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and its application in many different projects**

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Abstract. This paper gives an overview of the evolution of stochastic beam cooling from the very beginning (in 1968) until the present-day (2011). The early history, the main achievements and the growing number of the worldwide applications are outlined.

1 Introduction

Beam cooling [1–4] aims at reducing the size and the energy spread of a particle beam circulating in a storage ring. This reduction should not be accompanied by beam loss; rather the goal is to increase the particle density. The terms beam temperature and beam cooling have been taken from the kinetic theory of gases. Imagine a beam of particles going round a storage ring. Particles will oscillate around the beam centre in much the same way that particles of a hot gas bounce back and forth between the walls of a container: the larger the mean square of the velocity of these oscillations in a beam, the larger the beam size. The mean square velocity spread is used to define the beam temperature in analogy to the temperature of a gas which is determined by the kinetic energy of the molecules.

This report is devoted to the history and the development of one of the beam cooling techniques, stochastic cooling. The outline of the paper is as follows: in Section 2 we give a short summary of the different methods of beam cooling and their motivations. Section 3 is to illustrate some features of stochastic cooling. Section 4 exemplifies the early history, the debut of the theory and the basic proof-of-principle experiments. This section contains a detailed historical table. The final section is concerned with the application of stochastic cooling in different laboratories. Thus Sections 2 and 3 are meant to “set the stage”. Section 4 is a historical review and Section 5 aims to appraise the contributions made worldwide since the 1980s.

2 Nature and purpose of beam cooling

There are several basic motivations for the development of different beam cooling techniques:

- Collection and accumulation of rare particles, for example antiprotons or short lived particles such as radioactive ions or muons.

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- Improvement of interaction rate and resolution in collision experiments with antiprotons or ions.
- Preparation of sharply collimated and/or highly mono-energetic beams for fixed target experiments.
- Preservation of beam quality, mitigation/suppression of beam blow-up.
- Preparation of crystalline beams [5].

Several cooling techniques are operational or have been discussed:

- Radiation cooling (often referred to as radiation damping) of electrons and positrons.
- Stochastic cooling of (anti-)protons and ions.
- Electron cooling of (anti-)protons and ions.
- Laser cooling of particular ions.
- Ionisation- and friction cooling of muons.
- Resistive cooling of charged particles in ion traps.

It is not the place here to describe these different techniques in detail. We just want to offer a brief comparison at this stage of electron cooling and stochastic cooling: both methods can be applied to (anti-)protons and heavier ion beams. Electron cooling, which works by heat exchange with electrons moving at the average velocity of the heavier particle beam over part of the storage ring circumference, is most efficient if the particles are already fairly cold. Stochastic cooling, based on the correction of error signals, is most efficient if the particles are fairly hot. This lends itself to the combination of stochastic “pre-cooling” with “post-freezing” by electrons.

In the following parts of this paper we will focus on the evolution of stochastic cooling.

3 Basic features of stochastic cooling¹

Stochastic cooling uses a broadband feedback system (Fig. 1). The name “stochastic damping” was coined by Simon van der Meer to underline the statistical basis of the method. At its core is the observation that the beam density can be increased by a system that acts to reduce the deviation of small sections, called samples, of the beam. By measuring and correcting the statistical fluctuations of the sample averages (known as “Schottky noise”), the spreads in the corresponding beam properties are gradually reduced. Stochastic cooling may thus be viewed as a “sampling procedure” where samples are continuously taken from the beam and the average transverse position or momentum deviation of each sample is corrected.

A somewhat different picture is based on the behaviour of a test particle. At each passage it receives its own ‘coherent’ kick plus the ‘incoherent’ random kicks due to all other sample members. The sample length T_S (response-time) is given by the bandwidth of the system W through $T_S = 1/2W$ and the number N_S of particles per sample is proportional to T_S . Hence a large bandwidth is important to work with small samples. The sample error used later (Tab. 1) can be understood as the average deviation in position or momentum of the sample constituents with respect to the reference particle for transverse or longitudinal cooling respectively. Another important ingredient is ‘mixing’, that is the renewal of the sample population due to the different revolution frequencies of individual particles.

Based on the ‘sampling’ and/or the ‘test particle picture’ one derives in a few steps a simplified relation for the cooling rate $(1/\tau)$ of the transverse emittance ϵ (square of the beam size)

$$\frac{1}{\tau} = \left[\frac{1}{\epsilon} \right] \frac{d\epsilon}{dt}, \quad (1)$$

¹ See also contribution by Carlo Rubbia in this edition.

Fig. 1. The basic set up for (horizontal) stochastic cooling. The dotted curve traces the motion of a sample with full correction at the kicker. Ideally the population of the samples remains unchanged between pick-up and kicker but changes on the way from kicker to pick-up due to the spread in revolution time.

Table 1. Significance of the parameters appearing in (3).

N :	number of particles in the coasting beam	
W :	cooling system bandwidth	
g :	gain parameter (fraction of sample error corrected per turn)	$(g < 1)$
M :	desired mixing factor (mixing on the way kicker to pick-up = good mixing)	$(M > 1)$
$\tilde{M}$:	undesired mixing factor (slippage on the way pick-up to kicker = bad mixing)	$(\tilde{M} > 1)$
U :	noise to signal power ratio (for single charged particles)	$(U > 0)$
Z :	charge number of beam particles	$(Z \geq 1)$

or for the longitudinal momentum spread

$$\frac{1}{\tau} = \left[\frac{1}{\Delta p} \right] \frac{d\Delta p}{dt}. \quad (2)$$

$$\frac{1}{\tau} = \frac{W}{N} \left[\underbrace{2g(1 - \tilde{M}^{-2})}_{\text{coherent effect}} - \underbrace{g^2(M + U/Z^2)}_{\text{incoherent effect}} \right]. \quad (3)$$

The significance of the parameters appearing in equation (3) is shown in Table 1.

The cooling time constant τ (Eqs. (1) and (2)) determines the exponential damping $\varepsilon = \varepsilon_0 e^{-t/\tau}$ and $\Delta p = \Delta p_0 e^{-t/\tau}$. However for stochastic cooling systems, the value τ is usually not a constant but varies during the cooling cycle as a function of time and increases when U and/or M increase.

Lattice parameters are especially important for the achievement of ‘good’ values of M , and U , maximising the bracket in equation (3). In addition to the struggle for large bandwidth, the advance in stochastic cooling is intimately linked to progress in

dealing with the noise and mixing factors. In summary it can be said that present-day systems are working with a bandwidth of around 1 GHz for an individual cooling system with the possibility of extensions up to nearly 10 GHz by using several cooling bands in the same ring. Limitations on W are discussed in [6].

Turning to the mixing discussed at length in [7], we note that stochastic cooling only works if after each correction the samples (at least partly) re-randomises (desired mixing), and at the same time a particle on its way from pick-up to kicker does not slip too much with respect to its own signal (undesired mixing). The mixing rates $1/M$ and $1/\hat{M}$ are related to the fraction of the sample length by which a particle with the typical momentum deviation slips with respect to the nominal particle. Here M refers to the way from kicker to pick-up ('K to P'), and $\hat{M}$ to the way from pick-up to kicker ('P to K') (Fig. 1). Both depend on the flight-time dispersion which in turn is given by the local 'off-momentum factors'

$$\eta_{kp} = \left(\frac{dT}{T} \middle/ \frac{dp}{p} \right)_{kp} \quad (4)$$

and the similar quantity η_{pk} respectively. For a regular lattice the beam paths 'K to P' and 'P to K' consist of a number of identical cells and one has

$$\eta_{kp} \approx \eta_{pk} \approx \eta = |\gamma_{tr}^{-2} - \gamma^{-2}| \quad \text{with} \quad \gamma = \frac{1}{\sqrt{1 - (v/c)^2}} \quad (5)$$

where γ_{tr} is the γ -value at the transition energy of the storage ring. Equation (5) indicates that for the regular lattice, the local η -factors are close to the off-momentum factor for the whole ring. In this situation the ratio $\hat{M}/M$ is simply given by the corresponding path lengths (L_{pk} and L_{kp}). The usual compromise is to accept imperfect mixing, letting both $\hat{M}$ and M be in the range of 3 to 10, say. The price to pay is a slower cooling rate, than with $M = 1$ and $\hat{M} \gg 1$.

'Optimum mixing lattices' (also referred to as 'split ring designs') have been proposed [7, 8]. However, up to now they have not been used. The idea is to make the path P to K isochronous and the path K to P strongly flight-time dispersive. These lattice properties have to be reconciled with the many other requirements of the storage ring. The next generation of stochastic cooling rings may use such split rings lattices.

