## 1. INTRODUCTION

After initial tests of stochastic cooling in the ISR and ICE machines at CERN[1], the Antiproton Accumulator (AA) was the first machine in which this method was used extensively.

In a typical 48 h accumulation period, we receive 72 000 batches of $\bar{p}$'s that must be superimposed in phase space. Without cooling only about four of these could be accommodated in the AA ring, so that we need to increase the phase space density by at least a factor 18 000. A further large factor is needed to make the antiproton beam fit the longitudinal and transverse acceptances of the receiving machines (SPS, ISR and LEAR). In fact, after 48 hours of operation, we typically achieve a peak density increase by a factor 250 000 longitudinally and 60 both horizontally and vertically. In 6-dimensional phase space we thus gain a factor of about $10^9$.

The theory of stochastic cooling has been treated elsewhere[2] and we shall only repeat its main features here.

Signals from a pick-up are amplified and carried to a kicker. All components of this system are wide-band. Cooling (each particle by its own signal) and heating (signals from other particles and thermal noise) will occur at each Schottky band and the effects from all bands within the system bandwidth may be added. For a system without thermal noise, the rate -per Schottky band- at which the phase space density increases cannot be larger than the inverse of the line density versus frequency dN/df.

We therefore need a low density, i.e. a large spread of revolution frequency $f_0$ across the beam. For a given momentum spread this is obtained by choosing a lattice with a high absolute value of $\eta = p df_0 / f_0 dp$. This quantity, however, also influences the aperture requirements because most of the frequency spread stems from the different orbit circumference for particles of different momentum. In the AA, we have chosen the compromise $|\eta| \approx 0.1$. This value is still low enough to keep the Schottky bands from overlapping in those cooling systems that use filters to discriminate between particles of different momentum.

For reaching the fundamental limit mentioned above we should have optimum system gain and phase at each Schottky band and at each momentum. Practical limitations arise from gain and phase errors or from thermal noise, or simply from the fact that at the optimum gain the output power at the kicker may be higher than can be obtained at reasonable cost.

Each injected pulse of antiprotons (at present consisting of $\sim 6 \times 10^6$ particles) is first precooled longitudinally while it circulates on the injection orbit. This precooling period is freely available since the injection orbit must in any case be separated from the stack and we may as well keep the particles there for one machine cycle.

After precooling, the particles are decelerated by RF and deposited at the high-momentum (low frequency) edge of the stack tail. The longitudinal precooling greatly simplifies the further longitudinal compression needed for stacking the particles. The latter is subdivided into tail cooling (for particles in the low-density stack tail) and core cooling for the high density part.

Horizontal and vertical cooling are also separately applied to the stack tail and to the core.

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Stochastic Cooling
S. van der Meer
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Table 1

| Function | Type | Frequency band (MHz) | Typical power (W) | Number of pick-ups | Number of kickers |
|---|---|---|---|---|---|
| Precooling | long. | 150 - 500 | 2000 | 192 | 200 |
| Stack tail (2 slices) | long. | 250 - 500 | 500 | 16 + 16 | 144 |
| Stack core | long. | 1000 - 2000 | 5 | 1 | 1 |
| Stack tail | vert. | 100 - 300 | 1 | 4 | 4 |
| Stack tail | horiz. | 250 - 500 | 2 | 16 | 8 |
| Stack core | vert. | 1000 - 2000 | 2 | 1 | 1 |
| Stack core | horiz. | 1000 - 2000 | 2 | 1 | 1 |

The main characteristics of the seven cooling systems are given in Table 1, the layout in Fig. 1.

## 2. PRECOOLING

The precooling system handles a low-density beam and is correspondingly fast - it reduces the incoming momentum spread by a factor 10 in 2.1 s. To achieve this, a high power output is needed. In fact, during most of the precooling time, the performance is determined by the available power. This is automatically limited upward by a fast-acting power detector and gain control system to avoid saturation of the power amplifiers.

Filter cooling is used[2-3] and the total cooling period is subdivided into two stages with a different filter configuration for each. During the first stage the beam density is still quite low and a high gain could in principle be used if sufficient power were available. A considerable fraction of the power stems from thermal noise in the pick-ups and preamplifiers; a filter with an amplitude response that is peaked at each revolution band[4] is therefore used (Fig. 2, 3) in order to have a low gain outside the bands. As a consequence, the cooling near the centre of the distribution is somewhat less efficient; since the system gain is well below optimum, a sudden phase jump of exactly 180° in the centre of the distribution would be preferable. However, at this stage the first priority is to push the particles at the edges of the distribution inwards.

