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STACKING WITH STOCHASTIC COOLING

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Abstract

Accumulation of large stacks of antiprotons or ions with the aid of stochastic cooling is more delicate than cooling a constant intensity beam. Basically the difficulty stems from the fact that the optimized gain and the cooling rate are inversely proportional to the number of particles ‘seen’ by the cooling system. Therefore, to maintain fast stacking, the newly injected batch has to be strongly ‘protected’ from the Schottky noise of the stack. Vice versa the stack has to be efficiently ‘shielded’ against the high gain cooling system for the injected beam. In the antiproton accumulators with stacking ratios up to 10^5 , the problem is solved by radial separation of the injection and the stack orbits in a region of large dispersion. An array of several tapered cooling systems with a matched gain profile provides a continuous particle flux towards the high-density stack core. Shielding of the different systems from each other is obtained both through the *spatial* separation and via the revolution *frequencies* (filters). In the old AA, where the antiproton collection and stacking was done in one single ring, the injected beam was further shielded during cooldown by means of a movable shutter. The complexity of these systems is very high. For more modest stacking ratios, one might use *azimuthal* rather than radial separation of stack and injected beam. Schematically half the circumference would be used to accept and cool new beam and the remainder to house the stack. Fast gating is then required between the high-gain cooling of the injected beam and the low-gain stack cooling. RF-gymnastics are used to merge the pre-cooled batch with the stack, to re-create free space for the next injection and to capture the new batch. This scheme is less demanding for the storage ring lattice, but at the expense of some reduction in stacking rate. The talk reviews the ‘radial’ separation schemes and gives also some considerations to the ‘azimuthal’ schemes.

Keywords: stochastic cooling; feedback systems; beam cooling; stacking.

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1. Introduction

In the Antiproton Accumulators (AA) at CERN [1,2,3,4] and at FERMILAB [5,6,7], where stacks of 10^{12} antiprotons were/are accumulated from batches of 10^7 , very elaborate “stochastic stacking systems” had to be used. On the other hand in the FERMILAB recycler ring [8, 9] with stacking factors of < 20 , a simpler stochastic cooling and stacking system is in operation. New interest in these systems arises from the proposals to accumulate rare radioactive ions [10, 11, 12, 13]. This paper reviews the solutions adopted in the ‘old’ CERN AA [1, 14] (used up to 1985), the ‘new AA’ [3] (commissioned in 1987) and also gives some consideration to the ‘recycler scheme’ developed at FERMILAB around 1996 [8].

2. The old AA (1981-85)

2.1. Generalities

At CERN antiprotons are produced by 26 GeV/c protons from the proton synchrotron (PS) impinging on a target. They have a wide momentum distribution that peaks around 3.5 GeV/c. This momentum is therefore chosen to collect and accumulate the $\bar{p}$ -beam. Originally both the collection of the $\bar{p}$ -bursts typically $6 \cdot 10^6 \bar{p}$ (one every 2.4 seconds) and the accumulation to stacks of several $10^{11} \bar{p}$ per day took place in one machine, the “old AA” [14]. To achieve these functions within the same aperture, the injection and the stack orbits were horizontally separated by about 450 mm in a region of large dispersion ($D = r/(\Delta p/p) \approx 10 \text{ m}$). Schematically the aperture was subdivided into two parts: the space for the newly injected beam with an acceptance of $\Delta p/p = \pm 0.75\%$ and the space for the stack (at lower momentum!) with a total momentum width of 2.8% (Fig. 1 and 2). A gap of 160 mm ($\sim 1.6\%$ in $\Delta p/p$) with movable shutters separates the injection region from the stack. Both regions had their specific cooling devices; in total seven different systems.

2.2 Pre-cooling

Each injected pulse is subjected to fast ‘pre-cooling’ [15] of its momentum spread. The main features of the pre-cooling system are summarized in Table 1. The pre-cooling pick-ups and kickers are made of ferrite ‘frames’ surrounding the injected beam (Fig. 2). In this way their effect is strictly confined to the injection orbits. The frames are about 25 mm thick and provide $\sim 300 \text{ mm} \times 150 \text{ mm}$ aperture (h x v) for the beam. Signals are coupled in/out via a ‘back leg’ loop on each frame. The arrangement may be viewed as a transformer with the beam as primary and the loop as secondary winding or alternatively as a small ferrite-loaded cavity. When the pre-cooling is finished, the ‘front leg’ of each frame, built as a movable ‘shutter’ [16], is withdrawn (see Fig. 1 and 2) and the beam is moved (decelerated!) towards the stack by an RF-system.

