the root of the recent decision to continue fundamental research on antimatter at CERN with the addition of the ELENA ring.

Looking back at the early days of the proton–antiproton collider and the many contributions it gave to fundamental particle, nuclear and atomic physics, one cannot help but being impressed by the role it played in technological advances, which lead to the construction and exploitation of the LHC. Progress on the two fronts feed each other, accelerating the rate of innovative achievements in each of them. The degree of sophistication, in both accelerator and detector technology, which prevailed at the collider was inconceivable at ISR time, as that which now prevails at LHC was unconceivable by then. Yet, all this happened in less than fifty years. It is the pride of CERN, together with the Fermilab Tevatron, to have hosted and fostered such progress so successfully.

6.2 Stochastic Cooling: Technology to Compress the Beams

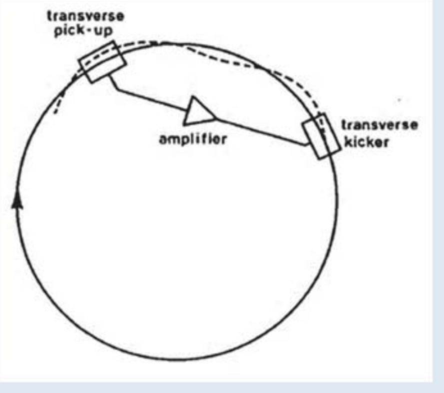
Fritz Caspers and Lars Thorndahl

Stochastic cooling of particle beams, pioneered by CERN, was a condition *sine qua non* for the feasibility and success of the proton–antiproton collider. The required novel technology was developed by a small team, whose nucleus had been formed for the cooling tests at the ISR and included S. van der Meer, the inventor of stochastic cooling. The development concentrated in particular on electrodes, picking up with high selectivity the signal from the beam, the “pick-ups” (PU), and on the pulsed elements (kickers) imparting a kick to the beam particles derived from the signal of the PUs [Box 6.2]. The signal on its way from the pick-up electrode (PU) to the kicker had to be conditioned, without introducing significant delays, such that the signal generated by a beam slice at the PU would arrive in time to impart a corrective kick on the same beam slice (Figure in Box 6.2). Cooling of transverse deviations requires a transverse kick, longitudinal cooling (i.e. in the beam direction), reducing the energy spread and increasing the longitudinal density, requires acceleration or deceleration of the slice. The signal treatment between the PU and kicker needs amplification in well-defined frequency bands and filtering. The systems must have a wide microwave bandwidth as the cooling rate is proportional to the bandwidth of the system. For technical reasons the bandwidth of a system is typically limited to an octave, so the required total bandwidth is often covered with several systems operating in adjacent ranges of frequency. The coupling to the beam should be as strong as possible to keep the power of the amplifier inserted between PU and kickers relatively low [16]. A few prominent examples of these technologies, some of which were at the time at the limit of feasibility, are given below.

Stochastic cooling: Domesticating beams **Box 6.2**

The purpose of stochastic cooling [1, 2] is to increase the density of a beam of charged particles. During this process, the particles are "compressed" into a denser beam with less angular divergence and less energy spread: empty space between the particles is squeezed out. The phase space occupied by the beam is reduced so that a new beam can be added during beam accumulation in the limited phase space of the accelerator, and the final beam can be made denser, imperative for achieving good luminosity in antiproton colliders. Cooling is also used to prevent the blow-up of a stored beam.

