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FIRST OPERATION FOR STOCHASTIC COOLING OF P-BARS IN THE CERN AD USING OPTICAL DELAY NOTCH FILTER AND PLANS FOR 2021 OPERATION

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Abstract

As part of the consolidation of the stochastic cooling system of the CERN Antiproton Decelerator a notch filter with optical delay lines has been developed. During the 2018 run this new notch filter for the longitudinal cooling at 3.57 GeV/c was successfully tested with beam for the first time. We summarize the hardware implemented including a comparison of hardware transfer functions of the new system and the original system using a coaxial cable plant for the same purpose. Automatic monitoring of the hardware transfer function, being prepared for 2021, will be provided in order to periodically check drifts of the system and send corrections to the control of the system. Integration of this monitoring and feed forward system into the CERN controls environment will be shown.

INTRODUCTION

The CERN antiproton decelerator (AD) has been conceived reusing parts of the former antiproton accelerator complex at CERN which has served to provide antiprotons to the Sp$\bar{\text{p}}$ collider from the 1980's onwards [1, 2]. The AD which started operation some 20 years ago in 1998 is designed to provide low energy antiprotons in the range down to 100 MeV/c momentum to a set of experiments located in the AD experimental hall [3].

Antiprotons generated at a target by a primary proton beam from the PS are injected at a momentum of 3.57 GeV/c into the AD ring. Stochastic cooling is applied in all three planes, horizontal, vertical and longitudinal, first at the injection plateau of 3.57 GeV/c and then after deceleration to 2 GeV/c [4].

AD CYCLE AND STOCHASTIC COOLING SYSTEM OVERVIEW

Initially projected for a cycle time of 60 s the AD is today run with a ~100 s long cycle with sufficiently long cooling plateaus in order to provide the nominal emittances with some margin. Ramp rates and idling time at flat-top are limited by magnet cooling and magnet power converters.

Figure 1 shows an overview of the stochastic cooling system. Two pick-ups are used, one horizontal and one vertical. The signal for longitudinal cooling is taken from a combination of the common mode signal from the two transverse pick-ups. The three paths of the signal processing are linked with coaxial 1 5/8" RF lines ($v \simeq c$) to the location of the 48 power amplifiers across the AD hall. These 100 W power amplifiers are installed on top of the shielding of the AD machine gallery. The overall bandwidth of the system ranges from 0.9 GHz to 1.65 GHz with smooth tapering of the gain at the edges of the pass band to minimise changes of delay with frequency that would be detrimental to cooling. The longitudinal signal is combined with the transverse signals at the amplifier platform before signals are split to feed the 24 kicker elements on plunging support structures in each tank through individual feedthroughs. The kicker tank features water cooled loads inside the vacuum tank and the pick-up tank combiner loads are cooled with liquid helium to provide a low noise signal source temperature.

The longitudinal branches of the cooling employ a comb type notch filter with a periodicity equal to the beam revolution frequency at the respective energy. The filter is obtained by combining a directly transmitted longitudinal signal with a signal delayed by one turn. In the original system the delayed branch is realised with coaxial cables with lumped circuits and amplification to match the frequency dependent attenuation, group delay, and the dispersion of the direct path. Part of the direct transmission is realised by a mechanically delicate, ~10 m long thin (< 0.5 mm) coaxial cable to achieve matching of the transmission characteristics. The overall length of the short path is critical at 3.57 GeV/c with a velocity factor of > 98% implemented for the combined length of ~ 40 m of 1 5/8" coaxial line.

In the new system, which was used for the first time with beam in 2018, the transmission for the 1-turn delay has been replaced by an optical fiber cable with low attenuation. Consequently the compensating circuits and the thin coaxial cable of the direct path could be suppressed gaining around 16 ns of delay. Commissioning of this new system is described in more detail further below.

Tables 1,2 shows the performance in cooling as achieved in regular operation and with the classical electric delay line notch filter.