Fig 1 Shutter pick-up with stack and injected beam and associated gain profile (old AA)

Fig. 2 Shutter-pickup and stack with size of beam and particle density

Principle	Δp -cooling by Thorndahl (filter) method
Filters used	Notch filter (using a low loss coax. line), peak filter (coax. lines) to reduce gain between notches Additional (active and passive) elements to 'sharpen' notches
Cooling performance	Reduction from $\Delta p/p = \pm 7.5$ to $\pm 1.5 \cdot 10^{-3}$ for up to $7 \cdot 10^6$ antiprotons in 1.9 s.
Number of pick-up tanks X gaps	2x100
Number of kicker tanks X gaps	2x100
effective impedance per PU gap	12.5 Ω
effective impedance per kicker gap	50 Ω
frequency band	150 – 500 MHz
noise figure of pre-amp (one for each P.U)	3 dB
Schottky signal RMS	~1 KW
Amplifier noise RMS	~1 KW
Rated output power (sine wave 1 dB compression)	5 KW

Table 1: Pre-cooling in the old AA

About 100 frames, housed in a common tank, constitute a pick-up or kicker unit. In total two pick-

up and two kicker units were used to achieve pre-cooling of up to $7 \cdot 10^6$ antiprotons from a $\Delta p/p$ of ± 7.5 to $\pm 1.5 \cdot 10^{-3}$ in ~ 2 s. The pre-cooling system uses the filter method of Thorndahl [17], which is based on the fact that the particle revolution frequency (f_0) depends on momentum (by virtue of $\Delta f/f = |\eta| \Delta p/p$ where $|\eta| = |\gamma^2_{transition} - \gamma^2| \approx 0.1$ in the AA). This method is well suited for low-intensity beams, where the amplifier noise is important: the sum pick-ups used to detect the passage of particles produce a much larger signal than the difference pick-ups necessary in the Palmer-Hereward method [17] of momentum cooling.

The periodic filter, with notches at the harmonics of the nominal f_0 , consists of several passive coaxial lines as well as of active components. They were frequently modified during the history of the old AA. The high quality "main delay line" creates the periodic notches. Additional lines help to ease the task of the amplifier: they reduce the high response between the harmonics, at frequencies where no particle signals are present. Thus the transmission of preamplifier noise, which tends to blind the system, diminishes. With a $\Delta p/p$ of $\pm 7.5 \cdot 10^{-3}$ in the AA, Schottky bands start to overlap only at ~ 1.2 GHz. Hence there was plenty of 'unused' space between adjacent harmonics in the range (150-500 MHz) employed for pre-cooling. A further ingredient helps to improve cooling speed and final $\Delta p/p$: additional lumped elements, both active and passive ones, that enhance the depth, steepness and harmonicity of the notches. This rather low-frequency range permits the use of ferrite frames, which have a double function as both pick-up and movable shutter

The pre-cooling path cuts diagonally through the ring. The two pick-up tanks are in the same straight section whereas the two kicker units are located in two sections with identical optical properties but half a betatron wavelength apart. This avoids transverse excitation ('betatron heating') of the particles: ideally the momentum kick adds but the transverse kicks $D \cdot \Delta p/p$ experienced at the second kicker cancels those at the first one.

After pre-cooling, the batch is captured by an RF system and decelerated by about 3% in momentum to the edge of the stack where it is de-bunched again. This whole process takes about 400 ms and is repeated once every 2.4 s. The stack cooling system

further decelerates the particles towards the stack core and merges the new batch with the stack.

