ISBN: 978-3-95450-243-1 ISSN: 2226-0374 doi:10.18429/JACoW-COOL2021-S302

RECOMMISSIONING OF THE CERN AD STOCHASTIC COOLING SYSTEM IN 2021 AFTER LONG SHUTDOWN 2

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Abstract

The power amplifier system of the Stochastic Cooling System of the Anti-proton Decelerator (AD) at CERN, installed on top of the shielding blocks of the AD ring, was completely dismantled during the long shutdown 2 (LS2) at the end of the 2018 run in order to gain access to the accelerator for magnet consolidation. At start-up, this required finding and verifying the correct electrical delays for all 48 power amplifiers feeding the two kickers, by means of beam transfer functions for the two cooling plateaus at 3.57 GeV/c and 2 GeV/c. We describe the methods used for the setting up and the results of the optimization for the cooling in all three planes, longitudinal, horizontal and vertical. An experimental set-up has been put into operation for automatic monitoring and correction of the notch position of the longitudinal cooling at 3.57 GeV/c with optical delay lines. We also comment on the lessons learnt during the recommissioning including the repair work for a vacuum leak in the water cooling circuits of the kicker following bake-out and the verification of the internal loads by RF reflectometry.

INTRODUCTION

In the CERN Anti-proton Decelerator (AD) anti-protons are routinely decelerated since 1999 and distributed to experiments located in the same hall as the AD machine [1]. The AD machine itself is covered for radiation shielding purposes by concrete blocks leaving only limited space for access to equipment inside the ring. In case a bulky element in the ring needs to be shifted or exchanged concrete blocks covering the AD ring have to be removed so that the equipment can be accessed by the overhead crane. The CERN Long Shutdown 2 (LS2) from 2019 to 2020 saw a number of interventions for consolidation in AD and for connection of beam transfer lines between ELENA and the newly installed experiments. Notably the change of a magnet in between the two kicker tanks of the stochastic cooling system and the installation of the extraction line from ELENA (LNE00) necessitated the temporary dismantling of the stochastic cooling power amplifier system.

RECAP OF STOCHASTIC COOLING PICK-UPS AND KICKERS

The stochastic cooling system in AD comprises four elements in the ring: horizontal pick-up UHM 3107 and horizontal kicker KHM 0307, and vertical pick-up UVM 3207 with vertical kicker KVM 0407 [2]. The longitudinal cooling is 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.

The basic element in these pick-ups and kickers is a rectangular short electrode of a length of 33 mm (in beam direction) and width of 46 mm. A total of 48 of these small electrodes are lined up on a rail with a gap of 10.85 mm to form what is called a “super-electrode” with a total active length of 2093.95 mm. The individual electrodes are grouped in 12 sets of four electrodes (Figure 1). For the kicker, each set is fed by a single 100 W power amplifier connected to a dedicated RF vacuum feedthrough on the tank.

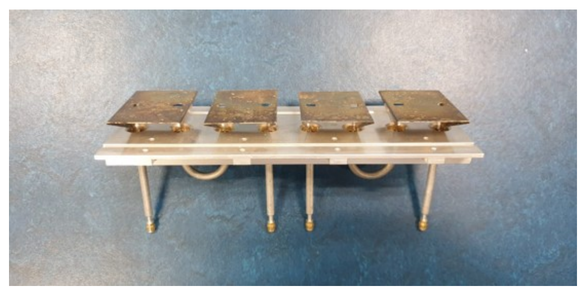

Figure 1: Set of four electrodes (length of support 175.4 mm) powered by a single amplifier (see text).

Within the set of four electrodes the power is distributed through a 2:1 splitter of Wilkenson type, but without matching resistor, mounted on the rail inside the vacuum tank. Power is then applied to two pairs of adjacent electrodes connected in series and proper terminations ensure that the lack of resistor in the power splitter does not result in adverse reflections. Electrical delays match the time of flight to give a maximum of the shut impedance at the beam momentum the structure was originally optimized for (3.57 GeV/c). Power is dissipated in 12 RF loads mounted on the side of the rail opposing the beam. Damping of higher order and propagating modes in the structure is achieved by ferrite tiles attached to two rails in the plane perpendicular to the electrodes.

The rails supporting the electrodes can be moved, however this movement is no longer used for the case of the kickers since LS1 (2014) and the mechanism has been blocked in the position giving the maximum acceptance for the beam. In addition to reducing the operational complexity, the suppression of the kicker movement also renders the performance less sensitive to beam position as the region of homogeneous field is larger with jaws open. Additionally, final smaller

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emittances were achieved in the past during routine operation with the jaws of the kicker kept fully open. These advantages outweigh the faster cooling times that would be possible with moving jaws and perfect adjustments of orbit. Sufficient power is available and the cycle length is designed to allow for the somewhat slower cooling times with the open jaws.

