PERFORMANCE AND EVOLUTION OF THE STOCHASTIC COOLING SYSTEM IN CERN'S ANTIPROTON DECELERATOR

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Abstract

The Antiproton Decelerator (AD) is part of CERN's Antimatter Factory which decelerates antiprotons from a momentum of 3.57 GeV/c to 100 MeV/c. Stochastic cooling is essential to reduce longitudinal and transverse emittances at the momentum plateaus in the first part of the cycle. The present hardware of the stochastic cooling system is optimized for a momentum of 3.57 GeV/c while it has reduced performance at 2 GeV/c. This work reports on recent performance improvements of the stochastic cooling system which have contributed to the record intensity of 6.3×10^7 antiprotons per cycle, decelerated and extracted from the AD. Possible future consolidation of the system with new kicker and pick-up structures, better adapted to the operation at both momenta, is outlined.

INTRODUCTION

The CERN Antiproton Decelerator (AD) ring [1] started operation in 1999. The decelerator relies on reused stochastic cooling equipment from the CERN Antiproton Collector (AC), the fixed energy collector ring that provided antiprotons at a momentum of 3.57 GeV/c in the 1980's for the Sp$\bar{p}$S collider project. For the design of AD, only the lowest frequency band (900 MHz – 1600 MHz) of the original three bands of AC, was retained [2]. Optimized for a fixed beam momentum of 3.57 GeV/c for AC, operation in AD extended the use of stochastic cooling to a second momentum plateau at 2 GeV/c.

Since the initial design study of the AD with a minimum aim of 1×10^7 antiprotons provided per minute [3], beam parameters have evolved and today a record 6.3×10^7 is every two minutes extracted from AD. A summary of intensity compared to initial AD commissioning [4] and earlier operation is given in [5].

The motivation of the present work is to assess how recent consolidation work, including the replacement of the comb notch filters originally implemented with coaxial cables by optical fiber technology [6, 7], has improved the system performance, notably by increasing the robustness of the cooling system and flattening the frequency response, while also identifying remaining performance limitations in view of possible future upgrades. In this longer-term perspective, the study of pick-ups and kickers is further motivated by the need for spare components, possibly with improved performance, highlighted by a vacuum leak in a kicker tank during start-up in 2021 [8].

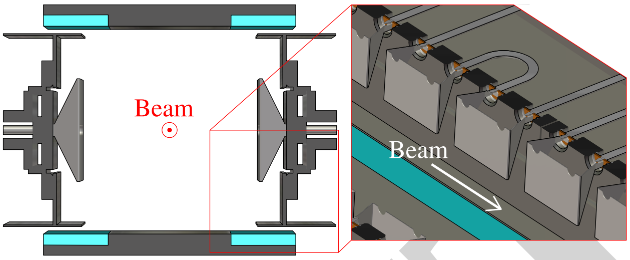

Figure 1: Model of the kickers and pick-ups. View perpendicular to the beam (left) and a side-cut through the double-loop geometry (right). Ferrites are colored in cyan.

KICKERS AND PICK-UPS

Identical electromagnetic structures are used for the kickers and pick-ups. Each kicker / pick-up features an array of 24 so-called double-loop devices [9] [10, p. 398] interacting with the beam. A double-loop device is seen on the right side of Fig. 1 in the center. A double-loop is a series connection of two striplines, powered from the up stream end, with a delay line in between. At the desired frequency, the delay corresponds to half a wavelength which leads to resonant enhancement of the shunt impedance at the expense of reducing the bandwidth by approximately a factor of two.

Figures of Merit

The efficiency of a kicker is determined by how much momentum change it can apply to a beam for a given amount of total RF power P_{incident} incident to its ports. The kickers in the AD stochastic cooling system are excited in longitudinal and transverse modes in order to selectively apply longitudinal or transverse kicks. The longitudinal and transverse kick factors

$$K_{\parallel/\perp} = \frac{V_{\parallel/\perp}}{V_{\text{incident}}}, \qquad (1)$$

are a measure of the efficiency of a kicker [11]. The longitudinal and transverse beam voltages $V_{\parallel/\perp}$ are proportional to the longitudinal and transverse momentum changes, respectively. The equivalent incident input voltage V_{incident} is determined by the total incident RF power P_{incident} and the reference impedance Z_0 by $V_{\text{incident}} = \sqrt{2Z_0P_{\text{incident}}}$.

The efficiency of a pick-up is determined by how much output power it delivers for a given amount of beam current or dipole moment of the beam. The longitudinal transfer impedance

$$Z_{p\parallel} = \frac{V_{\text{out}}}{I_{\text{beam}}}, \qquad (2)$$

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is used as figure of merit for the longitudinal case [11]. For the definition of the transverse transfer impedance $Z_{p\perp}$ the denominator of Eq. (2) has to be replaced by the dipole moment $\Delta x I_{\mathrm{beam}}$ of the beam. Both the kick factor and the transfer impedance are functions of frequency f and the beam momentum.