There have been many attempts to get bunched beam stochastic cooling operational in large machines. Starting in 1981 S. Chattopadhyay (partly together with Bisognano) [9, 10] established the theory bringing to perfection earlier treatments [11]. Yet bunched beam cooling turned out to be difficult despite the fact that, already in the Initial Cooling Experiment (ICE) at CERN it had been successfully established [11]. However the bunch length in ICE was large. Attempts which failed were in the frame of the SPS $p-\bar{p}$ programme at CERN and later (around 1990) also in the Tevatron at Fermilab. The subtle difficulty is related to unexpected and rather strong coherent signals which persist in the high frequency bunched beam spectrum of the short and intense bunches and which led to saturation of the front end amplifiers. It was only in recent years that this problem was mastered at BNL (at least for gold ions, see Chap. 5.9).

Optical stochastic cooling with a huge bandwidth has been proposed 1993 by Mikhailichenko and Zlotorev [12] and further studied by Zholents and Zolotorev [13]. It is an extension of certain concepts of microwave stochastic cooling into the optical frequency range using different pick-up and kicker mechanisms and structures. It is a potentially promising technique but has never been tested in practice so far. Challenges, amongst other items, may be the stability and linearity of the optical signal transmission chain as well as of the circulating beam.

4 Early developments and tests

In 1968 van der Meer had the first ideas on stochastic cooling. At that time it was already well known that coherent oscillations of the beam centre could be damped by means of a feedback system that uses a pick-up to detect and a kicker to correct the oscillation. Such “dampers” were used since the mid 1960s in several accelerators [14–17] to counteract coherent beam instabilities.

“In the same way the statistical fluctuations . . . , caused by the finite number of particles, can be detected with pick-up electrodes and a corresponding correction applied.” “In other words, the small fraction of the oscillations that happens to be coherent at any time due to the statistical fluctuations can be damped”

writes van der Meer in his 1972 publication [18] of the idea.

The group working on the Intersecting Storage Rings (ISR) at CERN had informal coffee meetings every morning where the latest “gossip” was exchanged and during many of these meetings the idea of stochastic cooling was vividly discussed. Kjell Johnsen, Hugh Hereward, Wolfgang Schnell, Werner Hardt, Brian Montague and many others participated in these excited debates. Schnell and Hereward were great believers and tried to persuade Simon to publish his idea but he refused arguing that it was *“too far fetched . . . to justify publication”*.

In 1971, almost by accident, the signals due to the statistical fluctuation caused by the finite number of beam particles were detected in the ISR [19] – just the signals that are at the base of stochastic cooling. The noise of a coasting beam was observed with very sensitive pick-up electrodes. This noise proved to have a characteristic structure with bands near all harmonics of the revolution frequency, and Schnell coined the name “beam Schottky noise” and “Schottky bands” because of the similarity with the noise of a “DC beam” studied by Schottky in a classical paper in 1918 [20]. Now that the beam Schottky noise had been observed, Simon finally agreed to publish the idea in 1972 [18], although only as an internal note which finishes with a remark that

“... it still may be unlikely, that useful damping could be achieved”.

Yet this very first paper is remarkable as it clarifies at least three important objections which had been thrown about during the coffee discussions.

- First of all the way by which Liouville’s theorem is circumvented. The theorem predicts [21] that (loosely speaking) the beam density cannot be increased by the use of external electromagnetic fields. Simon writes:

“However this theorem . . . is strictly only valid, for an infinite number of particles or for a finite number if no information is available . . . of the individual particles. Clearly, if each particle could be separately observed and a correction applied to it . . . the oscillation could be suppressed”.

Thus stochastic cooling works by acquiring partial statistical information of each particle over many turns.

- Secondly the importance of bandwidth:

“It is clear that . . . the feedback system should have a large bandwidth (that is a short response time). In this way smaller samples . . . of the circulating particles will be seen as separate entities . . . and the ideal of separate treatment of each particle will be more closely approximated”.

- Finally mixing:

“After the beam would have passed through such a damping system [assuming full correction, $g = 1$] . . . it would no longer present any coherent oscillation and further damping would be impossible. However there are . . .

effects that reintroduce randomness, and therefore some coherency: ... not all particles have the same revolution time, due to momentum spread".

On the basis of these observations, the paper gives the theory of betatron oscillation cooling with $g = 1$, with the ISR beam in mind. This was swiftly complemented by a paper by Wolfgang Schnell [22] in which he studied the engineering aspects of a cooling system for the ISR. The electronic noise of the pick-up and preamplifier system (which turned out to be negligible for the ISR but very limiting to later applications) was included in his analysis. The other great merit of Wolfgang was that he introduced Lars Thorndahl and Georges Carron to the subject mandating them with the preparation of the hardware for a test of stochastic cooling in the ISR. Both, Lars and Georges have since spent most of their professional life on stochastic cooling and have made invaluable contributions to both theory and practise.

Another prominent member of the "cooling club" was Hugh Hereward who communicated by distributing handwritten manuscripts (which were abundantly photocopied to many of the observers). On the 1st of December 1972 (a Friday!) he sent around a manuscript entitled: "a paradox in stochastic damping", where he speculates about the damping

"with parameters like Schnells ... of a certain 10^8 protons ... in a beam of 4×10^{14} ... It seems obvious that they are cooled [with the same time constant] just like the others. But if we had the above 10^8 alone in the machine we would not be able to damp them because the statistical signal is ... lost in the pick-up noise. So the damping of a 10^8 proton beam is made possible by adding $(4 - \epsilon) \times 10^{14}$ more protons to it? ... Answer next week."

In the answer Hereward introduces the fractional correction $g < 1$ instead of the full compensation ($g = 1$) and derives the cooling rate as $1/\tau = (W/N)[2g - g^2(1 + U)]$. It indicates that by the proper choice of g cooling may be extended to low intensity beams where the noise to signal ratio U is dominated by electronic noise, $U \gg 1$.

This is the case for antiproton beams and only after Herewards note stochastic cooling of antiprotons was deemed feasible. In another handwritten note "Cooling by Fourier components". Hereward gives a frequency domain analysis of stochastic cooling, pioneering the approach, which was subsequently used with great success both in the theory and hardware design. The frequency domain analysis also permitted him to shed new light on mixing which he did in another note "Mixing by harmonics".

In 1973 Palmer working at Brookhaven National Laboratory published a note [23] in which he considers transverse cooling of both proton beams with ISR-parameters and antiproton beams of an intensity as low as 10^7 . It was probably in a discussion of this note that he mentioned his method of momentum cooling to Thorndahl and Hereward who cite it as private communication (apparently no account published by Palmer exists). The essence of the "Palmer method" is to detect the momentum error through the concurrent radial displacement of the samples and to correct it by an accelerating/decelerating cavity. Hereward, in still another handwritten note: "damping rate for momentum spread and horizontal betatron oscillations", gave a thorough analysis of this method, including the simultaneous horizontal cooling if the distance pick-up to kicker cavity is properly chosen. It was only in 1977 that Hereward finally published some (but not all) of the information contained in his handwritten documents in a short lecture note [24].

In 1974, 7 years after the invention and almost 3 years after the initial publication a first experimental demonstration [25] of stochastic cooling was tried in the ISR. The initiative came from Schnell, Hereward and Hübner and the hardware was built by Carron, Thorndahl, and Bramham. One of the ISR rings was fitted with a simple vertical cooling system. It had a bandwidth from 0.8 to 1.5 GHz, an amplification of 95 dB and worked with 2×10^{13} protons at 26 GeV. When cooling was applied, the

Table 2. History of stochastic cooling I¹.

		Prehistory
Liouville	1838	Invariance of phase space area
Schottky	1918	Noise in D.C. electron beams
MURA group (Lichtenberg, Mills, Sessler et al.)	1956–1958	Liouville's theorem applied to particle storage rings
		History
van der Meer	1968	Idea of stochastic cooling
ISR staff (Borer et al.)	1971	Observation of proton beam Schottky noise in the ISR
van der Meer	1972	Theory of emittance cooling
Schnell	1972	Engineering studies
Hereward	1972–1974	Refined theory, low-intensity cooling, momentum cooling, mixing
Palmer (BNL)	1973–1975	Low-intensity cooling, momentum cooling
Thorndahl	1975	Design of hardware, low-intensity cooling (both transverse and Δp)
ISR staff (Bramham et al.)	1975	First experimental demonstration of emittance cooling
Strolin et al.	1975	$\bar{p}$ accumulation, schemes for the ISR using stochastic cooling
Rubbia et al.	1975	$\bar{p}$ accumulation, schemes for the SPS
Thorndahl et al.	1976	Experimental demonstration of momentum cooling
Thorndahl, Carron	1977	Filter method of momentum cooling
Sacherer, Thorndahl, van der Mee	1977–1978	Refinement of theory, signal shielding, Fokker-Planck equations, stochastic stacking
Kilian et al.	1977	Cooling to permit dense low-energy $\bar{p}$ through deceleration (proposal)
ICE team	1977–1978	Initial Cooling Experiment (ICE) at CERN. Detailed experimental verification of stochastic cooling
Herr, Möhl	1978	First theory and demonstration of bunched beam cooling in ICE
Carron	1979	Correlation notch filter for momentum cooling
Novosibirsk group	1979–1982	Stochastic cooling experiments in NAP-M storage ring, work on cooling theory
ANL-LBL-Fermilab group	1979–1983	Theoretical and hardware studies, stochastic cooling experiments at FNAL using a 200 MeV test ring

¹ Where no laboratory is mentioned, the activities took place at CERN (except for the prehistory).

beam height slowly decreased; without cooling it increased due to multiple scattering. The difference yielded a cooling rate of about 2% per hour which is in approximate agreement with expectation for the experiment. This was a celebrated demonstration, but, in the meantime, the ISR could stack several 10^{14} protons per ring, an intensity so high, that stochastic cooling was no longer necessary, and even impractical because of the beam density limitations by space charge and instabilities and the long cooling times to be expected at the high intensity.

