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STOCHASTIC COOLING IN THE CERN ANTIPROTON ACCUMULATOR

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Summary

A short description of the machine is followed by a review of the eight different cooling systems. Some new filter types used for the precooling system are presented, as well as initial experimental results.

General Description of the Machine

The Antiproton Accumulator (AA) was built to collect antiprotons at the rate of ∿ 6 x 10^{11} per day for use in p$\bar{p}$ collision experiments in the SPS (2 x 270 GeV/c), the ISR (2 x 26 GeV/c), or for low-energy $\bar{p}$ experiments with a small storage ring called LEAR that is now under construction. The antiprotons are produced in a target by 26 GeV/c protons and injected into the AA ring at 3.5 GeV/c (near the production peak) where they are cooled and stacked[1].

The most unusual feature of this machine is the stacking mechanism that increases the phase space density by a very large factor. About 36000 pulses are injected over a nominal stacking cycle of 24 h. Each new pulse is deposited by RF at the high-momentum edge of the stack and then pushed "on top" of the already circulating particles by stochastic cooling, so as to make space for the next pulse that will be deposited in the same place after the 2.4 s repetition time.

Before all this happens, each injected pulse is subjected to a fast longitudinal precooling process. This reduces the aperture needed for the stack and facilitates the design of the stacking system.

Finally, there are two horizontal and two vertical betatron cooling systems acting on the particles in the stack.

Figure 1 shows the ring layout with the various cooling systems marked by the transmission lines between their pick-ups and kickers. Because these have to cross the ring in straight lines, the machine was built in a large hall rather than a circular tunnel. This hall also houses much of the associated equipment.

The special egg-like shape of the ring was chosen to obtain two long straight sections (at top and bottom in Fig. 1) with zero dispersion[2,3]. In these sections the beam diameter is small (∿ 6 cm) so that the strength of the injection kicker is kept within reasonable limits. Elsewhere, the chamber is as much as 70 cm wide to accommodate a total momentum spread of 6%. Half of this is used for the stack, whereas 1.5% is needed for the injected beam before precooling. The gap between these two regions is necessary for the movable shutters of the injection kickers, the precooling pick-ups and the precooling kickers. These shutters separate the injected beam from the stack. They are opened for a short time when the precooled beam is displaced towards the stack, i.e. every 2.4 s.

