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EXPERIENCE WITH BEAM TRANSFER FUNCTION MEASUREMENTS FOR SETTING-UP THE STOCHASTIC COOLING SYSTEM IN THE CERN ANTI-PROTON DECELERATOR (AD)

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Abstract

Beam transfer function measurements have regularly been used to set-up the adjustable parameters for stochastic cooling systems. We report on the automation of these measurements at CERN that permit efficient set-up of the cooling loops in the anti-proton decelerator (AD) and enables insight into the bandwidth (nominal frequency range of 850 MHz to 1.7 GHz) of the overall system for the longitudinal, horizontal and vertical cooling at the two different beam momenta of 2 GeV/c and 3.57 GeV/c. Additionally, data collected during machine development sessions can be used to identify areas of improvement and will be indispensable in defining the planned path for consolidation and upgrade of the system. For example, it allows the comparison of the bandwidth with the computed shunt impedance of the currently used kickers. The unwanted crosstalk between the three different planes of cooling is also evaluated and will help to define improvements in the system for the future.

INTRODUCTION

Stochastic cooling is currently used in the CERN Antiproton Decelerator (AD) at two different beam momenta of 2 GeV/c and 3.57 GeV/c [1]. Anti-protons are routinely decelerated since 1999 [2] and since the start-up after long-shutdown 2 (LS2) exclusively provided for further deceleration to the new ELENA decelerator [3]. The transfer momentum to Elena is 100 MeV/c with electron cooling used at two further momentum plateaus in AD at 300 MeV/c and 100 MeV/c.

In the framework of increasing the efficiency and set-up time of the stochastic cooling system in AD it was highly desirable to conceive an automated beam transfer function measurement that could go beyond the normal setting-up, but also be used for diagnosis during the run, and to probe the efficacy and available bandwidth of the existing systems that operate in all three planes at the two beam momenta. The data collected during such measurements helps to define upgrades required in view of future operation, also possibly with the stochastic cooling used at a lower momenta.

OVERVIEW OF AD STOCHASTIC COOLING SYSTEM AND BEAMS

The stochastic cooling system in AD comprises four elements in the ring: horizontal pick-up UHM 3107, horizontal kicker KHM 0307, vertical pick-up UVM 3207 and vertical kicker KVM 0407 [1]. The longitudinal cooling is obtained using the same pick-ups and kickers in their common mode combining both signals from the horizontal and vertical pick-ups and splitting on the back-end the signal to feed both the horizontal and vertical kickers through notch filters.

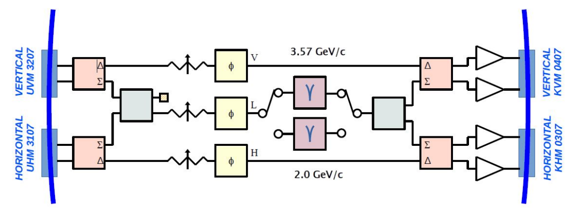

Figure 1: AD Stochastic Cooling Overview.

Layout and Optics for Stochastic Cooling at 2 GeV/c and 3.57 GeV/c

The two pairs of pick-up and and kicker are installed in locations opposing each other in the ring. For a ring circumference of 182.433 m the beam orbit length between pick-up to kicker and kicker to pick-up amounts to between 91.21 m to 91.22 m in length rounded to centimeters for nominal momentum. For the two cooling plateaus (2 GeV/c and

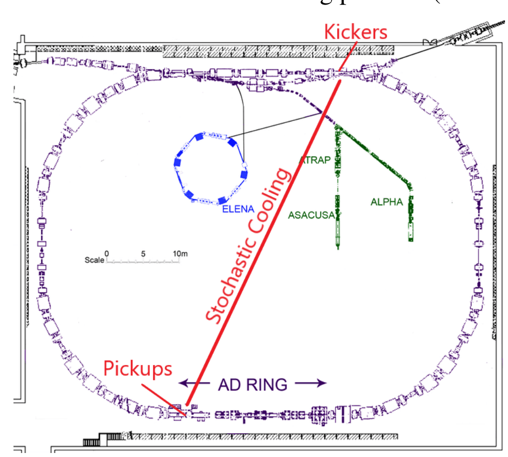

Figure 2: AD Stochastic Cooling.