The ISR experiment still used a relatively high number of protons as the early thinking had evolved around high intensity beams. A new era, – partly already

Table 3. History of stochastic cooling II¹.

AA team	1981–1982	Construction and start up of the Antiproton Accumulator (AA) at CERN. Accumulation of several $10^{11} \bar{p}$ from batches of several 10^6
Kilian et al.	1982	Stochastic cooling of heavy ions (proposal)
TARN group at INS Tokoyo	1983–1984	Stochastic cooling experiments in the TARN ring
Fermilab group	1983	Design report of the Tevatron-I project using a debuncher ring and an accumulator ring for fast stochastic cooling and stacking of several $10^7 \bar{p}$ per second
AA team	1983	Design report of the Antiproton Collector (AC) at CERN using fast momentum and emittance cooling
Berkeley group	1983	$\bar{p}$ collection scheme for 20 TeV colliders. Collection of $5 \times 10^8 \bar{p}$ per second (study)
SPS $\bar{p}$ team	1983	Feasibility study of bunched beam cooling in the SPS collider at CERN
LEAR team	1983	Start-up of low energy antiproton physics at LEAR at CERN
Nobel prize in physics	1984	Nobel prize in physics and awarded to Carlo Rubbia and Simon van der Meer

Table 4. History of stochastic cooling III¹.

Fermilab group	1985–1986	Construction and running in of $\bar{p}$ source
AA-AC team	1986–1987	Construction of the Antiproton Collector (AC) at CERN
Groups in several different labs	1986–1993	Commissioning of ion cooling rings with stochastic cooling
AA-AC team	1990	Record stacking rate of $6.13 \times 10^{10} \bar{p}/h$
Fermilab group	1990	Upgrading of the $\bar{p}$ -source. Record stacking rate of $24 \times 10^{10} \bar{p}/h$ (2010)
Several groups	1993	Bunched beam stochastic cooling in large colliders (studies)(Tevatron, RHIC, HERA, ...)
Mikhailichenko, Zohlents, Zolotorev (SLAC, LBL)	1993–1994	Stochastic cooling at optical frequencies (proposal!)
TEVATRON Fermilab	1995	Observation of the top quark
LEAR	1996	Observation of antihydrogen atoms
AD team	1997–1999	Conversion of the AC to the Antiproton Decelerator (AD)
AD Alpha experiment	2010	Trapping of antihydrogen atoms
RHIC Brookhaven	2011	Bunched beam stochastic cooling in RHIC. Improvement of the luminosity by a factor up to 4

¹ Where no laboratory is mentioned, the activities took place at CERN.

anticipated in Palmers 1973 paper –, began in 1975 when Strolin, coming back from a visit to Novosibirsk and Thorndahl realised the interest of stochastic cooling of low-intensity $\bar{p}$ beams for the purpose of stacking.

The process of stacking is discussed in more detail in Sections 5.1 and 5.5 and depicted in Figure 7. In short: in addition to the already existing, rather large circulating beam, consisting of many accumulated pulses, a new small batch is injected

on a slightly displaced orbit and then gently pulled into the main distribution by dedicated cooling systems (stack-tail and stack-core).

Thorndahl supplemented Hereward's notes with a very comprehensive (internal!) report on "Stochastic cooling of momentum spread and betatron oscillations for low intensity stacks" Möhl et al. [26,27] worked out antiproton collection schemes for the ISR, using stacking in an external antiproton accumulator. This centred the interest for stochastic cooling around low intensity beams.

At that time Rubbia et al. were considering the possibility of colliding counter-rotating beams of protons and antiprotons in one and the same ring [28]. The technique had been very successfully used since the 1960s for electron-positron colliders [29] where the positrons were accumulated with the aid of radiation damping. G. Budker had already proposed to use electron cooling of antiprotons to accumulate a sufficient number in order to reach high luminosity in a $p - \bar{p}$ collider [30]. Rubbia and McIntyre [28] proposed to convert the newly built CERN Super Proton Synchrotron (SPS) or the Fermilab Main Ring into a $p - \bar{p}$ collider in order to detect the W and Z bosons predicted by the electro-weak theory. In the first version they considered electron cooling of the antiprotons but finally stochastic cooling was adopted. The reason being that the energy of the antiprotons, about 3 GeV for production from the 26 GeV protons of the CERN Proton Synchrotron (CPS) impinging on a target, was deemed high and the size and energy spread of the antiproton beam were very large. These properties can be much better digested by stochastic cooling which is less sensitive to energy and longitudinal and transverse energy spreads. In the beginning many people, including the CERN and FERMI LAB Directors John Adams and Robert R. Wilson, were sceptical about Rubbia's idea and a renowned physics journal refused publication. But soon, manifestly doped by the advances in stochastic cooling, the attitude changes completely changed: a study group was set up and the proposal for an "Initial Cooling Experiment" (ICE) was readily accepted ("with compliments") by John Adams and Leon van Hove, the Directors-General of CERN at that time.

The ICE ring was assembled in a short time during 1977 from components of the g-2 storage ring previously used to measure the magnetic moment of the muon. The equipment for stochastic cooling was designed and installed by Thorndahl and Carron. A 2 GeV/c beam of around 10^9 protons injected from the CPS was used to verify the multiple aspects of stochastic cooling. An enthusiastic team headed by Guido Petrucci, including Thorndahl, Koziol, Herr (a young visitor from Bonn university) and many other participants ran the tests. Simon van der Meer, at that time still busy pushing the power converters for the SPS to design performance, soon joined in and worked during numerous night shifts. Rubbia came to the control room almost every night to keep himself informed about the progress and make proposals for new tests.

Transverse cooling and longitudinal cooling by the newly invented filter method by Thorndahl [31] and by the Palmer-Hereward method [24] were extensively tested. Even first attempts of bunched beam cooling were successful [11]. By the middle of 1978 all systems worked to expectation [32]. Apart from the increase of the 3-dimensional density, beam lifetimes of the order of a week were reached by counteracting the blow-up due to scattering on the residual gas, which without cooling would lead to lifetimes of only a few hours. This permitted a measurement of the lifetime of the antiproton. It was the very first "particle physics experiment" completed with the aid of stochastic cooling and this experiment improved the lifetime limit in one go from 120 μ s to 80 h. Only a few hundred antiprotons produced from CPS protons could be injected. One essential ingredient in the experiment was the technique to observe as few as 50 circulating particles in a non-destructive manner. This was made possible by stochastic cooling which reduced the momentum spread to 10^{-5} so that a resonant

Schottky noise pick-up, proposed by Schnell, with the corresponding quality factor could be used.

It may be worth to mention an amusing incident here: the filter used for momentum cooling was a transmission line (a “stub line”) with a length corresponding to half the particle revolution time. It was branched in parallel to the cooling path and shorted at the far end.

Accordingly the transmission was (almost) zero at the harmonics of the revolution frequency and increased for neighbouring frequencies, thus forming a “periodic notch filter”. With an additional 90° phase shift the arrangement was made to accelerate/decelerate – via a longitudinal kicker – particles that are too slow/fast until all particles had “fallen into the notches”. This is the principle of filter cooling. In this way, the length of the stub line determined the revolution frequency and with it the energy, to which the beam was cooled.

The stub line was built from a metallic tube into which an inner conductor was inserted and which was attached to the outside wall of the ICE hall. The lifetime experiment was performed in August 1978 and during the day a bright sunshine fell on the tube, leading to thermal expansion. This caused a shift in energy of the beam so that the Schottky cavity recorded a slowly decreasing signal, which could be interpreted as a loss indicating a mean life of the antiprotons in the order of a few days. A few weeks before Giuseppe Cocconi had given a talk where he mentioned that an antiproton lifetime of this order would explain the abundance of matter in the universe. Understandably all persons present got very excited when the “loss” was observed and even started to draft the publication until Lars Thorndahl and Georges Carron adjusted the trombone at the end of the filter line and all the antiprotons reappeared.

Subsequently Carron, Thorndahl’s inventive, meticulous and indefatigable assistant, suggested to change the filter for momentum cooling. Instead of the “stub arrangement” he proposed a “correlation filter”.