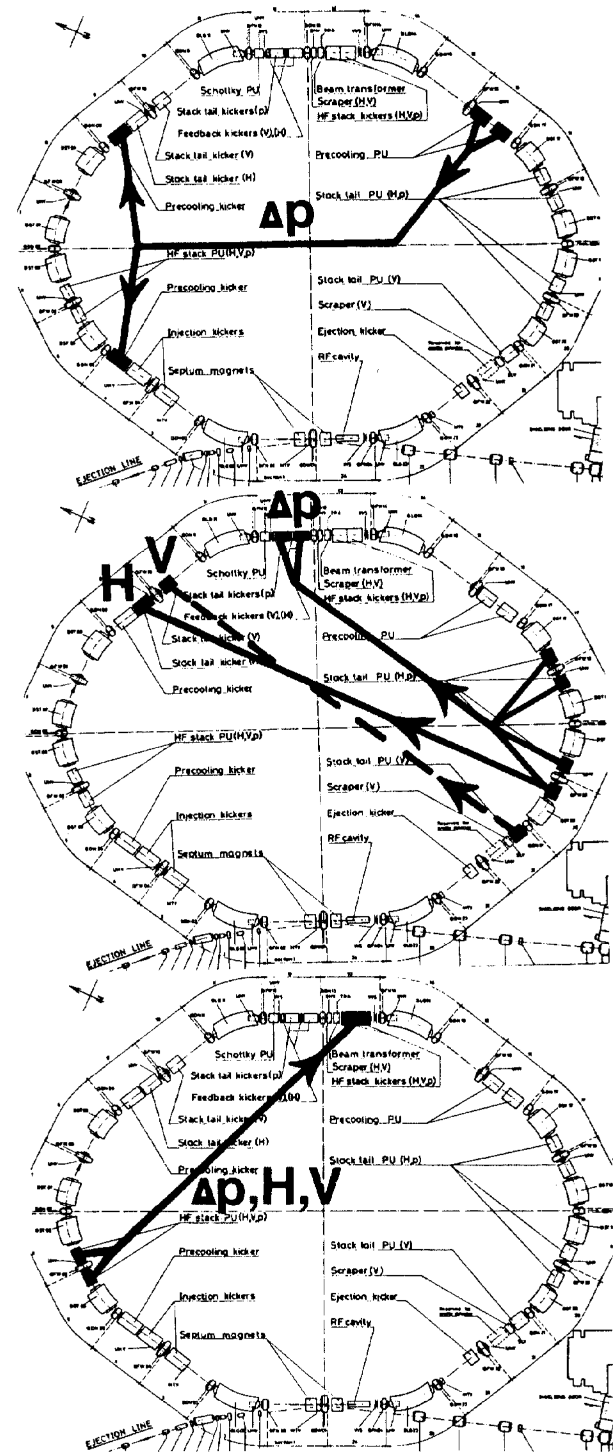

Fig. 1 – Cooling systems. From top to bottom: precooling (150-500 MHz), stack tail cooling (250-500 MHz) and stack core cooling (1-2 GHz). Δp cooling is decoupled from H cooling by placing the kickers where the dispersion is zero or (for precooling) using two sets of kickers at a spacing of half a betatron wavelength.

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Table I gives the main design parameters.

Table I - Main Machine Parameters

Primary p momentum	26 GeV/c
$\bar{p}$ momentum	3.5 GeV/c
p intensity per pulse	10^{13}
$\bar{p}$ intensity per pulse	2.5×10^{7}
cycle time	2.4 s
total filling time	24 h
filling rate	2.5×10^{10} $\bar{p}$/h
mean ring diameter	50 m
$\Delta p/p$ acceptance (full width)	6%
horizontal acceptance } vertical acceptance	10^{-4} π rad m
Q_H	2.27
Q_V	2.26
η = pdf/fdp	-0.1
average pressure	10^{-10} Torr

As of February 1981, about 10% of the nominal stacking rate has been achieved; roughly $^1/_4$ of the expected number of $\bar{p}$'s are injected and a factor 2.5 is lost during transfer to the stack. It seems that the $\bar{p}$ production estimates[1] are substantially correct, but that many small effects contribute to the losses, one of the worst being possibly the sensitivity of the machine to high-order resonances[3] (at least up to order 11). Efforts are made to diagnose and correct these effects. At least at the present reduced rate, the cooling systems seem to perform approximately as required.

Precooling System

This system should compress 80% of the injected $\bar{p}$'s into $^1/_9$ of the injected momentum spread within 2 s. The remaining 0.4 s of the cycle time are used for shutter movement and RF displacement of the precooled beam.

The original design was based on filter cooling, using sum pick-ups of the ferrite ring type, a notch filter and amplifiers covering the range from 150 to 500 MHz[4,5,6]. The ferrite cores of the pick-ups and kickers contain a movable piece ("shutter") to prevent coupling of the cooling circuit with the intense stack, while permitting the passage of the beam after precooling (Fig. 2).

The performance of this system was somewhat lower than hoped for, mainly because the effective impedance of the pick-ups and kickers at the upper end of the frequency range appeared to be lower than estimated from model measurements (Fig. 3). It is notoriously difficult to measure pick-up and kicker transfer functions at these frequencies without actually using a particle beam; in the present case the drop in performance seems to be connected with the increasing ferrite losses at high frequencies.

As a consequence, a somewhat higher electronics gain was desirable and the system became even more power-limited than in the original design. Although within the Schottky bands the signal (Schottky noise) is well above the background noise from the pre-amplifiers, the total power needed mainly depends on the latter, because it covers the entire frequency range between the bands. The sensitivity of the pick-ups is therefore just as important as that of the kickers in determining the output power.