Table 1: Parameters for Cooling at 3.57 GeV/c [4, 5]

Parameter	Design	Achieved
Intensity at 3.57 GeV/c	5×10^7	$\simeq 4 \times 10^7$
Cooling time	20 s	20 s
Hor. emittance (95%)	5π mm mrad	3π mm mrad
Ver. emittance (95%)	5π mm mrad	4π mm mrad
Momentum width	$\pm 0.5 \times 10^{-3}$	$\pm 0.35 \times 10^{-3}$

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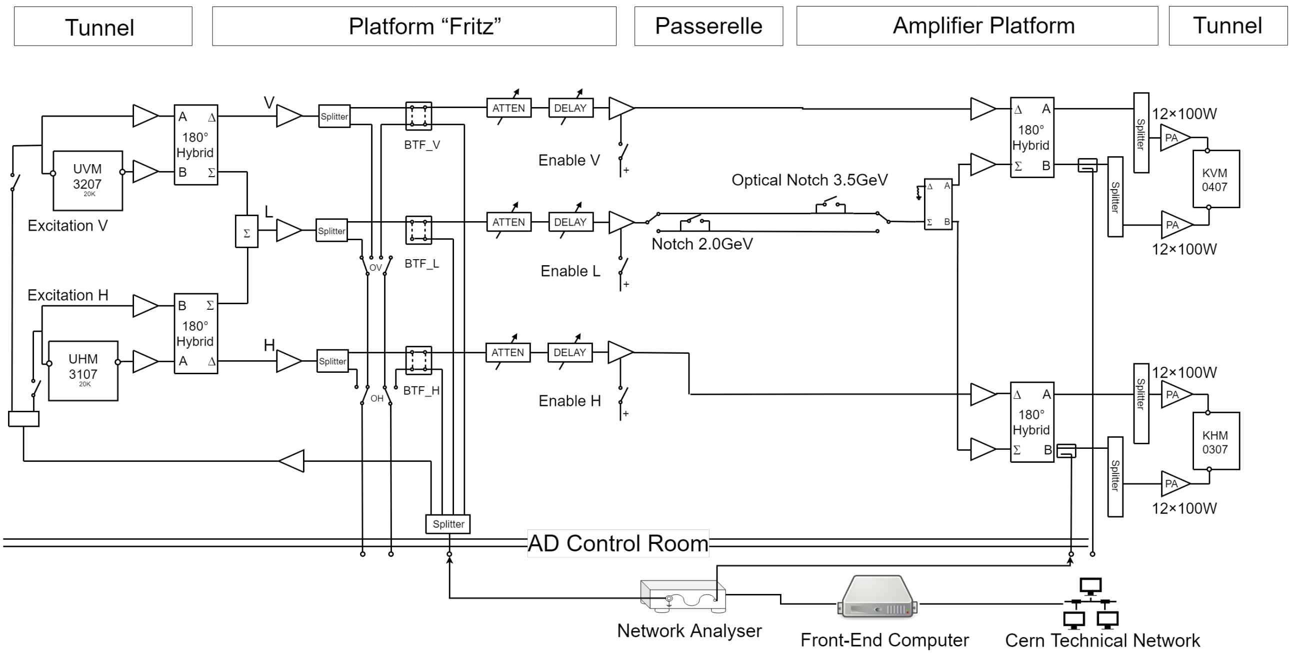

Figure 1: Stochastic cooling System Layout with pickups (PU) UVM 3207 and UHM 3107 and kickers (KI) KVM0407 and KHM0307.