Simulation Study

A selection of results of a simulation study [12] of the kickers and pick-ups is shown in Fig. 2. Finite Integration Technique (FIT) and Finite Element (FEM) solvers of the CST Studio Suite® [13] were used for the simulations. The electromagnetic properties of the ferrite tiles[1] (refer to Fig. 1) were taken into account [14]. The ferrite tiles are essential to damp higher-order modes and shield the surrounding vacuum tank from the RF fields applied to the double-loops interacting with the beam.

Limitations of the performance at 2 GeV/c due to the fan-out and recombination delays that are optimized for the original operating momentum of 3.57 GeV/c, can only be addressed for the kicker, for which twelve feedthroughs for each side allow for switching the delay of the drive signals between optimum values for 3.57 GeV/c and 2 GeV/c.

A delay switching scheme for the present pick-up is not possible as all signal combination takes place inside of the vacuum tank. This explains the large reduction in peak value of the pick-up response visible in Fig 2. The reduction in peak value leads to a decrease of signal-to-noise-ratio (SNR) of approximately 8 dB for the longitudinal signals and approximately 7 dB for the transverse signals. In addition to the peak value reduction, the bandwidth is reduced by a small amount at the upper end of the frequency band of interest due to the introduction of a zero at approximately 2 GHz.

The SNR at 2 GeV/c may be improved, without lowering the effective noise temperature, by a pick-up design with multiple feedthroughs per side that allows for switchable delays between the energies.

Performance of the pick-up in the stochastic cooling system is limited by thermal noise, the effect of which can be included in beam cooling simulations as an effective noise temperature or noise power spectral density. The effective noise temperature is obtained from the combined thermal noise from different resistive parts in the pick-up cooled to different temperatures by cryogenic cooling and the noise figure of the first amplifiers. Noise power spectral measurements at cold and at room temperature yield an effective noise temperature of the cold pick-up of between 100 K and 115 K, inline with previous estimates [15, chap. 2.5.2] [16, pp. 544–547].

PERFORMANCE OF OPTICAL DELAY LINE NOTCH FILTERS

The optical comb notch filters developed for the AD stochastic cooling system are based on a two-branch optical delay-line architecture, as shown in Fig. 3. A dedicated filter is used for each beam momentum, 3.57 GeV/c and 2 GeV/c. The filters generate a notch at each harmonic of the beam revolution frequency, i.e. 1.589411 MHz at 3.57 GeV/c and 1.487723 MHz at 2 GeV/c, over the frequency range from about 600 MHz to 1800 MHz. After RF-to-optical conversion, the signal is split into a short reference branch and a long branch. The difference in signal delay between long and short branch equals exactly one turn of the beam at the respective momentum. The system is installed in a temperature-controlled oven, where the long fiber branch is stabilized to ±0.02 °C [7]. A fine delay adjustment from 0 to 1120 ps allows the notch frequency to be tuned to better than ±1.5 ppm for one particular notch. After optical-to-RF conversion, both paths are recombined in a broadband 180° hybrid, followed by a phase shifter, to produce the notch response over the cooling band. Control of the notch filter is achieved by monitoring a notch position between cycles and making corrections when necessary [8].

A key requirement is a very close matching of the gain and phase responses of the short and long branches over the full bandwidth, demonstrated already for the prototype put in operation at 3.57 GeV/c in 2019 [6]. Any amplitude or phase mismatch reduces the notch depth and degrades the notch-frequency regularity across the band leading to an increase in the minimum momentum spread achievable by cooling.

SYSTEM POWER AND BANDWIDTH LIMITS

The 48 individual power amplifiers each have an output power at 1 dB gain compression of 100 W, but only some 30 W approximately is used as maximum RMS power during cooling. Increasing gain in the cooling systems is limited by the thermal noise from the pick-up. For best performance it is important to match the passband of all elements and avoid signal contributions from outside the main band where the phase response is already deteriorating with respect to an ideal constant group delay. The system design uses a bandpass filter to limit signals to the range with a good signal-to-noise ratio. In particular for the transverse cooling the possible use of a high pass filter has been tested to remove excess noise at lower frequency and may be advised to improve the transverse cooling.

PERFORMANCE WITH BEAM IN THEORY AND EXPERIMENT

Simulations of stochastic cooling are traditionally made using a stepwise integration of the Fokker-Planck equation [17]. The complementary approach is to use multi-particle tracking [18], made possible by the advances in computing power. Multi-particle tracking has the potential advantage to seamlessly interface with the beam manipulations such as bunch rotation before cooling and RF capture after cooling.

At the AD project kick-off, expectations were for a factor 40 for the reduction of the transverse emittances at

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[1] TT2-111R by Trans-Tech. Inc., a subsidiary of Skyworks Solutions Inc.

