique used in the Antiproton Accumulator to build up intense stacks of antiprotons.

second pulse is injected to receive the same treatment.

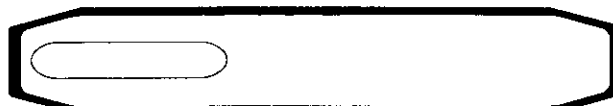
While the sequence of injection, precooling, and transfer to the stack proceeds, cooling systems act on the stack. Their aim is to further concentrate the beam, ultimately by a factor of a hundred million. (Compare this to the figures cited earlier from the initial tests!) After 150 pulses are stacked, some six minutes after injection began, about a thousand million (10^9) antiprotons are in the stack being progressively cooled.

After about 3 hours and four thousand five hundred injected pulses, when some 3×10^{10} antiprotons are orbiting in the stack, a distinct concentration at the value for which the cooling is tuned begins to appear. Within the stack a core is forming near the inside of the vacuum chamber.

After 120 hours and 180 thousand injected pulses, some million million (10^{12}) antiprotons are orbiting in the stack. The majority of them (6×10^{11}), after the many hours of cooling, are concentrated in the core, and radiofrequency fields are then applied to extract the core, providing the intense antiproton beam for colliding beam physics.

A residue of some 4×10^{11} antiprotons remains in the stack in the AA and this is used to start the formation of the next core. Injection of pulses of antiprotons continues so that after a time (about a day) another core of antiprotons is cooled and is ready for ejection.

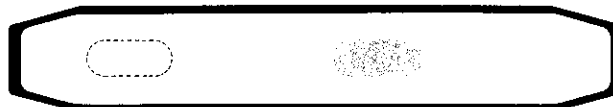
Because of space limitations in the AA ring, the injection and ejection systems are located in the same section of the ring. It is therefore necessary to turn the antiproton beam around in a loop of magnets so that it travels towards the PS, where it is injected to circulate in the opposite direction to that of the protons. In the PS the antiprotons are accelerated,



The first pulse is injected into the vacuum chamber.



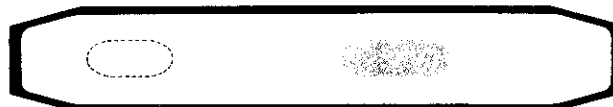
Precooling is applied.



The pulse is moved into the stack position.



The second pulse is injected 2.2 seconds later.



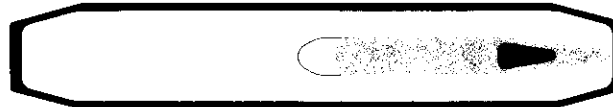
The second pulse is stacked after being precooled.



150 pulses later, the stack intensity is 10^9 antiprotons.



After 3 hours, a dense core is forming in the stack.



After 120 hours the core contains enough antiprotons to be ejected.



The remaining antiprotons are used to start the next core.

Roy Billinge and Co. in the control room of the Antiproton Accumulator during first successful tests in 1980.

(Photo CERN 77.7.80)



in several cycles a bunch at a time, from 3.5 to 26 GeV. At this energy they are sent to the SPS through a newly built transfer tunnel.

At the Super Proton Synchrotron the antiprotons and protons circulate in opposite directions in the same ring. Different injection schemes allow a choice of number of orbiting bunches in each beam. The two sets of bunches are accelerated simultaneously to 270 GeV using two separate radio frequency accelerating systems (an additional system was added to cope with the antiprotons). Using 'low beta insertions', special focusing magnets to squeeze the beams to small dimensions where they collide, the design luminosity (dictating the number of collisions which can be observed) is 10^{30} per square centimetre per second.

Since we are concentrating on the W and Z discoveries, this description of the machine scheme omits

the involvement of the Intersecting Storage Rings, which can also receive antiprotons in one of its rings, and of LEAR, the newly built Low Energy Antiproton Ring which receives decelerated antiprotons from the PS. (What a range of beam gymnastics the PS now has to perform; not bad for a machine which first came into operation 24 years ago!)

Performances to date

On 3 July 1980 proton beams were injected and stored in the Antiproton Accumulator for the first time, just two years after project authorization. Within days, magnet polarities were reversed and antiprotons were injected and cooled. Just a little earlier, on 16 June, the SPS began an eleven month shutdown for final modifications.