Review of Operation and Faults until 2018

In spring 2000 during the start-up phase a leak was found in one of of the two stochastic cooling kicker tanks in the AD. These tanks are in general difficult to remove, requiring a long intervention in the order of about six months. This would have caused a significant delay of the AD physics program, but was under consideration. However, a closer examination of the situation showed the possibility for an in-situ repair of the problem. The leak was minuscule, leading to an increase in vacuum pressure on the particular tank from about 10^{-8} mbar to around 10^{-5} mbar. A quick calculation showed that it could not be bigger than a few micrometers. Additionally it was confirmed that this leak occurred on the water cooling circuit in this tank which consists of very thin water pipes inside the vacuum. It was decided to blow a special mixture of a four component epoxy glue with very high viscosity through the water cooling circuit followed by continuously blowing hot air through the circuit at about 80° C for two days for the curing process. Everything was done in situ and with the actual tank kept under high vacuum. It was a very delicate operation, and a mistake could have lead to the destruction of the equipment. Although initially considered as a temporary fix for a year, the tank is still perfectly leak tight today and the procedure could be repeated if required.

Other than this the stochastic cooling system posed no worries with only very little downtime throughout the years leading up to 2018, start of the long shutdown 2 (LS2).

Following this long operational period with minimum downtime consolidation is becoming important to maintain the high availability. With respect to slow performance degradations observed since 2000, an optimization of the cooling, the bunch rotation before cooling and the debunching and re-capture process is advised to restore fast cooling rates and minimize losses. After LS2 the main RF cavity system will have been replaced by a finemet based cavity, and new means of observation will be available from the low-level RF system and the Schottky monitoring. Moreover, full RF voltage for the two bunch rotation systems will again be available with refurbished tubes following the completed consolidation of this system. The automatic transfer function monitoring system being planned for the stochastic cooling and described further below will help to diagnose issues and optimise the cooling performance.

Noteworthy are small faults on the transmission line connections that were repaired during LS2 when the entire power system was dismantled to gain access to the machine for the magnet consolidation program and a modification of the shielding walls.

The jaws of the pick-up are moving during cooling with all the electronics to drive the system having been consolidated in long shutdown 1 (LS1) in 2013. For the kickers the electronics was renovated as well, however, as the movement was no longer used, the mechanism is now blocked in the

Table 2: Parameters for Cooling at 2.0 GeV/c [4, 5]

Parameter	Design	Achieved
Intensity at 2.0 GeV/c	5×10^7	$\simeq 4 \times 10^7$
Cooling time	15 s	15 s
Hor. emittance (95%)	5π mm mrad	2.9π mm mrad
Ver. emittance (95%)	5π mm mrad	3.3π mm mrad
Momentum width	$\pm 0.15 \times 10^{-3}$	$\pm 0.08 \times 10^{-3}$

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open position. With a total of 2.4 kW RF power per kicker tank sufficient power is available in order not to need the kicker movement to increase kick strength during cooling.

Plans and Progress with Consolidation

A new cryogenic current comparator [6] is providing precise beam intensity measurements during the cooling plateaus. This has greatly improved observation of beam losses during cooling. Comparison with the consolidated Schottky measurement system [7] will be made from 2021 onward when the machine restarts. Both systems will be needed, as the cryogenic pick-up has not yet reached maturity in terms of availability and the Schottky system is complementary as it also provides information on the momentum spread of the unbunched beam. Improvement of the precision of the Schottky system for current measurement, currently at ±20%, is desirable and may be possible with the new digital system.

A new scraper system similar to the one installed in ELENA was commissioned in 2018 due to obsolete hardware and for standardization. Measured transverse emittances do not correspond to measurements done with the previous system which needs to be kept in mind when evaluating the stochastic cooling system performance.

More machine development (MD) time is desirable for the start-up in 2021 to recommission all systems and optimize performance. With respect to the stochastic cooling system and the RF system the optimization is rather for a smooth handover with minimum losses between the systems and for maintaining fast cooling rates than for minimum final emittances. Lowest emittances are achieved by the final electron cooling before extraction of the beam to ELENA.

A challenge is that currently the machine cannot be kept at 3.57 GeV/c for a prolonged time to optimize the cooling. This is due to insufficient cooling of magnets and too high interlock levels. It needs to be addressed by restoring a higher cooling capacity, adaptation of interlock levels if possible, and by automating the beam transfer function measurements in order to carry out the optimization in the short available time span at flat-top.

