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STOCHASTIC COOLING AT THE CERN ANTIPROTON DECELERATOR

C. Carli and F. Caspers

Abstract

When transforming the CERN Antiproton Collector (AC) into the Antiproton Decelerator (AD), the stochastic cooling systems were rebuilt to cope with the new requirements. Instead of using the original three frequency bands, (0.9 - 1.6 GHz, 1.6 - 2.45 GHz and 2.4 - 3.2 GHz) only the first of these was used due to lattice limitations and other constraints. The same pick-ups and kickers are in use at two different energies. As in the AC, simultaneous cooling in all three phase planes is required. Switching between two transmission paths (at 3.5 GeV/c and 2.0 GeV/c) became necessary, including separate notch filters and delay compensation for the kicker sections. The tanks had to be rendered bakeable (150 ^{o}C) to make the vacuum properties ($\leq 10^{-10}$ Torr) compatible with deceleration to low energies. Further improvements included programmable, phase-invariant electronic attenuators and amplitude-invariant delays. Experience during commissioning showed that careful optimization (depth and periodicity) of the notch filters, as well as efficient suppression of the common mode response in the transverse cooling systems, were essential to reach and even exceed design performance. The systems were operated with protons (about 10^9) as well as pbars ($2 - 3 \times 10^7$).

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1 INTRODUCTION

The CERN Antiproton Decelerator (AD) [1] aims to provide low-energy antiprotons in a simpler way than previously (AC, AA and LEAR), involving only a single synchrotron. Its functioning is best outlined with the help of Figure 1 showing the design cycle. The $\bar{p}$ are injected at 3.5 GeV/c into the AD, filling its large acceptance (about 200 π μm in both transverse planes and ±3 % in $\Delta p/p$). Immediately after injection, the bunches are very short, but have a large momentum spread. By means of bunch rotation cavities, the momentum spread is reduced and the bunches become longer. Then the beam is alternately cooled and decelerated, and finally fast ejected at a momentum of 100 MeV/c. At high energy, stochastic cooling is applied at two flat parts of the cycle, i.e. at 3.5 GeV/c and at 2.0 GeV/c.

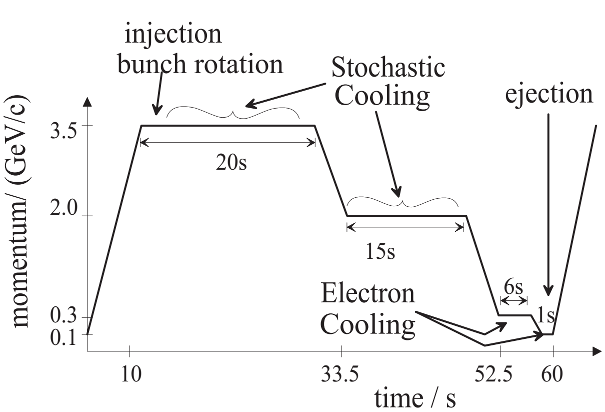

Figure 1: Design cycle for antiproton deceleration and delivery in the AD

2 STOCHASTIC COOLING IN AAC

AAC was the Antiproton production and Accumulation Complex in operation until 1996. It consisted of two fixed-energy synchrotrons. First the $\bar{p}$ were collected in the AC, a machine with large acceptances in all three planes. After fast stochastic cooling (typically during 4.8 s) in the AC, the antiprotons were transferred to the Antiproton Accumulator (AA) and deposited on an injection orbit at a higher momentum than the stack. After ”pre-cooling”, the newly injected $\bar{p}$ were brought close to the stack by an RF system, then merged into the stack with the ”stack-tail” stochastic cooling system, and finally further cooled with the stack-core system [2].

3 MODIFICATIONS FOR THE AD

In the AD, longer cooling times than in AC are acceptable. Thus, out of the three cooling systems covering a total bandwidth from 0.9 GHz up to 3.2 GHz, only ”band 1” was selected. Its range from 0.9 GHz to 1.65 GHz provides cooling rates sufficient for the AD. Another reason to use only band 1 is the fact that this band has the highest momentum acceptance at 3.5 GeV/c. An important complication when transforming AC into AD arose from the fact that, in the latter, stochastic cooling is applied at two different momenta (and thus at two different velocities of the particles). The second stochastic cooling at 2.0 GeV/c is needed to reach the required final longitudinal emittance, which is relatively large at the top energy, as the machine is close to transition there. The main implications of stochastic cooling with two distinct particle velocities are :

- Distinct transmission paths, one for each velocity. Therefore, commutating between them is necessary.
- Different notch filters for longitudinal stochastic cooling at 3.5 GeV/c and at 2.0 GeV/c respectively.
- Reduction of the signal-to-noise ratio at the 2.0 GeV/c level. The strip-line pick-ups (”super-electrode” type,

i.e. two $\lambda/4$ strip-line couplers connected in series with a $\lambda/2$ delay line in between) are optimized for the velocity of the $\bar{p}$ at injection. At the lower velocity the signals corresponding to the different "super-electrodes" no longer arrive with the proper delays.