The principle of stochastic cooling is illustrated for the case of reducing the wide horizontal dimension of a beam caused by oscillations of the particles around the nominal orbit. Consider first a single particle. A sensor (pick-up) acquires an electrical signal proportional to the displacement of the particle (see Figure) [1]. The signal takes a short-cut across the ring so that the particle receives the kick required to put it on the nominal orbit. Fast signal transmission from pick-up to kicker is vital for the cooling system, as the particles move close to the speed of light. In reality, pick-up and kicker act on a short slice of the beam which contains a small fraction of the total number particles *N*. The slice/sample duration is determined by the bandwidth *W* of the electronics. The damping of the oscillation of the particle is disturbed by the signals from the other randomly distributed particles in the slice. Given the finite number of particles and the sample containing different particles at each pass due to a spread in revolution frequencies (perfect mixing), the displacement of the slice will be different at each passage. The effect of the companion particles in the sample averages out to first order but they produce a second order adverse blow-up of the beam depending on the gain of electronic system. For a properly chosen gain the correction of many samples leads to a slow increase in beam density, i.e. cooling, at a rate $\propto W/N$. So high bandwidth is imperative, and the system works well for low N, typical of antiproton beams. Cooling rate is also reduced by imperfect mixing; thermal noise in the electronics, the power limit of the large-band amplifiers, and pick-up to kicker time-of-flight errors. Longitudinal cooling to reduce the energy spread in a beam and increase longitudinal density works according to the same principle. To sense the energy deviation, a pick-up is used at a point on the orbit where an energy error leads to a large transverse displacement. The signal feeds a kicker producing a longitudinal kick. Transverse and longitudinal cooling must be combined to achieve high beam density.



[1] S. van der Meer, *Rev. Mod. Phys*. **57**, 689-697, (1985).
[2] D. Möhl, *Stochastic Cooling of Particle Beams* (Springer-Verlag, Berlin, 2013).

For the cooling of the longitudinal momenta of the beam particles a method based on *filters with periodic frequency behaviour* was invented [17]. Longitudinal cooling must be sensitive to the different longitudinal momenta of the particles, making use of their slightly different revolution frequencies. The spread in longitudinal momentum is reduced by comparing the revolution frequency of the particles to the nominal value and by a subsequent correction of the deviation with an electric kicker field in a downstream gap, either accelerating or decelerating. The comparison is accomplished by a filter between the PU and kicker which generates the appropriate phase-shift of the signal, depending on the deviation detected leading to acceleration or deceleration. Such filters, having extremely high selectivity, were based on transmission lines with a length corresponding to the nominal revolution frequency. The signal of the beam slice is generated by a PU and amplified before filtering, yielding an excellent signal-to-noise ratio after amplification. This advantage is particularly relevant if the beam has a very narrow energy spread.

Novel *slot-type structures* [18] were developed for both PUs and kickers, for frequencies above 1 GHz, a frequency range not covered by the technology available at the time (coupling loops). They were superior to the loops, which are not wide-band and had no means for the suppression of undesired waveguide modes. The same type of structure acts as both PU and kicker for stochastic cooling of both transverse and longitudinal momentum spread. In order to improve the signal-to-noise ratio at the PU many of these elements were used in a sequential array in the ring. This type of structure was first tested and put into use in the ISR and later adopted for the Antiproton Accumulator (AA). Furthermore, these structures have the attractive features of constructional simplicity and requiring only a small number of vacuum feedthroughs. Figure 6.5 shows such a structure with the coupling slots between the beam chamber and pairs of (TEM) transmission lines on top and bottom. In a PU, these lines transmit the signal from the beam to the amplifier, and when used as kicker transmit the signal from the

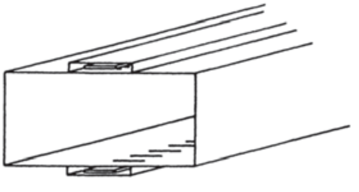


Fig. 6.5. Slot-type PU or kicker. The beam circulates at the centre of the chamber [16].

amplifier to the beam. signals from the individual slots add up to give strong coupling, provided that (i) the slots are small compared to the wavelength of the signals and (ii) the phase velocity in the transmission lines transporting the signal equals the particle velocity which is close to the velocity of light.

In order to satisfy the ever-increasing appetite of antiproton users, the Antiproton Collector (AC) was built around the AA in 1986. From 1987 on, it boosted the accumulation rate, eventually by an order of magnitude. As a maximum of antiprotons had to be accumulated, the beam had large transverse dimensions and the AC provided a matching large transverse acceptance. However, this beam had to shrink very quickly, within 4.5 s, to a size fitting into the acceptance of the AA. This was achieved by using novel *plunging pick-ups and kicker electrodes*, which maximized the coupling to the beam. They had moving electrodes, which followed the shrinking of the beam as it was cooled [19]. Even this was not enough: the PUs, pre-amplifiers, terminating resistors and combiner boards had to operate at cryogenic temperatures — as low as 20 K — to minimize the thermal noise in the RF circuits, which substantially complicated the mechanical design. Figure 6.6 shows such a PU in its vacuum tank.