3.57 GeV/c) the beam β equals 0.90532 and 0.96724, respectively, giving time of flights of ~ 336.1 ns and ~ 314.6 ns. The time of flight difference of ~ 21.5 ns must be properly compensated when switching between the two plateaus. Implementation of the switching is by means of RF relays controlled by a PLC system and with the total delay difference split into several parts located along the signal chain. The pick-ups have only one feed-through per side with internal delays being adjusted for 3.57 GeV/c, while the kicker

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has individual feed-throughs for the twelve amplifiers per side permitting a better adjustment of the delay difference between the two different plateaus.

Table 1 shows the values for the transverse tune and phase advances from pick-up to kicker. Phase advances deviate by

Table 1: Optics Parameters Transverse Cooling in AD

horizontal tune Q_H	5.385
Phase advance from H pickup to H kicker	256°
vertical tune Q_V	5.369
Phase advance from V pickup to V kicker	283°

less than 20° from the optimum value for transverse cooling. In an open loop beam transfer measurement this deviation will be visible in a Nyquist plot as a rotation of the circles corresponding to the lower and upper betatron side bands in the opposite sense [4].

Optical Delay Line Notch Filter

The notch filter is actually a comb filter structure as given in Figure 3. The output signal of such a structure in time

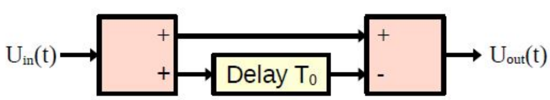

Figure 3: Comb filter principle.

domain is given by:

$$U_{out}(t) = \frac{1}{2}\Big(U_{in}(t) - U_{in}(t - T_0)\Big) \tag{1}$$

A Fourier transform performed on equation (1), modified to take into the account attenuation difference of long and short branch, gives the following transfer function:

$$H(\omega) = \frac{1}{1+a}\Big(1 - a \cdot e^{-j2\pi\omega/\omega 0}\Big) \tag{2}$$

where a characterizes the additional attenuation factor of

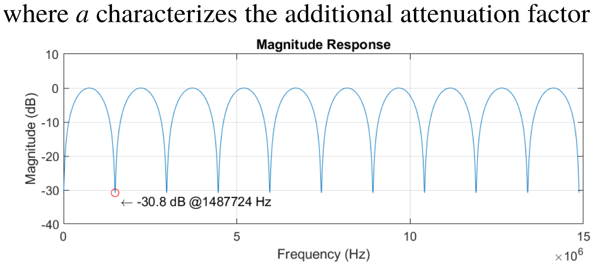

Figure 4: Simulated Comb filter magnitude @ 2.0 GeV/c.

the long branch with respect to the short branch. The notch depth in dB is $20\log_{10}((1-a)/(1+a))$. Figures 4 & 5 show ideal magnitude and phase for a filter with no delay in the short branch. The principle of periodic filters for stochastic cooling was invented at CERN [5] and has worked well for decades using coaxial cables. The search for greater cooling performances has led to test an optical notch filter prototype on the 3.57 GeV/c [6] similar to current usage

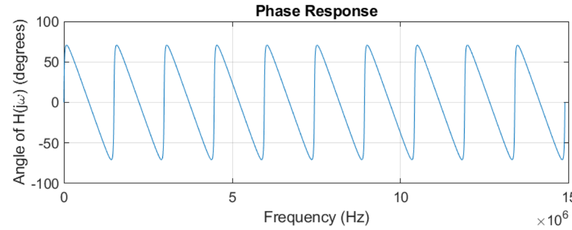

Figure 5: Simulated Comb filter phase @ 2.0 GeV/c.

in other accelerators. Replacing the RF devices by optical devices has enabled us to reduce the size of the system and the prototype now in use at CERN has shown not only greater performances but a greater robustness and ease for maintenance and diagnosis as well.