The purpose of these filters is for the implementation of strictly periodic notches in the frequency domain at each revolution harmonic. Particles circulating exactly at the nominal revolution frequency will thus not experience any correction that is acceleration or deceleration. Any other particles with different revolution frequencies will be individually accelerated or decelerated and thus after a certain time slide into the minimum of the notch. This may serve as a visualisation of longitudinal phase space cooling.

The correlation filter consists of a short signal path in parallel to a long path with an extra length corresponding to the nominal particle revolution time. This arrangement creates sharp notches at the revolution harmonics. Their form and their spacing are relatively easy to control and the filter can be realised with fibre optic lines. The “Carron filter” has therefore been used in virtually all filter cooling systems following the “ICE times”.

In parallel, and frequently triggered by the ICE results, further important advances of the theory were made. One of them is Thorndahl’s invention of momentum cooling by the notch filter method [31] already mentioned. Here the momentum of a particle is detected by measuring its revolution time. This is done with a sum pick-up which is more sensitive than the difference pick-up used in the Palmer-Hereward scheme. Another advantage is that the electronic noise of the pick-up and preamplifier system is filtered out at the critical frequencies. This, together with the higher pick-up sensitivity, is important for low intensity beams. In fact the cooling of the low intensity batches entering the planned antiproton accumulator (AA) at CERN would have been difficult, had the filter method not been invented in time.

In May 1977 Thorndahl published another important “technical note” where for the first time a Fokker-Planck type of equation is used to analyse stochastic cooling of

momentum spread. This approach has been applied (mainly for momentum cooling) with great success by many subsequent workers. It describes the detailed evolution of the beam distribution function rather than only the cooling of the root mean square width. Laslett working in LBL Berkeley was the first to extend it to transverse cooling [33]. Yet the equation for the energy distribution, was at first accepted with scepticism. In fact Thorndahl's result may be written as

$$\frac{\partial \psi}{\partial t} = \frac{\partial}{\partial E} \left[-F\psi + D \frac{\partial \psi}{\partial E} \right], \quad (6)$$

where $\psi(E, t)$ is the distribution function, F is given by the cooling and D by the diffusion. In plasma physics the Fokker-Planck equation is commonly used in the form

$$\frac{\partial \psi}{\partial t} = \frac{\partial}{\partial E} \left[-F\psi + \frac{\partial (D\psi)}{\partial E} \right], \quad (7)$$

see e.g. [34], where the diffusion constant is under the second derivative.

There was a temptation to use this second form also for stochastic cooling. Finally in August 1977 an experiment in the ISR [35] cleared the question and unambiguously indicated that (in the cooling context and with the definition of D used) the equation given by Thornahl is the correct one.

In 1978, only a few months prior to his tragic death in a mountain accident in the Mont Blanc Massive, Frank Sacherer published his paper on "Stochastic cooling theory" [36]. At that time Frank had already done most prodigious work on beam density limitations. He had come to CERN in 1971 from Berkeley, where he had written his thesis on beam space-charge effects under the supervision of Lloyd Smith. Amongst mountaineers he is famous for several difficult ascents including the "Frank Sacherer trail" pioneered by him in the Yosemite mountains.

His report on stochastic cooling is remarkable as it brings cooling and beam instability theory together. He introduces an effect, known as "feedback via the beam" or "signal shielding". A reduction of the Schottky signals at an intensity just below the threshold of an instability had already been observed in the ISR. Frank could explain this and extended the explanation to stochastic cooling: part of the modulation imposed by the kicker remains coherent over a turn and re-enters the cooling loop. If the gain is too large this leads to exponential growth (beam instability). At the "optimum gain" the instability is still absent but the Schottky signals are decreased compared to their open loop value. These findings show that stochastic cooling works best close to the instability limit and they provide a powerful diagnostic tool to optimise the gain. It can be said that with the "feedback via the beam" the final ingredient of the cooling theory was uncovered.

Having brought to perfection the SPS power converters, van der Meer fully returned to cooling. In parallel to his work for ICE he published a series of papers including his venerable 1978 report on: "stochastic stacking in the antiproton accumulator" [37]. He considers "stacking in momentum space" which makes wide use of the notion of particle flux previously introduced by Thorndahl in the derivation of the Fokker-Planck equation. Each new batch of antiprotons (containing a few 10^7) is deposited at the edge of the stack tail and displaced towards the core by the cooling system to make place for the subsequent batch arriving 2.4 s later. This is repeated some 10^5 times until sufficient $\bar{p}$ -s are stacked. A final density increase – from the stack edge to the core – comparable to the stacking ratio of 10^5 is obtained by two "stack tail" and a "stack core" cooling system. Their pick-ups are centred at different radial positions (corresponding to different momenta) in a region of "large dispersion" where the orbits strongly displace with momentum. This report paved the road

to the CERN Antiproton Accumulator (AA) which was entirely based on the stacking method described.

By the mid-70s interest arose in other laboratories. The work of R.B. Palmer (BNL) [23] and Laslett (LBL) [33] was already mentioned. In 1976 E. Courant convened a two day workshop at BNL on stochastic and electron cooling. It was attended by some 20 physicists/engineers. Further workshops in the USA (LBL Berkeley 1978, University of Wisconsin, Madison, 1978, ...) followed. In 1979 Ruggiero started with two publications in a long series of papers on stochastic cooling. Starting in 1979 Bisognano published several papers on cooling theory [38] using extensively distribution function analysis. In 1979/1980 the Fermilab/ANL-Argonne/LBL-Berkeley group performed a cooling experiment (somewhat similar to ICE) in a specially assembled ring with protons injected from the 200 MeV Fermilab linac [39]. Longitudinal cooling times of 20 s for 1.6×10^6 protons were achieved, in approximate agreement with calculations. The notch filter method was used. Pick-up and kicker were helices which worked as travelling wave structures. Additionally a vertical system also consisting of travelling wave structures was tested. The experiment served as a preparation for the Fermilab antiproton source.

In addition, the Novosibirsk laboratory took an interest in stochastic cooling and, starting in 1979, Derbenev, Kheifets, Demetev and others published papers on the subject, including a 1981 report [40] on tests in the NAP-M storage ring where electron cooling had previously been established.

Thus from a curiosity in 1972 stochastic cooling grew to an (almost) world-wide endeavour in 1980 with some 60 to 80 publications and experimental tests in 3 different laboratories. References to all this early developments are compiled in the bibliography of [41].

5 Application of stochastic cooling in different laboratories

5.1 The antiproton accumulator (AA) and the antiproton accumulator complex (AAC)

The antiproton accumulator proposed 1978 at CERN [42] had a circumference of 157 m and stored the beam at a fixed momentum of 3.5 GeV/c, close to the production maximum of antiprotons by 26 GeV/c protons from the CPS.

Construction of the AA began in 1979, running-in started in the summer of 1980, and since 1981 stacks of several $10^{11} \bar{p}$ per day were routinely accumulated from batches of a few $10^6 \bar{p}$ per second. Already in this early period the increase of the three-dimensional beam density was almost 10^8 , in spite of a missing factor of 8 with respect to the design performance. The layout of CERNs accelerators in 1981 is sketched in Figure 2. In April 1981 the ISR first took an antiproton beam from the AA followed by the SPS on 10 July 1981. The first W data were taken in 1982 and the discovery of the W and Z was announced in 1983. In order to satisfy the ever-increasing appetite of antiproton users, the Antiproton Collector (AC) [43] was built around the AA in 1986. From 1987 on, it boosted the accumulation rate, eventually by an order of magnitude.

In the original AA, a fresh burst of antiprotons remained on the injection orbit for at least 2.4 s for stochastic pre-cooling of the momentum spread using the filter method. The radiofrequency system then trapped and moved them to the stacking region where a first stack-tail momentum cooling system took over. The injection region was now free for the next burst of antiprotons, arriving 2.4 or 4.8 s later. This sequence was repeated during the whole accumulation period of typically 24 h.

Fig. 2. Layout of the CERN accelerator complex in 1981. LEAR, still under construction in 1981 is also shown. The AC has been built around the AA in the same building.

In the AC, a powerful “bunch rotation” RF system (1.5 MV, 9.5 MHz) reduced the momentum spread by turning the incoming 5 antiproton bunches into a nearly continuous beam of lesser momentum spread. Stochastic cooling in all three planes then reduced the beam size and energy spread by large factors. Another RF system (3.5 kV, 1.6 MHz) re-bunched the antiprotons, for ejection and transfer into a matched bucket on the AA injection orbit. Over a day, a stack with a dense core of several 10^{11} antiprotons was accumulated.