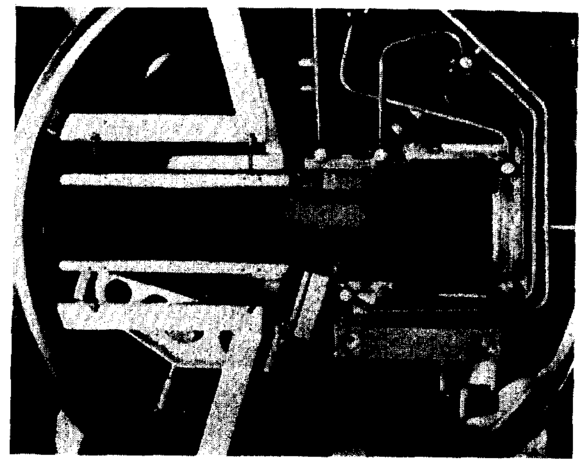

Fig. 2 - Tank with precooling kickers. At right, 100 rectangular ferrite cores, at left the space for the stack. The shutter pivots about a point at the far left and is shown in open (low) position. The ferrite is water-cooled and the entire assembly can be baked at 300°C.

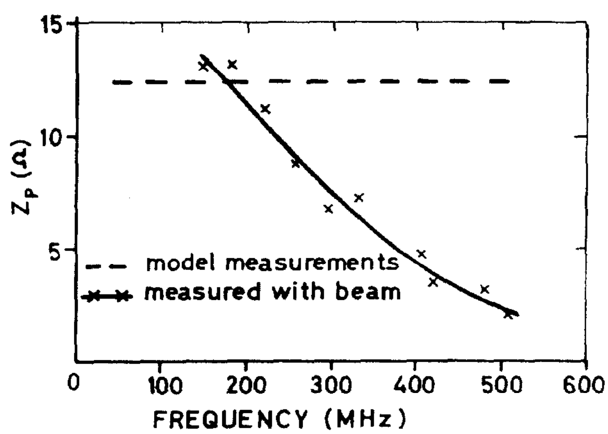

Fig. 3 - Effective precooling pick-up impedance vs. frequency.

An improvement was obtained by using a filter with peaks instead of notches at the Schottky frequencies (Fig. 4), reducing the amplifier noise contribution from between the bands. The opposite phase behaviour around the bands, compared to the notch filter, is compensated by a polarity change. The phase jump at each multiple of the revolution frequency is in practice much less sharp than for a high-quality notch filter, because otherwise the gain would be peaked too much in the centre of the bands. The signal component that is 90% out-of-phase with the particles is therefore more important, but, nevertheless, for the first half of the precooling period the rate is limited more by the available power than by the heating from Schottky noise, so that the peak filter gives better results than the notch filter.

It is in principle possible to make a peak filter by using an open-ended transmission line instead of a shorted one as for the notch filter (Fig. 5a). However, in practice it is difficult to provide the high parallel

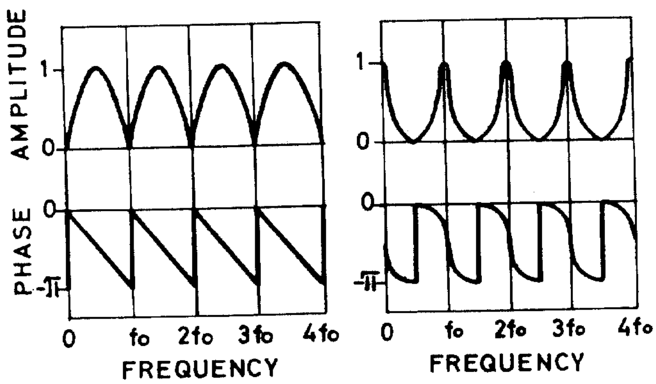

Fig. 4 - Phase and amplitude response of notch filter (left) and peak filter (right), both including an additional constant π/2 phase shift needed for cooling.

resistance that is needed to obtain sufficiently sharp peaks without at the same time suffering from parasitic capacitances at the input end of the line that tend to deteriorate the exact periodicity of the peak frequencies. In addition, the losses of the line itself are a serious limitation. A different design,