The peak filter consists of two sections. The first one (a) has an amplitude response with wide peaks at the longitudinal Schottky bands and deep notches half-way in between; its phase does not vary much inside the bands. The second one (b) is an active filter that produces much sharper peaks, but no notches. Both (a) and (b) contain equalizers that compensate for the frequency dependence of the losses in the long cables $L_1$ and $L_2$. The equalizer in (b) is adjusted so that the open-loop gain is higher at the low-frequency end; the peaks are therefore narrower in that region, fitting the narrower Schottky bands.

During the second cooling stage, section (b) is effectively removed by a voltage controlled 45 dB attenuator Att in the feedback loop and a notch filter (c) is added by powering the low-level amplifier A1 and switching off A2; the resulting response is shown in the lower part of Fig. 3. Filter (c) contains a shorted transmission line L3 of high quality, with an outer diameter of 186 mm. The notches produced by this line are situated at multiples of the central revolution frequency to within a relative rms precision of $10^{-5}$. This precision (necessary because the final rms frequency spread is only $5 \times 10^{-5}$) is obtained by careful machining of the inner and outer conductor and by using inner conductor supports whose extra capacity is compensated by the extra inductance from small grooves in the inner conductor.

The losses in the line produce a quadrature component at the notches; as a result these are less deep and the phase jumps less sharp than is desirable, especially at the higher frequencies. This effect is to a large extent compensated by the equalizer branch connected in parallel to the notch filter that adds a compensating signal varying in the same way with frequency; it is obtained by taking the difference between two signals propagating through two short lines of equal length but with different losses.

The 192 pick-ups and 200 kickers (Fig. 4) consist of rectangular ferrite frames, placed inside ultra-high vacuum tanks around the injected beam with coupling loops at the top and the bottom to extract (or inject) the signal. Each element has an overall length of 24 mm. At the frequencies used (150-500 MHz) the ferrite is quite lossy and separate terminating resistors are not needed. Compensating circuits are mounted inside the vacuum to ensure reasonable matching into a 50Ω line across the entire band. All the kicker power is dissipated in the ferrite and removed by water cooling.

One of the vertical legs of each ferrite rectangle is part of a "shutter"; it may be moved down and up rapidly to allow the beam to be displaced towards the stack. The shutters shield the precooling pick-ups and kickers from the intense stack; the precooling system is switched off while they are open to avoid interference.

It is difficult to measure the sensitivity of longitudinal pick-ups or kickers in a test set-up without beam and it was found that both were performing less well than expected from model measurements, especially at the high frequency end where the coupling impedance was found to be down by a factor five. This aggravated the power limitation problem. Recently, we have doubled the ferrite cross-section in the pick-ups, at the same time using a type with lower permeability but also lower losses at high frequencies (Philips 4E3 instead of 4E2). As a result, the pick-up performance has improved (Fig. 5) and the thermal noise contribution is less important than before; the system will now be able to handle the higher $\bar{p}$ intensities that are expected from various improvements over the next years. Nevertheless, it appears that with presently available ferrites 500 MHz is roughly the upper limit for this type of structure.

The kickers are located at points of large dispersion to obtain a good physical separation from the stack. As a consequence, longitudinal kicks will excite horizontal betatron oscillations because of the closed-orbit shift associated with each energy change. To minimize this effect, the kickers are arranged in two groups separated by half a horizontal betatron wavelength.

## 3. STACKING SYSTEM

After precooling, the particles are captured by RF, decelerated by a few percent and debunched at the edge of the stack. They are then pushed into the stack by the longitudinal stack tail and stack core cooling systems. As a result, the longitudinal density increases towards the stack core by a factor of about 25 000. The cooling rate correspondingly decreases but this is acceptable: while the newly deposited particles have to be removed within the cycle time of 2.4 s, the accumulation of the core takes many hours and the cooling may be much slower there.

The wide range of cooling rate and density across the stack requires a corresponding dependence of system gain on momentum. This is obtained by using pick-ups whose sensitivity depends strongly on the horizontal beam position and placing them at a point where the dispersion is high. The kickers, on the other hand, are situated at a point with zero dispersion so that they do not excite the betatron oscillations; they therefore kick all particles equally.