Two aluminium support structures (to the right and left) would move the many pickup loops (seen here as triangles) by 45 mm each towards the particle beam axis. The many horizontal channels (only their cross-sections are visible) were parts of the signal combiner for the multiple pickup loops. The upper and lower fixed aluminium support structures of 2.2 m length were holders of ferrite tiles absorbing undesirable microwave signals. The silver-plated undulated foils (adapting to the movement) were connections to fixed cold aluminium profiles. Similar flexible foils served as signal connections between the moving support structures and the vacuum feedthroughs. Fixed copper braids established the final thermal leads to the cryogenic sources. Six complete systems covering three adjacent bands in the 1 GHz to 3 GHz range were in operation in the AC. The two systems in each band were for horizontal and vertical cooling respectively; the sum signal of the two PUs served for longitudinal cooling.

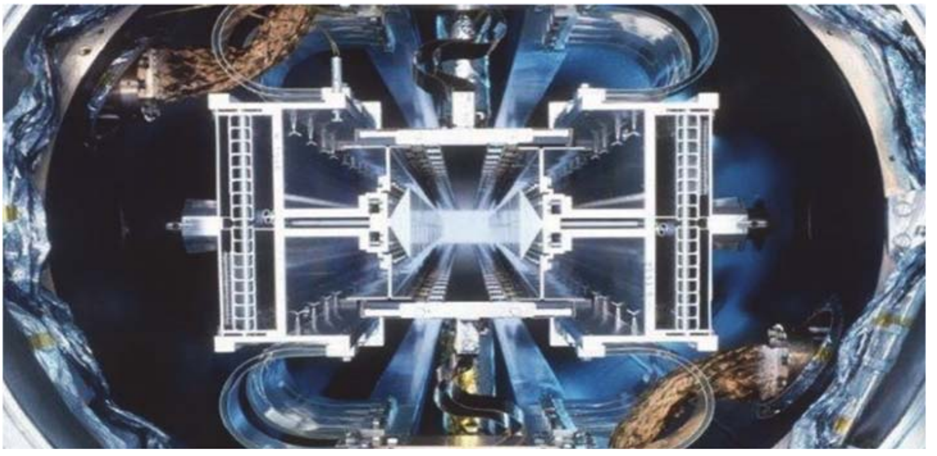


Fig. 6.6. Plunging PU in the AC, seen along the beam. The outer diameter of the vessel is 0.5 m.

The AC also required the development of 100 W *power amplifiers* for the bands 1–1.6, 1.6–2.4 and 2.4–3 GHz. These compact amplifiers were based on four power Field Effect Transistors (FET) per module and four modules per amplifier. Signal input splitting and output combination was performed with four-way elements absorbing electrical mismatches. This design was superior to the competing commercially available traveling wave tubes for several reasons: no high voltages, no cathode heating, better linearity, small phase change with amplitude and better life time [20]. The manufacture of the large series was entrusted to industry after a successful transfer of know-how.

6.3 Radio Frequency Quadrupole: Slowing Down Antimatter

Werner Pirkl

Many fundamental studies with antiprotons require extremely slow antiprotons, with velocities far below the kinetic energy of 5.31 MeV of the antiproton beam, extracted from the AD synchrotron [Highlight 6.7]. To this end a novel "Decelerator" was developed, a variant of the Radio Frequency Quadrupole (RFQ), which decelerated the antiprotons to 55 keV, followed by an integrated superimposed electrostatic energy correction to adjust the output energy between ~10 keV and 120 keV [21].

The RFQ is essentially a modified electric quadrupole consisting of two electrode pairs of opposite polarity, positioned at the diagonals of a square with the beam at the centre. This provides transverse focusing in one plane but causes defocusing at the orthogonal plane. Nevertheless, overall focusing can be achieved