On 7 July 1981 the SPS acceler-

ated its first pulse of antiprotons to 270 GeV. Two days later, with a proton beam orbiting in the opposite direction, there was the first evidence of proton-antiproton collisions. In August the antiproton count reached 10^9 and the UA1 calorimeter recorded some 4000 events. In October the first visual evidence of the collisions was recorded in the streamer chambers of UA5.

The first extended run for physics took place in November and December when there were some 140 hours of operation with one bunch of antiprotons in collision with two bunches of protons. The peak initial luminosity was 5.2×10^{27} per cm^2 per s and the integrated luminosity was 2.3×10^{32} per cm^2 . This was too low to have a reasonable chance of seeing a W but it gave the experiment collaborations a good first taste of collider physics to keep them busy while operation was suspended until late 1982 to sort out the accident to the UA1 detector.

In October and November 1982 there were 748 hours, mainly with three antiproton bunches against three proton bunches, giving an integrated luminosity of 2.8×10^{34} with a peak initial luminosity of 5.1×10^{28} . Typical beam coasting time was 15 to 20 hours and one antiproton shot lasted for 42 hours. The threshold of machine performance had been crossed for observation of the W particles.

The collider run beginning on 12 April this year was even more spectacular. It began with more than a fair share of teething troubles but with consistently improving performance and reliability. When the run was interrupted for maintenance on 16 May, the AA had been ticking over for 808 hours without losing a single stack. After the halt, the low beta quadrupoles were on and the peak initial luminosity climbed to

The experiments

1.6×10^{29} . By the time the run closed on 3 July the integrated luminosity had reached 1.5×10^{35} . The threshold of machine performance had been crossed for observation of the Z particles.

Future plans

At the PS the present ten bunches from the booster will be 'box car' stacked in the transfer line so as to give five bunches in the PS. This process can then be repeated to feed in another five bunches and the process of combination in the PS ring will result in putting more protons (some 2×10^{13}) on the antiproton production target at the AA.

In the AA new ferrite pick-ups will improve precooling at higher antiproton fluxes and a series of improvements to the cooling electronics are under way. A new injection damper should improve injection of the antiprotons into the PS. In the SPS, the number of colliding bunches will be increased from the present three per beam, the low beta insertion could be made stronger and it might be possible to increase the peak energy of the collider to 310 GeV to increase the W and Z production rates.

Longer term, the possibility of adding a separate ring, an Antiproton Collector, ACOL, has been studied with the aim of accumulating antiprotons at ten times the present rate. This is similar to the scheme at Fermilab where a proton-antiproton collider of up to 1000 GeV energy per beam has become feasible with the operation of their superconducting synchrotron (see page 380).

Although the collider, scheduled to run for physics again in autumn 1984, has yet to reach its somewhat ambitious design performance, this has hardly detracted from the richness of the physics results. Perhaps

never has a new energy range given so many important new results so quickly. A fitting tribute to the inventiveness, skill and ingenuity of the machine physicists who made it all happen.

UA1 and UA2 represent the accumulation of many years of knowledge and experience in the design, construction and operation of particle physics experiments.

The CERN Intersecting Storage Rings (ISR), a masterpiece of a machine, was built ahead of its time in the sense that only towards the end of its lifetime has it been equipped with detectors that do justice to the available physics.

The designers of the UA1 and UA2 detectors had no reason to be caught in the same trap. For the SPS proton-antiproton collider, the aim was to have maximum detector capability right from the start, with adequate tracking and calorimetry (energy deposition measurements); maximum solid angle coverage and powerful data handling systems.

Despite their immense size, the two experiments which discovered the W and Z particles are not readily visible to a visitor to the CERN site. The proton-antiproton collisions which the experiments study take place underground in the ring of the SPS machine, and the detectors are housed in deep caverns.

The 7-kilometre underground SPS ring was designed and built for 'fixed-target' experiments. For this research, high energy proton beams are made to fly off tangentially from the ring. These beams provide the particles which feed the experiments, installed in large, relatively easily accessible experimental halls. Viewed from the elevated gangways, these CERN experimental halls resemble aircraft hangars, but with beamlines and detectors replacing aircraft. The UA1 and UA2 underground halls look very different, but are of the portent of things to come at LEP and other giant new machines to supply colliding particle beams.

Detectors studying colliding beams have to surround the region

On 1 July, Herwig Schopper toasts CERN's achievements at a crowded party to celebrate the end of the epic 1983 antiproton run in the SPS.

(Photo CERN 39.7.83)