One of the upgrades identified with high priority is the replacement of the notch filters in the longitudinal path of the stochastic cooling. Once this upgrade is completed, it will be clear how much delay margin in the system is left to consolidate other parts of the system including the final power amplifiers where an improved mechanical layout may be desirable. Commissioning of the notch filter at 3.57 GeV/c is described in the next section.

COMMISSIONING OF THE NEW NOTCH FILTER AT 3.57 GeV/c

A particular challenge of the commissioning of the new notch filter with optical delay line has been the need to follow this through in parallel with delivering beams to the experiments with minimal dedicated beam time and without being able to measure beam transfer functions (BTFs) for the setting-up due to the magnet cooling issues previously mentioned. Success relied upon carefully comparing the hardware transfer functions (HTFs) in delay, phase and attenuation between old and new system and adjusting the notches to the correct frequency. Figure 2 shows a compari-

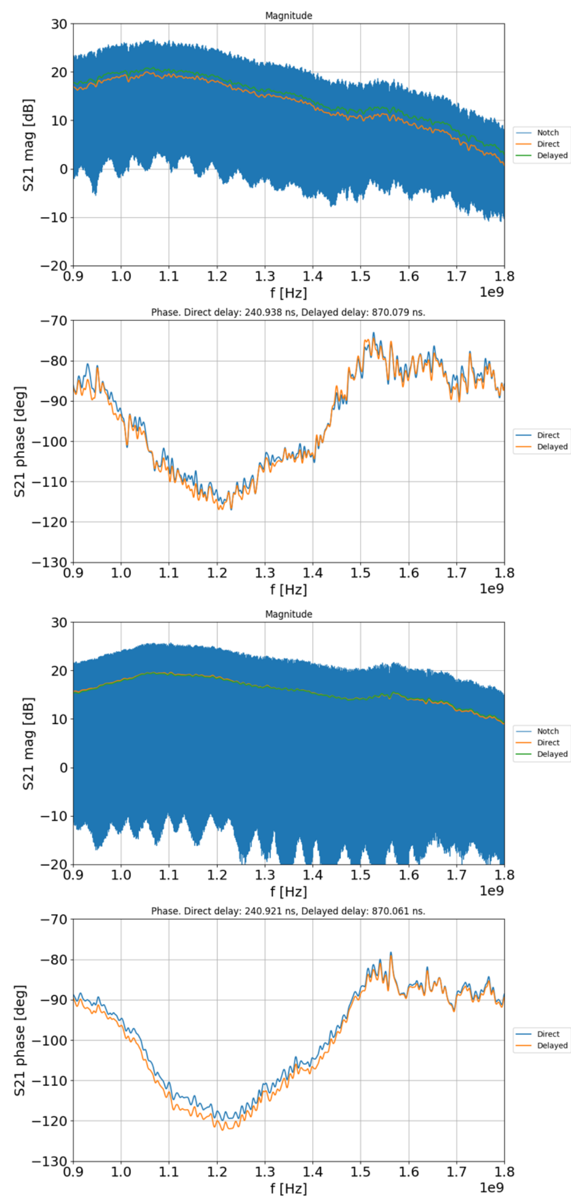

Figure 2: Hardware transfer function (HTF) of coaxial cable notch filter (top) and optical fiber notch filter (bottom); shown are attenuation and phase of the short and long branch and the transfer function with notches.

son of the transfer functions. The notch filter depth of the new optical path system is more than 30 dB over the frequency range of interest due to very good matching of phase and attenuation of the direct and delayed path. The variation of phase with frequency is similar for the new and the old system and amounts to 30°. The measurement includes the notch filter, signal transmission and pre-amplification, but neither the first stages of processing after the pick-ups nor

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the final 100 W power amplifiers (Fig. 1). A separate transmission path was used for the new system. It can also be seen that the new system provides an overall flatter response with frequency in amplitude. With gains adjusted accordingly the new system provides more gain at higher frequencies and less gain at low frequencies (Fig. 2).