The AA, and later the AC, had a large number of stochastic cooling systems: in total 7 in the original AA, 5 in the modified AA and 9 in the AC. As each had to be optimised for a specific task, their characteristics (including pick-up/kicker technology, bandwidth, gain and power, etc.) differed vastly. The pre-cooling systems, acting on the newly injected beam (less than $10^8 \bar{p}$), with time constants of a second, needed high-gain, high-power amplifiers. In the original AA, pre-cooling acted only on momentum spread, using Thorndahl’s notch-filter method. Pick-ups and kickers consisted of short ferrite-frames around the beam, which may be visualised as a fixed “U” shaped part, closed by a movable “I” shaped bar acting as a “shutter”. The “I” shaped bar was withdrawn upwards when the beam was moved out of the precooling region. Signals were coupled out or in, via single turn loops around the short part of the “U”. A 2 m long tank contained 100 frames made of ferrite bars in ultra high vacuum, and there were two kicker tanks and two pick-up tanks. The band used was 150–500 MHz, and the amplifier rating 5 kW.

In the AC, pre-cooling was applied in all three phase planes. Pick-ups and kickers consisted of loop couplers, with electrodes left and right, or above and below the beam. The difference signal served for transverse cooling and the sum signal for momentum cooling. Two plate pairs connected in series formed a “superelectrode”; 24–48 of these

Fig. 3. The AA in its Hall, before it disappeared from view under concrete shielding.

(depending on their frequency band) were housed in 2 m long tanks. The electrodes moved inwards, to follow the shrinking beam size during cooling, thus maximising pick-up sensitivity and minimising kicker power. The low-level components (pick-ups, terminations and preamplifiers) were cryogenically cooled to reduce their noise. Three bands (1–1.65, 1.65–2.4 and 2.4–3 GHz) were used, with three combined horizontal momentum and three vertical momentum systems a total of 6 pick-up tanks and 6 kicker tanks. These tanks, including the highly developed system for the movement of the electrodes, were designed by Millner. They worked reliably during the whole history of the AC. Amplifier ratings were 4.5 kW for the lower band and 2.6 kW for each of the higher bands.

The stacking system was designed in the following way [37]: filter cooling using loop couplers was chosen for the tail systems and Palmer-Hereward cooling using Falin-type slotted TEM lines [44] was applied to the core. Carron's correlation filters were used throughout for the repetitive notch generation. In the original AA, bands of 250–500 MHz and 1–2 GHz performed tail and core cooling, respectively.

When later pre-cooling was done in the AC, simplifications became possible in the AA. In particular, shutters on the injection kicker and on the cooling devices at the injection orbit were no longer needed. Transverse cooling was less demanding, as beams were already pre-cooled in the AC. On the other hand the higher intensity and density put greater demands on stack cooling. The performance was improved by further momentum pre-cooling on the AA injection orbit and by a powerful transverse stack-core cooling system using partly the difference signal from the momentum systems. All cooling systems of the original AA were replaced by higher frequency ones. More details can be found in the parameter lists [45].

From 1990 onwards up to $10^{12} \bar{p}$ /day could be stacked from pulses of 7×10^7 with an increase of the three-dimensional phase-space density of several 10^9 [46].

5.2 The antiproton program of the intersecting storage ring (ISR)

The ISR facility was included in CERN's antiproton program, as there was much promise for interesting physics with proton- antiproton collisions in its energy range. A dense antiproton beam could be transferred from the AA through the 26 GeV/c CERN Proton Synchrotron (CPS) to the ISR (Fig. 2). A major item was a new transfer line from the CPS to the ISR (TT6, Fig. 2). There was stochastic cooling for both protons and antiprotons [47]. When the ISR was used as a $p - \bar{p}$ collider a high intensity proton beam in ring 1 (R1) collided with a low-intensity antiproton beam in R2 for periods of up to two weeks with one single fill. The luminosity lifetime was increased with a vertical stochastic cooling system in R1 designed for currents up to 10 A ($\approx 5 \times 10^{13}$ protons) with a band of 0.85–2.5 GHz. Cooling rates up to 0.7%/h have been obtained. The system was based on the slot type pick-ups and kickers developed by Falin [44]. Both devices were divided into identical halves for treating inner and outer parts of the beam separately.

The antiprotons in R2 were cooled vertically with a 100–600 MHz system which decreased the initial beam height by up to a factor of 7. This increased the luminosity, which was almost entirely determined by the proton beam height, by a factor 1.3–1.4. Loop couplers were used as pick-up and kicker structures.

A momentum cooling system in R2 (frequency range: 55–155 MHz) created space within the stacking aperture. This allowed several stacks from the AA to be stored in the ISR. With this system, it was proven experimentally for the first time, that momentum cooling and horizontal betatron cooling could be obtained simultaneously with the Palmer-Hereward system. The cooling rate of the momentum cooling system which was power-limited was typically 4%/h at 26 GeV/c and for the horizontal cooling a similar rate (3%/h) was obtained.

In April 1981, the first 0.6 mA antiproton beam collided with an 830 mA proton beam, producing a luminosity of $1.1 \times 10^{25} \text{ cm}^{-2} \text{ s}^{-1}$. From then on, many technical and operational improvements led to ever-increasing performance, with a luminosity of several $10^{28} \text{ cm}^{-2} \text{ s}^{-1}$ at the end of the ISR $p - \bar{p}$ collider operation in December 1983. The record antiproton current intensity was 3.8 mA, and the corresponding record luminosity $4.5 \times 10^{28} \text{ cm}^{-2} \text{ s}^{-1}$ [47].

In 1984, the operation continued for a few months with only one ring only, colliding antiprotons at momenta between 3.5 and 6.5 GeV/c with a hydrogen jet target for the charmonium experiment R704 [48]. In these runs, stochastic cooling in all 3 planes was used for the first time to compensate beam heating on an internal target. This novel technique was subsequently practiced at LEAR and many ion cooling rings with stochastic or electron cooling.

5.3 The low energy antiproton ring (LEAR)

Stimulated by the idea for the SPS $p - \bar{p}$ Collider, Kilian et al. [49] realised in 1977 that cooling and deceleration of antiprotons would provide beams of unprecedented intensity and purity for low-energy physics. This led to the proposal to add to the antiproton project a small facility [50] for experiments with cooled $\bar{p}$ -beams in the energy range of 5–1200 MeV. The proposal received enthusiastic support and, in 1980, the Low-Energy Antiproton Ring (LEAR) was launched.

The ring (Fig. 4) with a circumference of 78 m was housed in the old CPS South Hall, which also served as its experimental area. Antiprotons from LEAR were first

Fig. 4. LEAR in the CPS South Hall (1990). The four long straight sections house (going around clockwise, starting with the section left of the red bending magnet in the foreground): electron cooling (SS3 of LEAR); RF-cavities (SS4); injection and ejection (SS1); the internal gas jet experiment “JETSET” (SS2). The detector of JETSET is partly dismantled. A web of coaxial transmission lines for stochastic cooling spans across the ring. The beam turns clockwise and can be ejected to the experiments installed behind the shielding wall which is partly visible on the right.

delivered to users in June 1983. After the end of the SPS collider program in 1991, LEAR remained the only user of the AAC. Its unique but complex and costly operation continued until November 1996 producing interesting results. The setup was used for some time to test ion cooling. In 2006 it began a new career as a Low-Energy Ion accumulation Ring (LEIR) for the Large Hadron Collider (LHC) [51, 52].

LEAR worked with a single bunch, of usually a few 10^9 antiprotons. This bunch was skimmed off the AA stack at intervals ranging from 15 min to several hours. The average consumption, $10^6 \bar{p}/s$, was only 10% of the maximum accumulation rate of the AA. The bunch was decelerated in the CPS to 609 MeV/c and transferred to LEAR, where it could either be decelerated to momenta as low as 100 MeV/c (5.3 MeV kinetic energy), or accelerated, up to nominally 2000 MeV/c (1270 MeV). In the “beam stretcher mode”, used for most of the experiments in order to avoid pile-up of accidental coincidences, ultra-slow extraction provided a continuous spill until the next fill. In the “internal target” mode for the JETSET experiment, a beam with an initial intensity of as much as $5 \times 10^{10} \bar{p}$ was kept circulating for many hours, even days, until most particles had been consumed by interaction with the gas jet target. For trap experiments, one or several bunches were extracted by a fast kicker.

Stochastic cooling in all three planes was optimised for several strategic momenta: 609 (injection), 300, 200 and 100 MeV/c, and 1000, 1500 and 1940 MeV/c on the high-energy cycle. Cooling compensated the adiabatic beam growth during deceleration

and counteracted various heating mechanisms, such as multiple Coulomb scattering, notably on the internal targets of the JETSET experiment. Final cooling was applied at the momentum at which the beam was delivered to the users, to provide a highly monochromatic and small-sized beam. A complex cooling system with a great number of different pick-ups and kickers and containing a plethora of switchable delays was necessary to permit cooling at all momenta.