2.3 Stacking theory

The principles of ‘stochastic stacking’, using tapered momentum cooling systems together with elaborate filters, have been developed by van der Meer [18]. The process can be modelled via the Fokker-Planck equation [17]

$$\frac{\partial \Psi}{\partial t} = \frac{\partial}{\partial E} (-F\Psi + D \frac{\partial \Psi}{\partial E}) \quad (1)$$

Here $\Psi(E) = dN/dE$ is the particle distribution with respect to energy. The addition of ΔN ($\sim 7 \cdot 10^6$) particles every Δt ($= 2.4$) seconds can be approximated by a constant influx.

$$\Phi(E_1) = \frac{dN}{dt}(E_1) = \frac{\Delta N}{\Delta t}$$

This yields the boundary condition

$$\Phi(E_1) = -(-F\Psi + D \frac{\partial \Psi}{\partial E})_{/E_1}$$

The coefficients $F(E)$ and $D(E)$ depend on the gain of the system and Eq. (1) can be used to determine the optimum gain profile. In the simplest case (negligible amplifier noise and negligible intra beam scattering) the optimum gain decreases exponentially and the resulting particle density increases exponentially (as indicated in Fig 1) from the stack edge (‘top’, at the right in Fig.1) to the densest part (‘bottom’, at the left in Fig.1) by an amount comparable to the stacking factor. More realistic situations can be analyzed numerically from Eq. (1); in all practical cases the required gain decreases very steeply from edge to the dense part of the stack.

2.4. The tapered stack cooling system

The required gain profile is realized by a tapered cooling system. It consists (Tab. 2) of three different systems (four were foreseen in the design report [1]). A comb filter is added, similar to the one used in the

pre-cooling system, with notches at the harmonics corresponding to the densest part of the stack. The three systems have different pick-ups and amplifiers and additional filters to approximate the desired conditions. All three sections are basically ‘Palmer’ systems, detecting momentum via the horizontal deviation $\Delta x = D \Delta p/p$. Systems 1 and 2, use pick-ups with a sensitivity that depends strongly (Tab. 3) on the horizontal position of the particles. They work most efficiently in the low and intermediate density region of the stack and have the corresponding very high-gain amplifiers required. System 3, which mainly acts on the densest part, has linear pick-ups and lower-gain amplifiers, which eases larger bandwidth. The pick-up (and also the kickers) of section 3 are of special slotted TEM line type [17] which works in travelling wave mode in the band from 1 to 2 GHz.

System	Pre-cooling	Stack tail 1	Stack tail 2	Stack core (system3)
Type	Filter	‘Palmer’ +filter	‘Palmer’ +filter	‘Palmer’
PU	Ferrite loops (with shutter)	Loop coupler (partial aperture)	Loop Coupler (partial aperture)	Slotted TEM line (full aperture)
Kicker	Ferrite loops (with shutter)	Ferrite loops (full aperture)	Ferrite loops (full aperture)	Slotted TEM line (full aperture)
PU gaps	2x 100	2x8	2x8	1 tank (~30 slots)
kicker gaps	2x 100	4x36	4x36	1 tank (~30 slots)
Band [MHz]	150 – 500	250 – 500	250 – 500	1000 – 2000

Table 2: Old AA momentum cooling systems (pre-cooling and stack); to ease comparison some parameters of Tab 1 are repeated

Systems 1 and 2 with more conventional pick-ups and kickers (loop couplers in sum mode) work in the 250-500 MHz band. Additional filters in systems 1 and 2 reduce the influence on frequencies (momenta) outside their working region, especially at the dense core where particles are most sensitive to noise.

Whereas all momentum pick-ups are located in sections with large dispersion, the kickers are at $D = 0$ and thus ‘seen’ by the whole stack. However as the frequencies are different and the pre-amplifier noise is filtered, the stack tail kickers do only tolerable harm to the core and the (weak!) core kickers have negligible influence on the tail.

Horizontal and vertical cooling of the stack, with cooling times of the order of hours, uses partially the same difference pick-ups employed for the momentum (Palmer-) cooling, partially the same kickers in difference mode instead of sum mode for Δp kicks and partially dedicated pick-ups and kickers (Fig 3). A summary is given in Tab. 2 and more details can be found in [14].