Subsequently, an industrial version has been studied and built where all the optical devices are inside a temperature stabilized enclosure as shown in Figure 6. The long branch is made of a fixed 120 m fiber and additional short patch fibers to approach the nominal target length. An optical delay line is then used to fine tune the notch frequency.

The long fiber is wound on an aluminium reel which is heated to a stable temperature within ±0.02°C. The reel acts as well as a heater for the whole enclosure and provides thus a good temperature stability for all the other less critical optical elements. The steady state temperature is kept at 40 degrees with no active cooling. Steady state temperature is reached after a few hours.

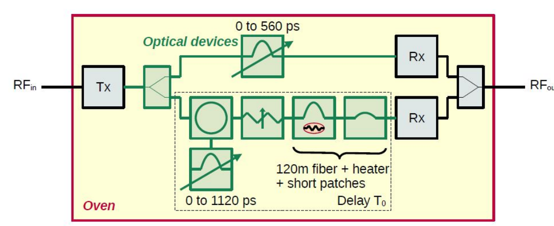

Figure 6: New optical notch filter synoptic.

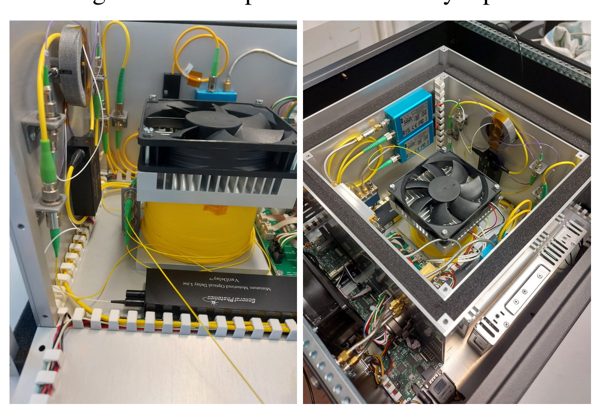

Figure 7: New optical notch filter.

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SET-UP FOR MEASURING BTFS

Beam Transfer Functions (BTFs) are performed using a Vector Network Analyzer (VNA). A transmission measurement S21 is performed in open loop for the targeted plane using a swept frequency covering a few revolution harmonics. The signal from the VNA feeds power amplifiers and the beam response is recovered with signals from the pick-ups. A number of relays are remotely controlled in a predefined sequence. BTFs are measured in several (typical 11) intervals distributed over the frequency range of 800 MHz to 1.8 GHz. With three planes to measure and two plateaus this gives a total of 66 BTFs needed for a reasonable set-up and check of the stochastic cooling system. The BTFs are

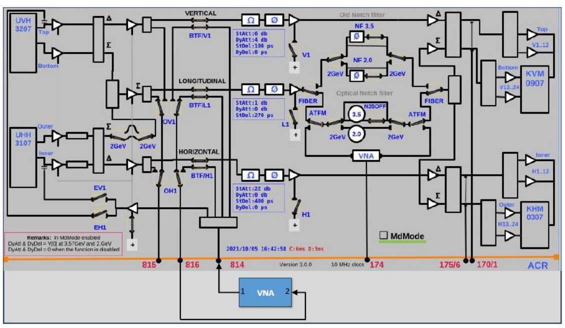

Figure 8: BTF measurements setup.

conducted during the annual machine commissioning and periodically throughout the year whenever modifications or maintenance have been performed. Previously, this process required two full days of work.