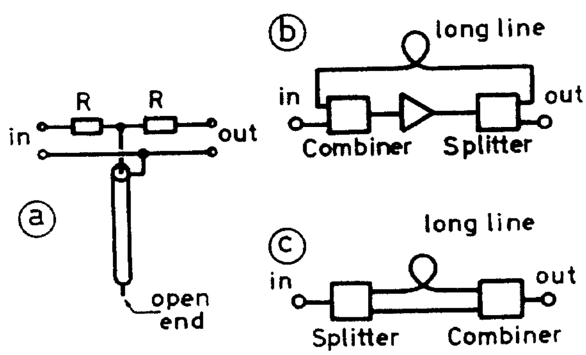

Fig. 5 - Different peak and notch filters

due to L. Thorndahl, was therefore adopted (Fig. 5b). This consists of an amplifier across which positive feedback is applied through a delay line whose electrical length is equal to the nominal machine circumference (i.e. twice as long as the line of Fig. 5a). If the open-loop gain of this active circuit is real, positive and slightly lower than unity, the required peaks will be produced. An advantage compared with Fig. 5a is that the entire circuit may be executed with standard 50 Ω components and that the filter performance is easily adjustable and not limited by the quality of the transmission line (although, as always, the latter must be reflection-free to obtain sufficiently periodic spacing of the peaks). Moreover, by properly adjusting the amplifier gain vs. frequency, the sharpness of the peaks may be made to decrease with increasing frequency, thus matching the increasing width of the Schottky bands.

One difference between Figs. 5a and 5b is that the former also produces notches halfway between the Schottky bands and therefore offers a somewhat better noise power reduction. To compensate for this, we used the filter of Fig. 5c (proposed by G. Carron) in addition to that of Fig. 5b; this produces the notches and it can be shown that Figs. 5b and 5c combined may provide exactly the same response as Fig. 5a. The difference in delay between the two branches of Fig. 5c is again equal to the revolution time. Both Fig. 5b and 5c require equalizers to compensate for the increase with frequency of the losses in the long lines.

With these new filters, the first half of the precooling period has become more effective. For the second half we still use the old notch filter. The overall performance is now about equal to the design figures, although it must be noted that the particle density during precooling is still three times lower than foreseen. Further improvements are being studied.

Table II - Precooling Parameters

Bandwidth	150-500 MHz
No. of pick-ups	192
No. of kickers	200
No. of power amplifiers	50
Total sine wave rating	5 kW
Maximum noise power used	2 kW
Noise figure of preamplifiers	2 dB
Initial Δp/p (full width)	1.5%
Final Δp/p (80% of particles)	0.17%
Total cooling time	2 s

Stacking System

In a normal momentum cooling system (such as the precooling described before), where only a density increase by one order of magnitude is needed, the speed at which the particles must be pushed towards the density peak should be largest at the edges of the distribution and may decrease somewhat towards the centre, where the density (and therefore the diffusion term) increases. However, it is hardly necessary to adapt the system gain precisely to the density profile - as is shown by the successful use of peak filters that produce a gain variation quite different from the theoretically desired one.

In the antiproton stack the density varies by a factor 2×10^4 from the edge where each pulse is deposited towards the peak. Moreover, the particles must be removed from the edge at maximum speed to make space for the next batch, whereas near the peak the cooling may be very much slower. The steadily increasing density and density gradient towards the stack centre require a correspondingly large system gain variation across the profile. This is what makes the stack cooling system so special.

The large gain variation vs. momentum is obtained in our case by the use of pick-ups located at a high-dispersion point in the lattice, and with a sensitivity that depends strongly on the beam position. A complication is that the resulting low sensitivity for particles near the stack centre would make the signal-to-noise ratio too unfavourable in that region. Therefore, the system is subdivided into three different sections[7], each with its own pick-ups located at a different radial position and with properly adjusted system gain.

The kickers belonging to these three systems are located in a zero-dispersion straight section of the machine (Fig. 1, centre and bottom). All particles are therefore kicked equally and it is necessary to protect those at the peak of the distribution (where the cooling is slow) from the high-power noise produced by the faster systems 1 and 2. This is done by inserting noise filters into these systems that reduce the power at Schottky frequencies corresponding to the high-density core of the stack. The filters are made by combining five notch filters for slightly different revolution frequencies to obtain a bandstop characteristic covering the densest part of the stack. The phase shift produced by these filters at the frequencies used for cooling (in the passbands corresponding to the stack tail) is a necessary evil; its average value can be compensated, but the variation with frequency within each Schottky band is unavoidable.