For sufficient signal level, the pick-up arrays had to be long. As much as possible they were installed inside the vacuum chamber in the bending magnets where space was “cheap”. An ever-growing web of coaxial lines was spun across the ring for the transmission of the signals from pick-ups to kickers. Diagonal paths were necessary at high energy to catch up with the particles nearing the velocity of light. For low energy, shorter paths were possible and favourable to avoid de-synchronisation between off-momentum particles and their correction signal (“unwanted mixing”). Bands from 20 to 200 MHz were used at the lower and 50 to 500 MHz at the higher energies. Several types of pick-ups, mainly loop couplers, but also ferrite rings, and special travelling wave structures were employed at various stages during the history of LEAR. The filter method was widely utilised for momentum cooling. Cooling time constants of a minute at $10^9 \bar{p}$ were reached in all three planes.

From 1987, electron cooling complemented stochastic cooling. The electron cooler, which had already been tested in ICE was resuscitated and upgraded for service in LEAR. The combination of both cooling methods, was thus for the first time practiced. It lead to very high beam quality; emittances of less than 1π mrad mm and momentum spreads of 10^{-4} for $10^9 \bar{p}$ at 5.3 MeV as low as space-charge and instabilities permit.

During the 14 years of operation, the number of antiprotons consumed by LEAR increased from a few 10^{11} to 2.6×10^{13} per year. The total number of antiprotons supplied was around 1.5×10^{14} (0.24 nano-gram). In January 1996, a few months before the final shut-down of LEAR, the detection of 8 anti-hydrogen atoms produced by JETSET was announced. This event found great attention in the media.

5.4 The antiproton decelerator (AD)

Since 1999, 5.3 MeV antiprotons are again available to three (since 2003: four) experiments installed in the same hall as the AD ring.

By 1994 it had become evident that one could not afford for much longer the complex and costly operation for low-energy antiprotons (involving CPS, AC and AA again CPS, and LEAR). The desire of the users’ community to continue the highly interesting physics with low-energy antiprotons initiated a search for a substitute facility, which would satisfy at least part of the program, such as the production of anti-hydrogen.

Studies [53, 54] resulted in the following scheme: the target area for the production of antiprotons would remain as it was; the AA would be removed; the AC would be modified to be ramped from the injection momentum of 3.5 GeV/c down to 100 MeV/c; only fast ejection of antiprotons in a single bunch of about $10^7 \bar{p}$ every minute would be provided. Compared to LEAR one had to accept a large decrease (factor 10) in antiproton flux and the lack of ultraslow extraction, but the number of machines involved was reduced from 5 to 2 and the operational burden greatly relieved.

In 1997, the AA was dismantled and the conversion of the AC into the AD started.

Apart from the magnetic aspects, it is the adiabatic increase of beamsizes during deceleration that posed the greatest challenge. The beam has to be cooled, not only right after injection, but also on intermediate plateaus. The AC stochastic cooling

Fig. 5. A typical cycle of the antiproton decelerator AD at CERN.

system was therefore adapted for additional use at 2 GeV/c. Electron cooling had to supplement it at lower energies.

A typical cycle [55] is shown in Figure 5. Upon injection, the antiprotons fill the acceptances. The bunch rotation system, taken over from the AC which reduces the momentum spread and lengthens the bunches, whereupon stochastic cooling in all 3 phase spaces reduces the transverse beam size and the momentum spread. This now permits deceleration to 2.0 GeV/c, where further stochastic cooling is applied, allowing the next deceleration to 300 MeV/c. Now electron cooling is called upon before the last deceleration to 100 MeV/c where final electron cooling contracts the beam to high density. The particles are then rebunched and rotated in longitudinal phase space by RF, whilst cooling continues, to provide a bunch of only 90–200 ns length as required by the trap experiments, still with a $\Delta p/p$ of a few 10^{-4} . In this way, some 10^7 antiprotons are provided for the experiments every 1.5 min. In November 1999, the first 100 MeV/c antiprotons were sent to the ASACUSA experiment [56]. In 2000 operation started in earnest, with beams given to three experiments.

Deceleration of antiprotons in the AD goes a long way towards the needs of the experimenters, but the 5.3 MeV energy of the extracted beam is still far above what the experiments, accumulating antiprotons in stationary traps, require. The further deceleration in a degrader foil, still in use for two of the AD experiments, is accompanied by a big loss of density. An additional “Extra Low Energy Antiproton ring” (ELENA) [57] to post-decelerate the AD beam from 5.3 MeV to 100 keV was recently (June 2011) adopted. ELENA has a circumference of about 30 m, it will be constructed in the AD-hall and will work with electron cooling. It is planned to be ready in 2015.

5.5 The Fermilab antiproton source

In 1983 the Tevatron-I project at Fermilab was approved and since then carried through with great success. The aim was to collide 1 TeV antiprotons with 1 TeV protons in the superconducting Tevatron. Originally the required antiprotons source

Fig. 6. The system for the production and accumulation of antiprotons at Fermilab.

consisted of two rings, a debunching ring and an accumulator ring. The 1984 design report [58,59] called for accumulation of 4.3×10^{11} antiprotons in 4 h, of which typically 1.8×10^{11} antiprotons from the high-density core of the stack are injected into the Tevatron. The concept is similar to that of the CERN AAC except that it works with higher energy (8.9 instead of 3.5 GeV/c) and smaller transverse acceptances (20π mrad mm instead of 200π mrad mm). As with the AAC, it uses two concentric fixed energy rings, the “Debuncher” with a circumference of 503 m and the “Accumulator” with a circumference of 474 m.

The short proton bunches, arriving at 120 GeV from the “main ring” (later from the new main injector), strike a tungsten target, producing a train of 82 short antiproton bunches with a total of 7×10^7 antiprotons (design value), collected by a lithium lens and transported to the debuncher. The momentum spread of the beam is almost 4% and a high RF-voltage (5 MV/turn) is applied to rotate and stretch the bunches transforming the narrow time – large momentum spread structure into a broad time – small momentum spread structure with 0.2% momentum width. The horizontal and vertical emittances are then stochastically cooled in the debuncher from 20π mrad mm to 7π mrad mm during 2 s (design value) before the next antiprotons are to be injected.

The antiprotons are extracted from the Debuncher and injected into the Accumulator. Successive batches are accumulated by transporting each batch to the edge of the stack. A new pulse is deposited every 2 s and moved by the coherent force of the momentum cooling system towards the high density core of the stack. The process is repeated some 5×10^3 times until sufficient antiprotons are stacked. Figure 7 shows the computed evolution of the stack.

Like in the AA three different sets of partial aperture pick-ups are used for stacking: the two tail systems and the core systems. They are located in regions of large dispersion where the orbits separate with momentum. Notch filters in the tail systems with flat peaks at the tail and sharp notches at the core frequencies protect the core from the high gain tail systems, in addition to the separation in space. The gain profile decreases by more than four orders of magnitude from the deposit region to the core. The betatron amplitudes are also cooled during the whole stacking process. In total the accumulator alone used, already in 1985, six specific cooling systems working in the 1–2, and 2–4 GHz range (Tab. 6), each of them combining a large number of pick-up and kicker loops [58].

Fig. 7. Evaluation of the longitudinal density of the stack in the Fermilab Accumulator (computed, [58]). The new batch is deposited with an energy difference at around +10 MeV from the bottom of the stack every 2 s.

Table 5. Basic design parameters of the cooling systems for the Fermilab Debuncher (design values 1984, adapted from [58]).

Frequency band	2–4 GHz
Number of pick-up pairs (loops)	128
Amplifier equivalent noise temperature	100 K
Amplifier gain (net)	138 dB (variable)
Output power	
- Schottky	100 W (typical)
- Thermal	400 W (typical)
Number of TWT’ amplifiers	8
Number of kicker pairs (loops)	128

The value of $\eta = |\gamma_{\text{transition}}^{-2} - \gamma^{-2}|$ is carefully chosen in both rings. In the Debuncher a compromise between the RF requirement for the bunch rotation (which favors a small $|\eta|$) and stochastic cooling (which favors a larger $|\eta|$) lead to the choice of $\eta = 0.006$. In the accumulator a value of about 0.02 allowed the operation of the Palmer-Hereward type core cooling system up to 4 GHz and the filter type stack tail systems up to 2 GHz. To decrease the noise-to-signal ratio U, which tends to be large for the low intensity systems in the Debuncher and the stack tail systems in the accumulator, a large number of high-impedance pick-ups are used (Tabs. 5 and 6) to increase the beam signal and cryogenic cooling of the pick-up terminating resistors and the preamplifiers to reduce the noise. The number of kicker units chosen lead to a power requirement of 1600 W for the stack tail system and of 2×600 W for the Debuncher. These values require a large number of the 200 W travelling wave tube amplifiers to be used.

The Fermilab antiproton source started operations at the end of 1985 with an increase of the 3 dimensional density of several 10^6 and proton-antiproton collisions in the 1 TeV Tevatron of a luminosity of about $0.2 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ early 1987 [60]. Since then the system has been continuously improved.