Machine	Old AA	New AA
Intensity of injected batch	$7 \cdot 10^6$	$6 \cdot 10^7$
$\Delta p/p$ initial/final after pre-cooling /stack core (90% beam) [10^{-3}]	$\pm 7.5 / \pm 1.5 / \pm 1.5$	$\pm 1. / \pm 0.26 / \pm 1.5$
Initial/final emittance after stacking (95% beam) [π mm mrad]	85 / 1	6 / 2
Pick-ups and kickers	ferrite frames with shutter	partial aperture loop couplers
Largest stack/stacking factor attained	$2.8 \cdot 10^{11} \bar{p} / 4 \cdot 10^4$	$1.3 \cdot 10^{12} \bar{p} / 2 \cdot 10^4$

Table 3: Comparison of the old and new AA rings

3. Cooling and stacking in the “new AA”

In 1986 a new ring, the Antiproton Collector (AC) [3, 19] was built around the AA to increase the available flux by a factor of ten. The AC had larger acceptances than the AA (by a factor of 4 for momentum and about 2.3 for each transverse emittance) and was designed for fast cooling, in all three planes, of the burst from the target

The batch was then transferred to the AA before a new injection in the AC could start. A similar two-

ring scheme has been used right from the start for the FERMILAB $\bar{p}$ -source [5, 6, 7].

The performances of the old and the new CERN AA rings are compared in Tab. 3 and the parameters of the cooling systems in the new AA are summarized in Tab. 4. With respect to the old AA the following can be noted:

- The stacking factor changes only insignificantly but the intensity of the batches increases whilst their emittances and $\Delta p/p$ after pre-cooling in the AC decrease, each by about a factor of ten. Thus basically the same philosophy and similar systems but all with a much larger bandwidth had to be used.
- Shutters separating the injection orbits from the stack are no longer necessary, because the injected beam, thanks to its small size, can be accommodated with a sufficient horizontal distance from the stack.
- Although the AC / new AA was designed for a 2.4 s cycle usually a 4.8 s interval between injections was adopted (with little ‘penalty’ on the $\bar{p}$ flux but the advantage of leaving more PS-cycles available for other uses)
- Time required for bunching/de-bunching

Fig 3 Pick-up with strong transverse variation of sensitivity; layout and associated gain profile

System:	Pre-cooling	Stack tail 1	Stack tail 2	Stack core
Type	Filter	Palmer + filter	Palmer + filter	Palmer
PU structure	Loop coupler (partial aperture)	Loop coupler (partial aperture)	Slotted TEM line (partial aperture)	Slotted TEM line (full aperture)
Kicker structure	Loop coupler (partial aperture)	Slotted TEM line (full aperture)	Slotted TEM line (full aperture)	Slotted TEM line (full aperture)
Nr. of PU gaps	2x 96	1 tank (~36 loop)	1 tank (~30 slots)	2 tanks (~2x30 slots)
Nr. of kicker gaps	1x 96	1 tanks (~30 slots)		2 tanks (2x~30 slots)
Band, overall [GHz]	0.9 - 2.4	0.9 - 1.7	1-2	1 - 4

Table 4: Pre-cooling and stacking system in the new AA

4. Azimuthal stacking in the FNAL recycler

4.1 Short description and function of the recycler

The FNAL recycler [8, 9] is a 8 GeV, 3.3 Km circumference storage ring. Its role is to store several batches of $\sim 10^{12}$ antiprotons from the FERMILAB AA, an to re-condition ‘used’ antiprotons decelerated from the TEVATRON after several hours collision at 980 GeV. The RF-system is designed to produce two or several pairs of barrier voltage pulses per turn [20] that can be timed to different positions on the circumference. These pulses may be viewed as movable walls (Fig 4). They are used to contain different portions of the beam, adiabatically compress or expand them and to create gaps for the injection of new batches. The recycler ring has four stochastic cooling systems. The transverse planes are cooled by betatron systems operating in the 2-4 GHz band. A pair of 0.5-1 GHz and 1-2 GHz stoch. cooling

systems using the filter method is applied for momentum cooling.