A suite of software tools, called the 'BTF toolbox,' has been developed to automate these measurements and analysis. With this automation, a full plateau can now be achieved in 15 minutes instead of a day. This not only offers a more efficient way of saving data and performing analysis but also allows for quicker measurements. As a result, more measurements can be performed in the same time-frame, making it possible to adjust certain parameters. This has improved the understanding of setting-up stochastic cooling and has helped in identifying lingering errors.

The automation process involves sweeping frequency in steps across the bandwidth. For each frequency step, a span of 3 MHz is captured using 1600 points. RF relays are then controlled to calibrate the VNA, eliminating the effects of the cables' length from the VNA to the measurement points. After calibration, the relays are adjusted to set the machine to the desired plane. In the longitudinal plane, the notch filter is turned off by opening the long branch with a relay. As the VNA sends a signal to the kicker, it disturbs the beam which trends to blow-up. Before starting any new measurement in the sequence, the tool controls the relays to reactivate the cooling.

Figure 9: BTF toolbox analysis.

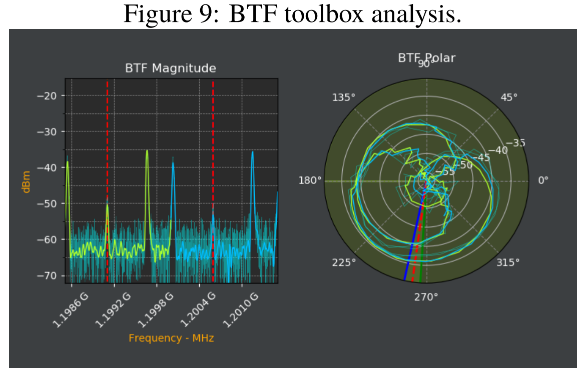

Figure 10: 1.2 GHz vertical response @ 2 GeV/c showing betatron side bands and unwanted response at harmonics of the revolution frequency due to beam offsets.

CONCLUSIONS

The Beam Transfer Function toolbox has enabled to reduce the measurement time and increase the number of analysis iterations and machine adjustments. Phase and delay errors could be identified in the longitudinal plane at 2 GeV/c and corrected. Thanks to the improved cooling at 2 GeV/c it has provided an overall transmission increase of 4% and it has been identified a potential reduction of the AD decelerating cycle time. In addition it enables to reduce significantly the yearly commissioning time after the machine end of year technical stop. This ends into more anti-protons available for physics experiments.

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REFERENCES

[1] F. Caspers and C. Carli, "Stochastic Cooling at the CERN Antiproton Decelerator", in *Proc. EPAC2000*, Vienna, Austria, 2000, pp. 2014–2016.

[2] P. Belochitskii *et al.*, "Commissioning and First Operation of the Antiproton Decelerator AD", in *Proc. PAC'01*, Chicago, Ill., USA, June 2001, pp. 580–584.

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[3] L. Ponce, L. Bojtár, C. Carli, B. Dupuy, Y. Dutheil, P. Freyermuth, *et al.*, "ELENA - From Commissioning to Operation", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 2391–2394. doi:10.18429/JACoW-IPAC2022-THOXGD1

[4] H. Stockhorst, T. Katayama, R. Maier, "Beam cooling at COSY and HESR, Part 1 Theory", *Schlüsseltechnologien*, Volume 120, ISBN 978-3-95806-127-9, Forschungszentrum Jülich, Jülich, 2016. https://juser.fz-juelich.de/record/807739

[5] L. Thorndahl, G. Carron, "Stochastic cooling of momentum spread by filter techniques", CERN-ISR-RF-78-12, CERN, Geneva, Switzerland, 1978.

[6] F. Caspers *et al.*, "First Operation for Stochastic Cooling of p-Bars in the CERN AD using Optical Delay Notch Filter and Plans for 2021 Operation", 12th Workshop on Beam cooling and Related Topics, *in proc. of COOL'19*, Novosibirsk, September 2019. doi:10.18429/JACoW-COOL2019-MOY01