Table 6. Cooling systems in the accumulator (design values 1984, adapted from [58]).

	Stack tail Momentum	Stack tail Betatron	Core Momentum	Core Betatron
Frequency band	1–2 GHz	1–2 GHz	2–4 GHz	2–4 GHz
Number of pick-up pairs (loops)	170	32 (x2)	32	8 (x2)
Amplifier gain (net)	150 dB	125 dB	110 dB	106 dB
Output power		V+H		
- schottky	1400 W	10 W + 200 W	30 W	10 W (x2)
- thermal	200 W	10 W + 10 W	0	0
- total	1600 W	20 W + 210 W	30 W	10 W (x2)
Number of TWT's (200 W)	40	1+2	1	1 (x2)
Number of kicker pairs (loops)	160	32 (x2)	32	8 (x2)

Table 7. Stochastic Cooling Systems at Fermilab 2011 from [62].

Machine	No. of Systems	f [GHz]	Type	Cooling time [s]	Max. installed power [W]
<i>Debuncher</i>	4	4–8	Momentum	2	6400
	4	4–8	Horizontal	2	3200
	4	4–8	Vertical	2	3200
<i>Accu- mulator</i>	1	2–4	Stacktail Momentum	1200	6400
	3	4–8	Core Horizontal	1200	15
	1	4–8	Core Vertical	1200	15
	1	2–4	Core Momentum	1200	400
	1	4–8	Core Momentum	1200	15
<i>Recycler</i>	1	0.5–1	Momentum	1800	200
	1	1–2	Momentum	1800	400
	1	2–4	Horizontal	1800	200
	1	2–4	Vertical	1800	200

A third ring, the 8 GeV “Recycler” [61] with a circumference 3319 m was added in 1997. It was originally planned to recondition antiprotons re-decelerated from the Tevatron at the end of a run. The Recycler is installed in the tunnel of the main injector and uses permanent magnets. It is used to store several high intensity pulses from the accumulator prior to a transfer to the Tevatron.

A total of 25 independent stochastic cooling systems (Tab. 7) [62] are at present (2011) implemented in the upgraded source, 21 in the Antiproton Source and 4 in the Recycler. High energy electron cooling was pioneered in 2005 at the Recycler and is used to supplement stochastic cooling [63].

In 1999 the bandwidth of the stack tail systems was upgraded to 2–4 GHz and a 4–8 GHz system was added to the core system. New pick-up and kicker arrays were designed using micro-strip and strip-line techniques. These planar structures take full advantage of integrating signal combining and splitting on the same circuit board [64], where the loops are located. Planar loops have been designed in frequency bands between 0.5 GHz to 8 GHz. A significant improvement to the Debuncher cooling systems was completed in 2000 by upgrading the bandwidth to 4–8 GHz and including a momentum pre-cooling system. A new technology of slotted waveguide pick-ups (Fig. 8) was developed which employs sandwiched waveguides with coupling slots [65].

Fig. 8. The slotted waveguide structure [65]. Waveguides above and below the beam chamber couple to the beam via slots in the chamber.

The slotted waveguide technique is also used with three bands in the core transverse 4–8 GHz cooling system.

A wide variety of technologies have been exploited for the development of correlation type notch filters: superconducting coaxial delay lines [66], Bulk Acoustic Wave (BAW) delays [67] (a piezo-electric device that relies on the velocity of acoustic waves in the bulk of a crystal), and fibre optic delay links [68]. The notch filters implemented at the start of the Antiproton Source spanned a bandwidth of 1–2 GHz and were based on superconducting coaxial delay lines [66,69]. BAW filters are used in the accumulator stack tail and Debuncher transverse cooling systems [67] of the upgraded source. Microwave to fibre optical delay links are the third technology used [68,70]. The new Debuncher momentum cooling uses four fibre optical notch filters working within 4–8 GHz. One such filter remains in the stack tail system of the accumulator and optical based notch filters are also used in the Recycler.

The improvements brought a spectacular increase in the performance: 6×10^{12} antiprotons have been accumulated in the Recycler. Peak luminosities in the Tevatron of $4.3 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ (430 times the original design value!) have also been attained. The average antiproton accumulation rate has increased to about $24 \times 10^{10} \bar{p}/hr$ with a peak that exceeds $28 \times 10^{10} \bar{p}/hr$. In part these achievements are due to improvement in the antiproton production. In fact “slip stacking” [71] is used to double the intensity of the production beam. Also the acceptances and other lattice parameters of virtually all rings have been carefully optimised. Yet the considerable upgrade of the cooling systems [62,72] and the advent of the Recycler play a major role.

The Fermilab Tevatron programme lead to impressive results including the detection of the top quark in 1995. Now, that the LHC surpasses the Tevatron in energy and luminosity it has been decided to close down this unique machine at the end of 2011 after 26 years of operation.

5.6 Cooling test at the TARN ring in Tokyo

The heavy ion accelerator project NUMATRON, (for NUClear MATter synchroTRON) was proposed by the Institute for Nuclear Study, University of Tokyo, in 1976. As preparatory work, the construction of a small Test Accumulation Ring for the Numatron (TARN) with a magnetic rigidity of 1.1 Tesla · m was started in 1978 [73] where the injector was a Sector Focusing Cyclotron.

Fig. 9. Two pick-up superelectrode modules (from [80]).

One of the goals was to demonstrate stochastic cooling, aiming at its future application to Radio Isotope beams [74]. After several years of preparation, in 1984 a stochastic cooling experiment was performed using 28 MeV/u alpha particles or 7 MeV protons [75]. Travelling wave structures of helical type were used both as a pick-up and kicker. The momentum spread of the ions, 1.4×10^{-2} initially, was cooled down to 8×10^{-4} in 400 s. The number of ions was 10^6 – 10^7 and the band width 100 MHz [76].

Theoretical and simulation work was developed for momentum cooling with the Fokker-Planck approach [77]. Since the experiment at TARN, stochastic cooling has not been further tested nor applied in accelerators in Japan.

5.7 Stochastic Cooling at GSI

The Experimental Storage Ring (ESR) [78] at the “Gesellschaft für Schwer-Ionenforschung” (GSI), Darmstadt (Germany) has been operating since 1990. It is a 108 m circumference storage ring for experiments with a wide range of ions, ranging from protons to fully stripped Uranium. It can store Uranium with an energy of up to 560 MeV/u. Stochastic cooling was foreseen from the beginning [78] for operation of relatively low intensity ion beams occupying a large phase space volume. A paper on the design of the system architecture was published in 1988 [79]. First cooling was achieved in 1997 [80]. In 2000, e-folding cooling times of about 400 ms for 3×10^6 ions of $^{238}\text{U}^{92+}$ were reported [81]. The system is widely used for the pre-cooling with subsequent electron cooling. It works in the frequency range 0.9–1.7 GHz and at energies around 400 MeV/u. All pick-up and kicker systems are installed inside the vacuum chambers of quadrupole and dipole magnets. Two cooling loops cut diagonally across the ring. The electrodes consist of so-called superelectrodes, that is two loop couplers connected in series. Each of the two systems employs 8 modules of pick-up and 8 modules of kicker superelectrodes. They can be used for vertical, horizontal and longitudinal cooling. A module (Fig. 9) consists of two plates above and two below the beam to the right of the beam centre, and the same arrangement left of the beam centre [80]. Different signals can be taken in the right and left half-systems with variable delays corresponding to the time of flight of the particles in each, the right and left half-system. Because of the relatively large value of the slip-factor, $\eta = |\gamma_{\text{transition}}^2 - \gamma^{-2}| \approx 0.3$, a severe undesired mixing problem arises and, for longitudinal cooling, a Palmer-Hereward system is used as this is less sensitive

Fig. 10. Layout of Cooler Synchrotron COSY.

to the mixing between pick-up and kicker. With only one of the two systems beams of 10^8 heavy ions of up to $\Delta p/p = \pm 0.35\%$ ($\pm 2\sigma$) and $E_{x,y} = 20\pi$ mrad mm (87% beam) were cooled to $\pm 0.1\%$ and 2.5π mrad mm in about a second [82].

The system has been used for mass measurements and decay experiments of exotic rare isotopes. In particular, for very low intensity beams, it leads to extremely well cooled states only a few seconds after injection. As of 1999 Schottky mass spectrometry [83] was very successfully practiced, with stochastic pre-cooling followed by electron cooling.

Stochastic cooling will also play a major role for the cooling of antiprotons and of rare isotope beams at the Facility for Antiproton and Ion Research (FAIR) [84] under construction at GSI.

5.8 Stochastic cooling in COSY Jülich

The Cooler Synchrotron (COSY) [85] at the Forschungszentrum Jülich (FZJ) was constructed in the years 1989–1992. It uses a cyclotron as injector. It has a circumference of 184 m and accumulates, stores, and cools up to several 10^{10} protons and deuterons, both polarised and unpolarised. Several internal target places are available. The first protons circulated in September 1992. The proton energy ranges from 50 MeV to 2.6 GeV. Electron cooling is available near injection energy and stochastic cooling above 800 MeV/u, both horizontally, vertically and longitudinally [86].