Improvements to the hardware, not directly related to the second stochastic cooling plateau, are :

- Phase-invariant programmable attenuators. During the cooling process, the movable cooling pick-ups and kickers close, in order to increase the signal-to-noise ratio and to limit the power needed from the end-amplifiers, in particular for the transverse systems. This leads to an increase of the effective gain during the cooling process, whereas a decrease is required. With these programmable attenuators, the gain can be optimized during the entire process.

- Gain-invariant programmable delays. These allow to adjust and to optimize the phase during the cooling process.

4 DIAGNOSTIC TOOLS

For the set-up, operation and trouble-shooting of the stochastic cooling system, standard diagnostic devices are available. They include :

- Longitudinal and transverse Beam Transfer Functions (BTF). Initially, it was expected that BTF measurements would not be possible with the low intensity $\bar{p}$ beams, due to a small signal-to-noise ratio. Thus, adjustments of delays were done with protons. However, recently, it has been possible to do transverse BTF measurements with $\bar{p}$ at 2.0 GeV/c, in order to check the delay of the transverse systems.

- Shielding factor measurements for the transverse systems (gain adjustment), and observation of down-mixed longitudinal signals on a 100 kHz band using a FFT (Fast Fourier Transform) analyser.

- General Schottky diagnostics for tune observation and adjustment.

- Scrapers (destructive) for transverse emittance measurements. For $\bar{p}$, these rely on scintillators for sensitivity and do not use the beam current transformer.

5 EXPERIENCE FROM THE COMMISSIONING

5.1 Cross-BTF

During tests with proton beams (intensity of about 10^9 particles), it was observed that the transverse cooling systems caused considerable longitudinal blow-up. The desired longitudinal emittance could not be obtained with simultaneous cooling in all three planes. The problem was that the transverse system saw residual signals at multiples of the revolution frequency due to an offset between the beam and the electrical centre of the pick-up. If in addition, a similar offset occurs at the kickers, this leads to a longitudinal blow-up.

In order to diagnose, to control and to quantify this kind of difficulty, cross-BTF was developed. It consists essentially in exciting the beam transversely, by injecting the signal from a network analyser into the transverse stochastic cooling system, at integer multiples of the revolution frequency. If the electrical centre of the kicker does not coincide with the beam position, a parasitic longitudinal excitation occurs. Then the longitudinal signal from the stochastic cooling system is measured. If the beam position coincides with the electrical centre of the kickers, the cross-BTF is zero. The electrical centre of the kickers is adjusted by switching off selected end-amplifiers on the one or the other side until the observed cross-BTF is sufficiently small. It should be noted that this method was needed in 1999 to obtain the design momentum spread. However, in spring 2000, after some renovation of the end-amplifiers, good final longitudinal emittances were achieved without cross-BTF and with all end-amplifiers switched on.

5.2 Asymmetric sidebands of transverse Schottky spectra

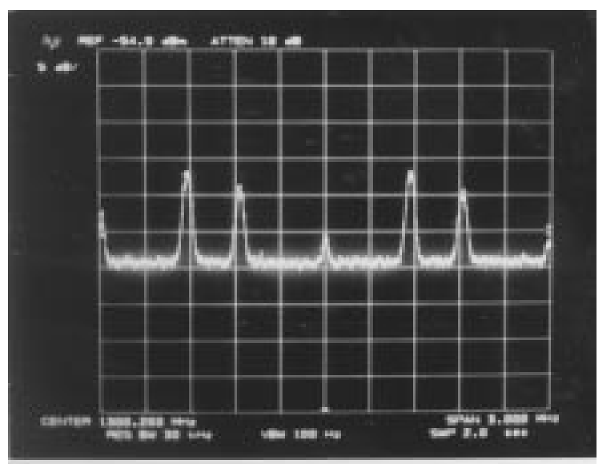

Figure 2: Transverse Schottky spectrum at the centre of the transmission band at 2.0 GeV/c.