RESULTS WITH BEAM

After closing the loop cooling was optimised by adjusting the gain for best transmission and lowest momentum spread after cooling. Fig. 3 shows the final result as viewed on the down converted FFT spectrum from the online application in the control room. This signal from the longitudinal magnetic pick-up is measured at $2 \times f_{\mathrm{rev}}$, using an analog down conversion to a fixed frequency of 50 kHz and subsequent FFT with a signal analyser. The cooling is also visible in Fig. 4 where two consecutive cycles are shown with green dots representing the momentum spread and 3×10^7 antiprotons after the first cooling plateau (red).

Following these successful tests the plans for LS2 include a second instance of the optical delay notch filter for cooling at 2 GeV/c. Full integration into the control system is foreseen including an automated measurement of transfer function as described in the following, to monitor and pilot adjustments during operation.

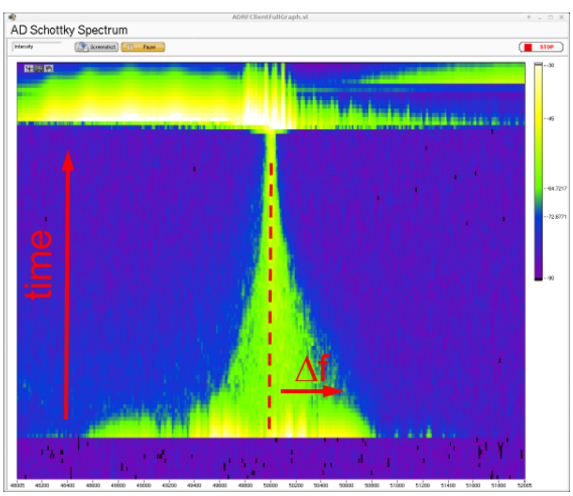

Figure 3: Results with Beam: FFT spectrum during cooling (200 Hz/div); down converted to an IF of 50 kHz from h=2.

ONLINE MONITORING OF HARDWARE TRANSFER FUNCTION

The newly developed optical delay line has been shown to experience drifts. While the majority of this is suspected to be due to an adjustable optical delay line with insufficient stability, a system to periodically monitor the hardware transfer function as basis for automatic or manual corrections is highly desirable. The proposed system which is now being implemented consists of a compact network analyzer that can be remotely controlled and triggered to do a measurement. From the change in transfer function, settings can be

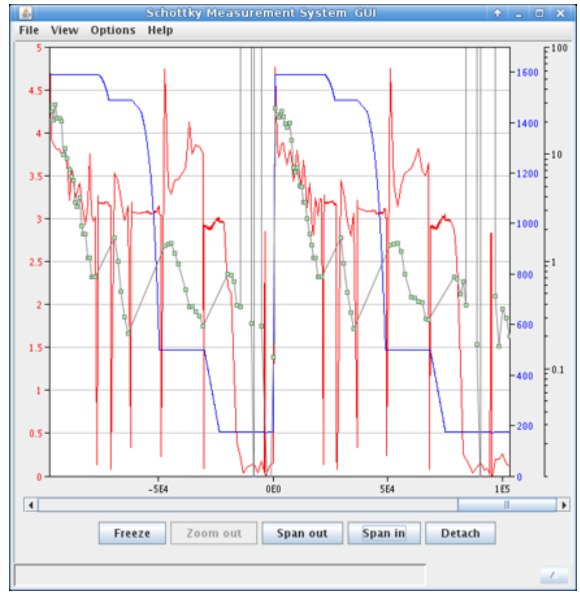

Figure 4: Cooling during the AD cycle; blue: revolution frequency in kHz, green: momentum spread (a.u.); red: beam intensity in 10^7 antiprotons.

deduced for manual correction or for automatic feedback. The measurement can be performed at any time during the AD cycle where stochastic cooling is not used.