The stochastic cooling system works simultaneously in two bands [86]: 1 to 1.8 GHz, and 1.8 to 3 GHz, and has separate signal paths for horizontal (H) and vertical (V) cooling (Fig. 10). Figure 11 shows a photograph into the interior of a vertical kicker tank, with $\lambda/4$ electrodes (loop couplers) above and below the beam centre and ferrite material to the right and left to damp unwanted microwaves. The time required for transverse cooling from 5π to 1π mrad mm is about 30 s for 10^{10} protons above 1.5 GeV. The electrode-bars of the pick-up and corrector structures can

Fig. 11. Vertical kicker tank.

independently be moved and allow an aperture change from 140 mm during the injection to a minimum of 20 mm during cooling. The interior of the pick-ups, including the electrode terminations, are cooled down to 30 K. The variable energy requires many RF feed-throughs. The amplifiers are broadband components and cover a relative bandwidth $W/f_{\max}$ of at least 50%.

The first successful reduction of the beam dimension was monitored by the detector of the EDDA experiment in 1977 [87,88]. The beam size of 2×10^9 protons at 1.8 GeV was reduced from 3 mm to 0.8 mm within 20 min. The first longitudinal cooling was established at the beginning of 1998 using the vertical 1–1.8 GHz system in sum mode together with a simple notch filter (Thorndahl filter cooling). Stochastic cooling has been used for the internal gas cluster target (experiment COSY11 [89]) at 10^{10} protons. The cycle length was increased up to 1 h. Less than 10% of the stored protons were lost. The cooling reached an equilibrium state after 20 min, where the energy loss of the protons through the gas target was compensated by the longitudinal cooling system. The shape of the particle distribution remained unchanged until the end of the spill. A first improvement of the notch filter was achieved by changing the long delay line from an air-filled coaxial line to an optical one. Notch depths of more than 30 dB have been reached over the whole frequency range. Further improvements have been achieved by building both paths of the notch filter as optical lines.

In the frame of the Facility for Antiproton and Ion Research (FAIR), a High Energy Storage Ring (HESR) is under preparation. This facility, located at GSI, will be realised in collaboration with the Forschungszentrum Jülich (FZJ). This machine will be built as an anti-proton cooler ring in the momentum range from 1.5 to 15 GeV/c. Numerical simulations have shown the great benefit of the stochastic cooling system in achieving the requested beam spot and the high momentum resolution at the internal target. The results of theoretical investigations [90] were compared to measurements using the stochastic cooling system of COSY.

The aperture of the HESR will be rather low (90 mm). A cooling structure with such an aperture but without movable parts will significantly simplify the whole tank design. As a first solution, printed loop couplers were analysed similarly to those developed at the FNAL. An alternative are “slot ring couplers” developed by Stassen and Thorndahl. They look like a classical linac cell design where each iris is heavily loaded by 50Ω connections. Both structures have been tested with beams from COSY.

Fig. 12. Test-tank installed at COSY for stochastic cooling utilising slot ring couplers. (a) Stack of 16 slot ring couplers with combiner boards. (b) Schematic of test-tank.

The sensitivities of the slot ring couplers in transversal and longitudinal mode are comparable to the 1.8–3 GHz structures of the COSY stochastic cooling. The test-tank design depicted in Figure 12 already included a cryo-system to cool down the structures and a movable x - y support to centre the structures according to the beam.

Filter momentum cooling will be applied in the HESR above 3 GeV. At lower momentum time of flight cooling [91] is necessary because of the limitations of the filter method due to unwanted mixing from pick-up to kicker. In 2009, time of flight cooling, which had never been tested before, was established in COSY demonstrating the higher momentum acceptance but weaker cooling forces [92].

5.9 Bunched beam cooling in RHIC at BNL

The Relativistic Heavy Ion Collider (RHIC) [93,94] at Brookhaven National Laboratory (BNL) came into operation in 2000. It is a 3.8 km circumference system of two interlaced rings which intersect at six locations. It works with superconducting magnets and accelerates and stores ions, typically 60 bunches of gold $79+$ per ring, 10^9 ions per bunch, and an rms bunch length of about 0.4 m at the top energy of 100 GeV/u. Stochastic cooling is applied in RHIC to increase the luminosity life time, which is mainly determined by intra-beam scattering. Early studies [95–98] agreed that despite the short bunches cooling times of the order of an hour could be envisaged with systems working in the 10 GHz region. This is sufficient to counteract luminosity decay. However the longitudinal kicker power needed turned out to be extremely large.

Since 2002 a new effort is under way at RHIC to advance the technique of bunched beam cooling. Several innovative steps were explored: the coherent signals were carefully studied, both theoretically and by observations at RHIC (see Fig. 13) and theoretically. In this figure, the parabolic shaped signal distribution represents the incoherent response from individual particles (the Schottky signal). The narrow peaks on top of the parabolae, situated at each revolution harmonic show the coherent contribution of particles due to a residual bunching effect. Note that due to the logarithmic scale the contribution of the coherent part is roughly a thousand times higher in power compared to the incoherent contribution. This effect which was seriously underestimated for more than 2 decades and has hampered successful stochastic cooling in large storage rings worldwide. An explanation was published [100] linking the high

Fig. 13. A spectrum at 5.6 GHz, showing coherent and incoherent signal components of the bunched beam in RHIC (from [99]). The bell shaped curves present the Schottky noise at three consecutive high frequency harmonics. Superimposed are strong spikes which are explained in [100] as the result of solitons in the beam.

Fig. 14. Model of a kicker cavity used at RHIC (from [99]). It has a 20 mm bore and two matched coaxial coupling ports.

frequency activity to “solitons” that is humps or holes in the beam, which result as stationary solutions of a coupled Vlasov-Poisson equation. Both theory and observation suggest that the effect is weaker for beams of 10^9 Au^{79+} ions in RHIC than for the $10^{11}\bar{p}$ in the SPS or the TEVATRON. Around 2004 the notion of using narrow-band cavities with a “Fourier series implementation” was introduced [101,102]. This approach allowed for multi-kilovolt kicks with affordable equipment. It is fair to say that this break-through made stochastic cooling in RHIC practicable.

Several 5–8 GHz systems with cooling times of about one hour are nowadays used in RHIC. For optimal cooling of gold $79+$ ions at 100 GeV/u, up to 3 kV must be supplied to the kicker. A 50 Ω kicker, to cover the whole 3 GHz span, would need 90 kW of microwave power. Instead the kick for the short bunches can be synthesised with much less power by employing high-Q cavities. The cavity frequencies are spaced at 200 MHz intervals in the 5 to 8 GHz band. Thus a total of 16 cavities per cooling system are needed. One can think of the arrangement as a Fourier synthesis of the kick, and because the bunch has a full width of only 5 ns, the basic harmonic of the series is 200 MHz. The bandwidth of the cavities is chosen to allow filling and emptying between bunches (100 ns). This determines the Q of the cavities (about 600) and a high shunt impedance is achieved by using a four-cell TM_{010} like structures with $R/Q \approx 100 \Omega$. A computer model of a cavity is shown in Figure 14. The cavities have

a small ($\phi = 20$ mm) beam bore hole matched to the beam size at high energy. They are split on a vertical mid-plane, are opened during injection and ramping, and then closed for operation during the store. The power required is about 20 W/cavity.

Another challenge of bunched beam cooling is the difficulty caused by the coherent components in the Schottky spectra (Fig. 13). The large spikes at the revolution harmonics may easily overdrive electronic components and cause inter-modulation distortion which defeats the cooling. In order to reduce the peak voltages, a filter with sharp notches at the revolution harmonics is used that precedes the amplifier system. Longitudinal cooling, based on the filter method has been installed since 2009 in both rings. Also in 2009, cavity systems for vertical cooling were installed in both rings, designed due to similar considerations. A transverse deflecting mode is excited on these cavities, rather than the longitudinal field on the momentum kickers. Different highly developed schemes of transmitting the pick-up signals to the kickers [103, 104] are used. Wireless open air microwave links cutting across the rings are employed for longitudinal, fibre optical links inside the tunnel for the vertical systems. Horizontal cooling is achieved by coupling the horizontal to the vertical betatron oscillation. A factor of 2 in integrated luminosity of a run has been obtained with cooling in only one ring and another factor of 2 is expected when all cooling systems are commissioned in both rings [105].

In summary: the technique of stochastic cooling of the bunched beam in a high energy collider has been proven and considerably advanced by the outstanding developments at BNL.

6 Conclusion

Stochastic cooling has led to spectacular achievements including the experimental observation of the W and Z bosons, the top quark and anti-hydrogen atoms. The technique has grown from a curiosity in 1972 to one of the most powerful tools of accelerator technology.

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