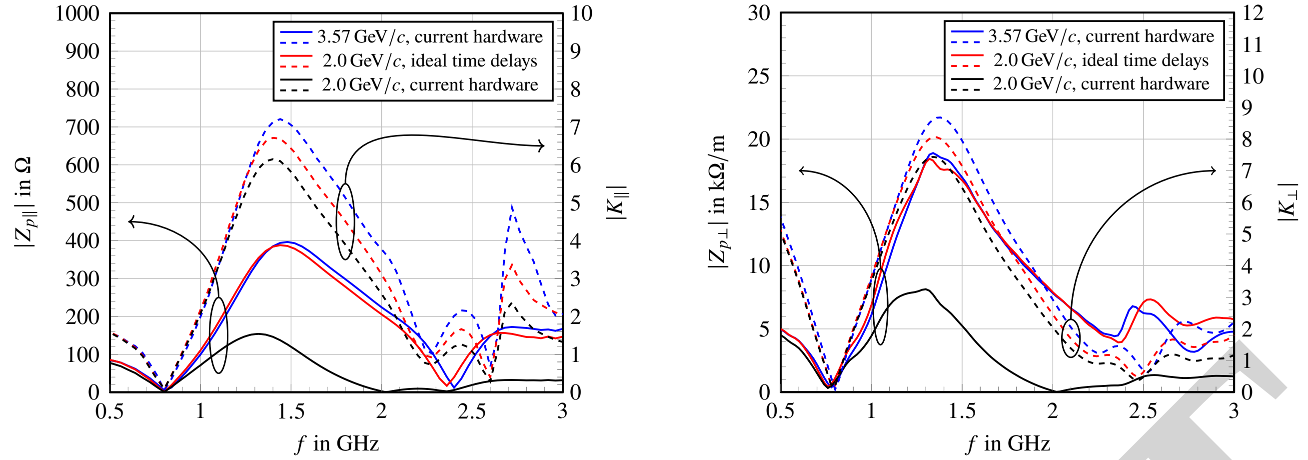

Figure 2: Simulated magnitudes of longitudinal (left) and transverse (right) frequency domain response functions of the kickers and pick-ups. Solid traces: transfer impedance $|Z_p|$ of one pick-up. Dashed traces: kick factor $|K|$ of one kicker.

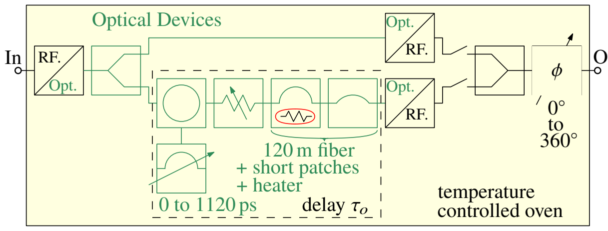

Figure 3: Optical delay-line comb notch filter.

3.57 GeV/c as well as a factor 1.8 at 2 GeV/c and reductions of momentum spread by factors 15 and 6 for cooling plateau lengths of 20 s and 15 s, respectively [19].

Today, the scraper system to measure transverse emittances uses new analysis software [20], optimized for gaussian-shaped distributions providing 1 σ values, which introduces some uncertainty in comparison with historical data. Table 1 compares today's transverse emittances achieved with values from 2001, whereby the 2001 values are divided by four to convert from a 87 % definition used in [4] to 1 σ values. For the longitudinal cooling momentum spread reduction factors (start of plateau with respect to end of plateau) have improved from 15 at 3.57 GeV/c and 6 at 2 GeV/c in 2001 [4] to 23 and 7 in 2026. This improvement is attributed to the better performance of the optical delay line notch filters.

Table 1: Emittances in 2026 Compared to 2001 [2, 4]

year	**2026**	**2026**	**2001**	**2001**
momentum GeV/c	ϵ_H **µm**	ϵ_V **µm**	ϵ_H **µm**	ϵ_V **µm**
3.57	0.3–0.4	0.4–0.5	0.7(5)	1.0(0)
2	0.6–0.7	0.6–0.7	0.7(5)	0.8(8)

UPGRADE OPTIONS

Faster transverse cooling times could be achieved by lowering the effective thermal noise from the pick-up which would allow to operate at a higher gain. This path requires to further study and discriminate the sources of thermal noise and quantify the individual contributions. The reduction of thermal noise was previously identified as one the key elements of system improvement [15, chap. 2.5.2].

Further operational improvements and consolidation include planned work for new power amplifiers replacing eventually the original amplifiers [21] in GaAs technology from the 1980s. A better shielding of the equipment from electromagnetic interferences, now present due to increased usage of wireless communication signals, is also advised.

Performance improvements for 2 GeV/c could be achieved by a new pick-up tank with more feedthroughs making independent delay adjustment possible, but retaining the present double-loop design. Both for pick-up and kicker alternative designs were explored, with a triple-loop employing a phase inverter between the individual striplines representing the most promising candidate of the structures investigated [12].

CONCLUSION

Using a single band for stochastic cooling in three planes and at two energies the AD has reached unprecedented performance in 2025 with more than 6.3×10^7 antiprotons extracted per cycle. The optical delay line notch filter has been a key consolidation contributing to this improvement. Revisiting the electromagnetic design of the pick-ups and kickers permitted to explore possible upgrade paths and directed further study to the assessment of system noise and shaping the bandwidth to best match operation at today's two energy plateaus. Improved control contributes to the stability of the system and permits to support experiments in defined settings for benchmarking with simulations.

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