The high power systems 1 and 2 also perturb the particles in the precooling region. This effect is reduced by an order of magnitude by feeding a fraction of their signal into the precooling kickers with the proper gain, delay and phase to obtain compensation.

System no. 3 (for the dense core of the stack) works in the 1-2 GHz band and uses transverse pick-ups and longitudinal kickers of the slotted type[8]. The pick-ups have a sensitivity curve vs. beam position as shown in Fig. 6. The low-gradient part in the centre

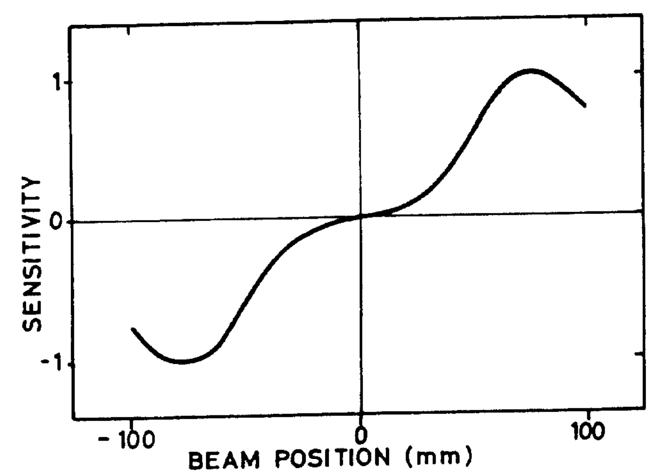

Fig. 6 - Sensitivity vs. position for the 1-2 GHz stack core $\Delta p/p$ pick-up

coincides with the stack peak; it was obtained by choosing a sufficiently wide dead space between the positive and negative rows of slots and it serves to create a more or less flat central part of the stack distribution. This is illustrated in Fig. 7, which also shows how the profile should develop with time. The full-drawn curves were obtained by detailed numerical calculation[5,7], the dotted one shows a measured profile.

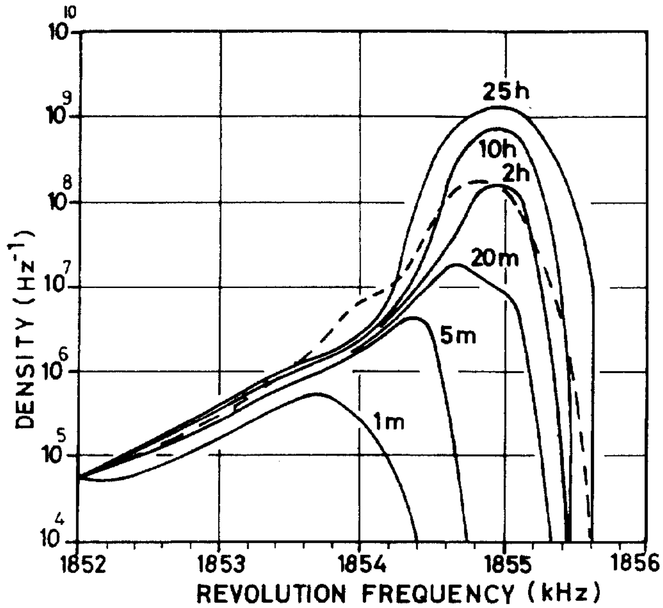

Fig. 7 - Development of stack profile with time (calculated and measured)

The steep flanks of the dense stack core that should be produced by the 1-2 GHz system no. 3 are less pronounced in reality than was expected. Recent adjustments to system 3 have improved this, and as a result the theoretical profiles are now reproduced more closely.

Up to now, antiproton stacks containing up to 3×10^{10} particles have been made, as well as proton stacks with 2×10^{11} particles, i.e. 20% of the design figure. At that value, stacking still continues at the same rate, but instabilities of the 1-2 GHz system tend to develop. These seem to be provoked by reflections from imperfectly matched feedthroughs in the pick-ups and kickers that produce undesirable amplitude and phase response at a few harmonics. Methods to solve this problem are being studied.