Description of Hardware

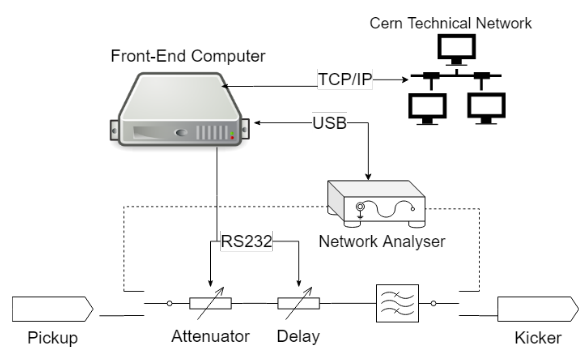

Figure 5: Hardware transfer function monitoring system.

The selected 2-port network analyser (VNA) from Copper Mountain Technologies (model S5085) will be permanently installed in a rack in the AD control room. Remote control functionality is provided by an USB-interface. An external 10 MHz reference ensures synchronisation in frequency with the accelerator for precise determination of notch frequencies that have to match the beam revolution frequency and the RF re-capture frequency. A measurement can be manually initiated from the software or configured to be started by machine timing at a particular moment during the AD cycle (Fig. 5).

In order to send a test signal through the notch filter two relays are used to switch the input and output of the filter to the instrument. As shown in Fig. 1, the signal path to

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the filter input can come from either the pick-up, or the control room. Likewise, the output can be directed to either the kicker-tank, or back to the control room. In order to make the VNA accessible to the CERN technical network and to handle the USB communication, a controller unit is required. The same unit can also be used to run the control software if automated correction is desired, and to command the motorised delay lines and attenuators. A VME rack mount Men-A25 front-end computer running the CERN CentOS7 operating system complying with current CERN accelerator operations standards is used for this purpose. It is a disk-less and headless computer for high reliability and maintainability. The software will receive timing signals from the technical network to synchronize the measurement with the AD-cycle. The same hardware can also be used to measure beam transfer function triggered by machine timing in a more automated way for periodic checks.

Development of Software Tools

Feedback control software to correct settings of the notch filter is being developed as a FESA-class [8] to also run on a front-end computer on the technical network. This way the control of the feedback system is easily integrated with the CERN-wide standard for accessing devices on the internal network. The software solution consists of three layers: The lower layer is an existing driver that handles the USB-link to the instrument, and enables communication with the instrument by setting up a TCP/IP connection. This is already developed by the VNA manufacturer, but needs to be modified to function correctly on CERN CentOS 7 (CC7). The second layer is a general FESA-class that abstracts the communication with the instrument. It is a general purpose layer that can be used by specialists to set individual parameters in the instrument. The third layer is the control loop itself, utilizing the second layer to command the VNA. The software can be configured for automatic control in regular intervals or for interaction with the operator to request a confirmation to changes proposed by the system.

Demonstration of feedback from HTF

The bulk part of the one-turn delay branch of the notch filter is a long optical fiber inside a temperature-controlled box. The overall delay can be fine tuned by a motorised delay line. Location and depth of the notch is a result both of delay and attenuation. For a first demonstration, only the delay was acted upon using a simple P-controller and measuring the S21 amplitude response and setting the delay line accordingly to place the 1000th notch to 1.589477 GHz. The correction loop was executed in the test every 10 minutes and the actuator is driven only if the error deviates from the set-point more than a programmed limit. This is done to limit the number of times the motorised delay line is driven. The method can be extended to also monitor the notch depth and accordingly adjust the attenuation in one of the branches to keep the notch depth better than a specified limit.

CONCLUSION

The stochastic cooling system in the CERN antiproton decelerator has reliably run for almost two decades, with a minimum of interventions. Investments to consolidate the system are now required and the presented optical delay line notch filter is a key part of the ongoing program. Monitoring and adjustment tools are being developed for setting up the system and for performance control and optimization.

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