4.2 Cooling and stacking scenario in the recycler

The operation of the recycler is complex because both ‘used’ beam from the TEVATRON and cooled batches from the accumulator are combined to build up the stack. A detailed description is beyond the present scope. Instead we concentrate on the elements which are of interest for more general stacking schemes

Fig 4. The principle of stacking with a pair of barrier voltage pulses. Full ring longitudinal phase space sketch. In the top drawing (a) the cooled beam starts off un-bunched. In the bottom drawing (b) a rectangular barrier voltage system adiabatically squeezes the beam into a small fraction of the circumference [8]. New beam can then be injected into the free space and can be cooled and merged with the stack. The recycler uses up to three pairs of barrier voltage pulses which define three portions of the circumference for different beam operations. Merging of stack and new beam is then possible, without passing via a beam de-bunched around the full circumference; {courtesy: Fermilab}

The stacking scheme takes advantage of several (maximum 3 pairs) RF barrier pulses. The spacing of these barriers is carefully selected to reach a suitable compression factor leading to a momentum deviation of slightly less than ± 10 MeV/c which is appropriate for cooling. Several constraints are observed in this operation. For instance in order keep room available for the next batch to be injected, including

contingency for the kicker rise and fall time, the azimuthal space occupied cannot be made too long

The equilibrium momentum spread is given by the interplay between cooling force and heating mechanism, here mainly intra-beam scattering. In addition the effect of stray magnetic fields from the Main Injector causes non adiabatic modulation of the orbit length. At the moment of transfer towards the TEVATRON a very small momentum spread ($\Delta p/p \approx 3 \cdot 10^{-4}$ rms) is required. These considerations determine the momentum cooling strength. By a similar token: betatron cooling has to balance the transverse heating rate due to (very weak) intra-beam scattering and other external heating mechanism (probably due to residual gas) so that the required transverse emittance of 10π mm mrad is reached. For more details we refer the reader to references [8, 21]

4.3 Potential use of a fast azimuthally gated cooling system

For the situation described above, the cooling system parameters are constant or vary slowly over the stacking cycle. This is adequate for the recycler since there is no large difference in density between the newly injected beam and the stack. However for a more general use, in particular if there is a need to 'hide' a big stack from a small newly injected beam, it might be useful to gate the cooling system. With fast switching, one could then hope to approach optimum conditions (gain, bandwidth...) for different portions of the circumference, containing beam with largely different properties (density, emittances, etc). A simple concept is to provide two different cooling conditions, one for the stack and another for the injected beam. One could even think of an additional intermediate section.

The basic limitation in the switching speed is given by the system bandwidth and for 1GHz bandwidth (equivalent to 300ps rise and fall-time) one should foresee at least 3ns rise and fall time for the pin or GaAs FET switches to obtain 40 dB signal separation should be foreseen. Taking into account the length of each barrier bucket and/or kicker gaps shown there should be enough time available to switch between different conditions two or three times per revolution even in 150 m circumference

rings. Any transient noise (glitch) generated from such fast switches would not hit the particles to be cooled and should thus not lead to heating. A critical point is that power amplifiers sometimes show memory effects.

Extrapolating such a scheme from the recycler to a much smaller machine like the Riken AC [4, 14] with about 150m circumference requires fast switching of the cooling system and close control of all transients, ringing and nonlinear phenomena.

Azimuthal stacking does not need the large dispersion required in the antiproton accumulators. On the other hand stochastic cooling is somewhat less efficient due to the higher particle density. Both the stack and the injected beam occupy only part of the circumference and cooling is correspondingly slower than for an un-bunched beam.

Of more concern is the stacking ratio that seems limited by the difference in density, which the cooling system can digest. It has to be kept in mind that the stack needs to be cooled continuously so that after the pre-cooling time there is room for the new batch.

Finally the time required by the RF manipulations may slow down the stacking speed desired for the accumulation of short-lived radioisotopes.

5 Conclusion

Practical and theoretical experience over the last 25 years has shown the feasibility of building large stacks (well beyond 10^{12}) of antiprotons. In all cases a fairly complicated RF gymnastic has to be made operational. When there is a large ratio of stack density to phase space density of the injected beam, adequate matching of the cooling system gain must be foreseen. In this scenario the problem, of how to hide the dense stack from a hot low-density injected beam must be addressed and solved. This stack/injected beam separation has been implemented via specially designed periodic filters in the cooling system as well as radial separation methods (orbit, shutters, special pick-ups). In addition azimuthal separation methods are used. These latter techniques might be extended to future machines where the stacking factor is less extreme than in the antiproton accumulators.

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