Table III - Stacking Parameters

	System 1 (tail)	System 2 (tail)	System 3 (core)
no. of pick-ups	16	16	1
type of pick-ups	loop	loop	slotted
notch filters (coax-lines)	--- 5 ---		0
no. of kickers	-- 144 --		1
bandwidth, lower limit	250	250	1000 MHz
upper limit	500	500	2000 MHz
output power (calculated)			
Schottky noise	-- 150 --		30 W
amplifier noise	-- 150 --		2 W
rated	- 3600 --		200 W

<u>Transverse Cooling</u>

The injected $\bar{p}$ beam has a large emittance and fills the entire acceptance of the vacuum chamber (10^{-4} π rad m in both planes). At the end of stacking, values of a few 10^{-6} π rad m are needed to facilitate transfer to the users and to obtain a high ultimate luminosity.

Horizontal and vertical cooling systems working in the 1-2 GHz range and covering the dense part of the stack are used to achieve this. Since these are not essential for stacking, their performance has not yet been studied in great detail, but is has been verified that typical cooling times are of the order of 15-30 minutes and that the emittance obtained after long periods of stacking is of the order of 5×10^{-6} π rad m.

Additional horizontal and vertical systems covering the stack tail region (where the 1-2 GHz system is ineffective) and working at lower frequencies have been installed as an insurance against possible slow transverse blow-up caused by the longitudinal stack tail cooling. Pick-ups and kickers with sensitivities depending strongly on beam position are used to adapt the gain to the strongly varying particle density; the horizontal pick-ups are, in fact, the same ones as used for longitudinal stack tail cooling. These systems are limited by amplifier noise and cooling times of the order of 10 minutes are expected. In practice, although their cooling action has been observed, they have not appeared to contribute much to the stacking rate.

<u>Adjusting and Testing the Cooling Systems</u>

Most cooling tests have been performed with protons (and inverted polarity of the ring magnets). This operation mode is essential for obtaining dense test beams rapidly.

Because of the large number of cooling systems, the development of suitable test methods has been of great importance. All systems have been equipped with remotely-controlled coaxial relays to permit adjustment of gain and delay, opening or closing the cooling loops, switching on and off individual pick-up or kicker groups, injecting test signals at various points or bypassing the filters to facilitate measurements.

Transfer functions of amplifier chains or filters can be measured from the control room with a network analyser that displays amplitude and phase vs. frequency. It has been found especially useful to inject a strong proton beam with narrow momentum spread, position it at the required momentum by using the RF system, then debunch it and measure the transfer function of an entire cooling loop including kickers, beam and pick-ups. This is done by interrupting the loop somewhere, injecting the test signal after the interruption and comparing the signals before and after the interruption, using two precisely matched cables to the network analyser inputs. This is the best way to establish the correct system phase and delay, by observing the phase as the signal sweeps through each Schottky band (Fig. 8).

For most systems, it was found necessary to design equalizers compensating undesired amplitude and phase characteristics.

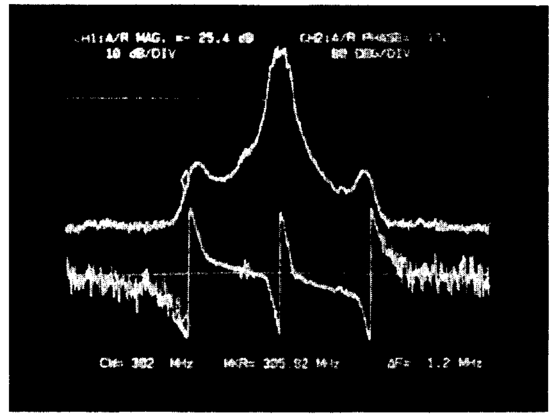

Fig. 8 - Transfer function measurement of the pre-cooling loop (with the filter bypassed). The central amplitude peak (top) corresponds to a longitudinal band where the phase of the beam response (bottom) jumps by 360°; two transverse bands with 180° jumps are also visible

The initial gain adjustment was usually carried out by comparing the measured output power without beam (from amplifier noise) to the calculated one. Final adjustments were done with the beam, optimizing the cooling performance.

<u>Acknowledgements</u>

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