While the pick-up sensitivity profile provides a strong attenuation of signals from the core particles, the thermal noise from the preamplifiers is not attenuated and it could strongly disturb the core where the cooling rate is low. This problem is solved by using three cooling systems for different momentum slices of the stack. The system that treats the low-density tail particles has a high gain, but its thermal noise components at frequencies corresponding to the stack core may be filtered out; the phase shift caused by the filter is tolerable because the core is treated by a different system. The second tail slice that treats the intermediate-density region uses the same kickers but has its pick-ups nearer to the core so that its gain may be lower. Again, filters remove its output frequencies in the core range. The third system, finally, cools the core. It works at higher frequencies than the other two (1-2 GHz vs 250-500 MHz) and its output power is much lower.

The core cooling system must not only decelerate the particles towards the core, but also accelerate those with the lowest energy because the effect of intra-beam scattering tends to spread out the momentum distribution in both directions. Therefore, the core pick-ups are of the differential type. In Fig. 6 the pick-up sensitivities for the three systems are shown together with a typical density distribution. The filter attenuation curves are also included.

The filter consists essentially of three sections like c) in Fig. 2, without the compensating circuitry and with wider tolerances. These sections are connected in cascade; a fourth section containing two transmission lines in parallel is added. All 5 lines have slightly different lengths, so that the band-stop characteristic of Fig. 6 is obtained.

The tail pick-ups should be quite insensitive to the core particles. This is necessary not only because the high core density requires a low gain at core frequencies -the filters will in any case take care of that- but also because any signal components at the tail frequencies, not attenuated by the filters, will modulate the entire stack; if the tail pick-ups would see the dense core, the system might become unstable owing to this coherent modulation. A few compensation pick-ups (4 out of a total of 32) are therefore installed nearer to the core than the tail pick-ups and their signal is subtracted from the main tail signal, so that the overall response to the core particles is quite low. Unfortunately, with dense stacks some instabilities still tend to develop at particular frequencies, apparently because small asymmetries between the top and bottom halves of the pick-ups permit the detection of wave modes with a vertical electric field component. These modes, generated by interaction of the dense core with asymmetric structures around the beam, are easily propagated in the horizontally wide chamber. The perfomance of the tail cooling is limited by these instabilities, but it is still sufficient at present intensities. It is hoped that the suppression of top-bottom asymmetries in the near future will reduce this problem.

The tail pick-ups are made of quarter-wave coupling loops and their terminating resistors are cooled to about 20°K to improve the signal-to-noise ratio. The tail kickers are of the ferrite-ring type like the precooling kickers, but since they are placed at a zero-dispersion point where the beam cross-section is small, the rings are mounted outside a ceramic vacuum chamber.

The core pick-ups and kickers are of the slot-box type[5]. Although less sensitive per unit length than loop couplers, they are much simpler to construct with the required precision.

The choice of the many free parameters of the stack cooling system was based on lengthy numerical calculations, taking all foreseeable effects into account. The performance to date -except for the small instabilities mentioned above- is not much different from what we expected. In particular, the core particles are not much disturbed by the very strong noise signals at the tail frequencies. It is true that this is predicted by theory; however, this stacking system was an extrapolation of pre-existing experience by several orders of magnitude and probably represented the most important risk in building the $\bar{p}$ accumulator.

## 4. TRANSVERSE COOLING

The injected $\bar{p}$ beam has a maximum emittance of ~90π mm.mrad. For an efficient trar of 1
stacking system (increasing the density by four orders of magnitude) in any way, and it may
be argued that we took a certain risk by starting the project without being able to verify
the core frequencies in the tail cooling systems. These filters also rotate the phase near
the core region in an undesirable way; this does not matter, however, because the cooling of
the core is done by a third system of larger bandwidth (1-2 GHz).

While the particles move towards the core, they are also cooled horizontally and vertically, first by tail cooling systems, then by 1-2 GHz core systems. The layout of the various cooling circuits is shown in Fig, 14. In the general view of Fig. 15, some of the transmission lines transporting the signals for the pick-ups to the kickers may be seen.

When the stack contains a sufficient number of antiprotons (typically 2 × $10^{11}$), a fraction of these (~ 30%) is transferred to the PS and from there to the SPS machine. This is done by bunching a part of the stack, of a width that may be adjusted by properly choosing the RF bucket area[19]. These are accelerated until they are on the same orbit where normally particles are injected. They can then be extracted without disturbing the remaining stack. This process is repeated (at present three times); each time one RF bucket of the SPS is filled. The remaining $\bar{p}$'s form the beginning of the next stack.

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## 11. DESIGN OF LONGITUDINAL COOLING SYSTEMS; FOKKER-PLANCK EQUATION

The main difference between transverse and longitudinal cooling systems is that the latter will change the longitudinal distribution on which the incoherent (heating) term depends, as well as effects such as the beam feedback. This complicates the theory; still, everything can be calculated if all parameters are given.

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