During the commissioning of the stochastic cooling, asymmetric sidebands in the transverse Schottky spectra at 2.0 GeV/c were observed. As an example, a Schottky spectrum measured with about 5×10^8 protons circulating in the machine at a momentum of 2.0 GeV/c is shown in Figure 2. This asymmetry is present in both the horizontal and the vertical phase space and can be observed over the entire range of the stochastic cooling band. It has not yet been possible to explain this observation completely. However, the pattern (unequal height of the "side-bands") is a typical signature of an (unexpected) narrow band FM (frequency modulation) signal superimposed on the usual AM (amplitude modulation) signal.

5.3 Performance

For the 3.5 GeV/c level, the design performance was already exceeded in 1999 (see Table 1). The gain-versus-time characteristics shown in Figure 3 aims to compensate for increasing pick-up sensitivity when reducing the aperture from 200 π μm to 20 π μm as shown in Figure 4.

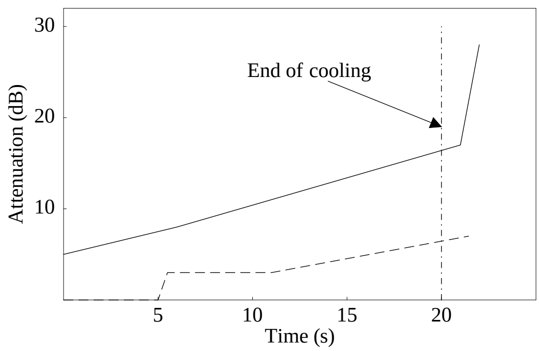

Figure 3: Programming of the dynamic attenuation during the stochastic cooling flat-top at 3.5 GeV/c. The solid line is for the transverse cooling systems and the dashed line for the longitudinal one.

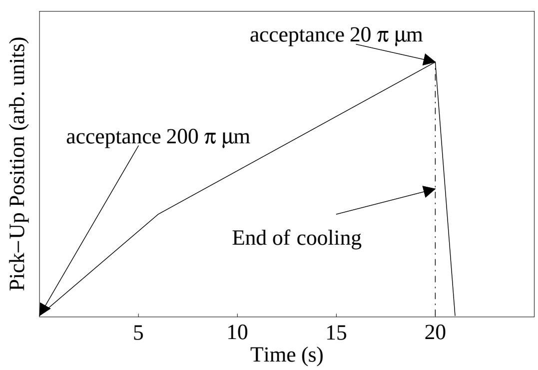

Figure 4: Programming of the closure of the stochastic cooling pick-ups during cooling on the injection flat-top.

For the 2.0 GeV/c level, transverse cooling was barely visible in 1999, leading to final emittances of about 5-6 π μm. In a recent machine development, it was found that good results (see Table 2) could be obtained by NOT closing the kickers. A possible explanation for this surprising behaviour could be the closed cooling loop (beam) impedance and/or field inhomogeneities from the loop couplers.

6 CONCLUSIONS

The AD stochastic cooling systems have met or exceeded the design performance in most respects. It was observed on several occasions, when the RF system was not switched off, that bunched beam stochastic cooling worked reasonably well, but required significantly longer cooling times, due to the smaller bunching factor.

In the next phase, attempts will be made, to reduce the length for the given plateaus, while maintaining the performance. Also the option of $\bar{p}$ - stacking has not yet been tried, but, from experience gained with protons, one expects that the stochastic cooling systems can cope with the higher intensities.

Table 1: Design performance and achieved performance of the stochastic cooling system at the injection flat-top.

Flat-top	3.5 GeV/c	
	design	achieved
Intensity	5×10^7	3×10^7
Acceptance in $\Delta p/p$	$\pm$ 0.5 %	$> \pm$ 1 %
Cooling time	20 s	20 s
Hor. emittance (95 %)	5 π μm	3 π μm
Vert. emittance (95 %)	5 π μm	4 π μm
Momentum width	$\pm 0.5 \cdot 10^{-3}$	$\pm 0.35 \cdot 10^{-3}$

Table 2: Design performance and achieved performance of the stochastic cooling system at the 2 GeV/c plateau.

Plateau	2.0 GeV/c	
	design	achieved
Intensity	5×10^7	3×10^7
Cooling time	15 s	15 s
Hor. emittance (95 %)	5 π μm	2.9 π μm
Vert. emittance (95 %)	5 π μm	3.3 π μm
Momentum width	$\pm 0.15 \cdot 10^{-3}$	$\pm 0.08 \cdot 10^{-3}$

7 ACKNOWLEDGEMENTS

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8 REFERENCES

[1] S. Baird at al., *Design Study of the Antiproton Decelerator : AD*, CERN/PS 96-43 (AR)

[2] F. Caspers, *Stochastic Cooling*, Proc. of Eloisatron Workshop on Crystalline Beams and related Issues, and CERN/PS 96-03 (AR)