For the pick-up the movement is still used, closing the electrodes to increase sensitivity as the beam is transversely cooled at 3.57 GeV/c, and electrodes are closed for the cooling at 2 GeV/c. Water cooling has been originally only applied to the electrodes supporting the RF loads. However, when the equipment originating from the CERN AC machine was recommissioned as part of the AD machine in 1999 water cooling got added to the rails supporting the ferrite tiles, presumably related to vacuum specifications that called for an improvement that could be compromised by outgasing of the ferrites. Therefore the presently installed kicker tanks each feature four water cooling circuits two of which do not form part of the original construction documentation from the 1980's.

One of the cooling circuits in the horizontal kicker tank developed a leak during bake-out in the early years of operation of the AD in 2001. It was at the time in-situ repaired by injecting a resin (araldite) into the circuit. Twenty years later in 2021 a similar leak developed on the same horizontal tank on the cooling circuit of the opposing electrode following the bake-out needed at the end of LS2. The leak could again be repaired in spring 2021 using the same procedure as 20 years ago. This event of 2021 demonstrates the fragility of the system in case a future bake out is required for one of the kicker tanks. It also motivates, combined with a lack of a spare, the launch of a study to construct full spares of improved design. Apart from mechanical improvements the study can also review and explore the electromagnetic and RF design. In particular in view of today's usage of the cooling system on a second plateau at a beam momentum of 2.0 GeV/c, for which the structure was originally not optimised, improvements might be possible. Consolidation of the power amplifier system will need to wait until the results of the study show which path for consolidation should be taken. Alternative paths could leverage on developments of kickers for similar systems under study or construction for FAIR at GSI in Germany [3], NICA at JINR in Dubna, Russia and HIAF in China [4].

For the pick-ups, the signals of all individual electrodes of a super-electrode are combined within the vacuum tank. The required termination resistors of the combiners inside the pick-up are cooled by conduction using gaseous He from a cryo pump. Instrumentation inside the tank is insufficient to precisely determine the relevant equivalent noise temperature to use in a simulation of the cooling process. Outside the pick-up tank a set of two low noise amplifiers in series per electrode amplify the signal before it is combined in a hybrid to yield the transverse and longitudinal signal for beam cooling.

The homogeneous region of the field in the center is limited to a small area for both pick-up and kicker. The limited possibilities of adjusting for a displaced orbit, and for ensuring in the system a perfect symmetry between the two sides of both pick-up and kicker electrodes, represent an operational challenge to keep high cooling efficiency. Increasing the means to compensate for these effects electronically, represents an option for future consolidation of the equipment.

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 182.43 m the beam orbit length between pick-up to kicker and kicker to pick-up amounts to ~ 91.22 m in length. For the two cooling plateaus (2 GeV/c and 3.57 GeV/c) the beam β equals 0.90532 and 0.96724, respectively, giving time of flights of 336 ns and 314 ns. The time of flight difference of ~ 22 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. Table 1 shows the values for the transverse tune and phase advances from pick-up to kicker. Phase advances deviate by 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 [5]. During setting-up of the system this can be discriminated from an error of the delay in the system which will rotate these circles in the Nyquist plot in the same orientation sense. While the delay can be easily adjusted remotely in the system, no means to adjust for the phase advance are presently used. In the past, a comb filter was used to make an adjustment possible. This filter used a resonant line. However, such a filter achieves the phase advance adjustment by adding to the directly transmitted signal a delayed signal that will increase the undesirable mixing from pick-up to kicker.

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°

Acceptance and Initial Conditions for Stochastic Cooling at 3.57 GeV/c

The longitudinal acceptance of the AD machine is quoted to be ±3 % in relative momentum $\Delta p/p$ corresponding to ±111 MeV in energy with an almost flat distribution used in a preliminary simulation of the bunch rotation [6] in line with previous experience [7]. In the same preliminary study

13th Workshop on Beam Cooling and Related Topics COOL2021, Novosibirsk, Russia JACoW Publishing
ISBN: 978-3-95450-243-1 ISSN: 2226-0374 doi:10.18429/JACoW-COOL2021-S302

a bunch length of 35 ns was used (2σ, parabolic distribution) yielding after rotation an energy spread of 16.86 MeV rms with no particles outside ±45 MeV for an optimised voltage program of the 10 MHz bunch rotation system respecting the limits of this system. Studies are needed to confirm the previously quoted acceptance of the stochastic cooling system in the range of ±0.5 % to ±1.0 % in $\Delta p/p$. In principle these parameters are experimentally accessible by comparing the time evolution of Schottky spectra and losses in different combinations of machine conditions with bunch rotation "off", "on" and stochastic cooling "off" and "on". Future studies are expected to be made easier by an improved Schottky diagnostics system. The procedure to align the two bunch rotation cavities in phase with respect to each other and the incoming beam is outlined in [8] and an important pre-requisite for efficient stochastic cooling.

PREPARATIONS FOR 2021 RUN AND SHUTDOWN WORK

Power Amplifiers

Power amplifiers had the usual maintenance during the long shutdown 2 and reference measurements saved for each re-installed amplifier. These 100 W amplifiers feature 40-41 dB gain at a mean delay of 10.5 ns in the frequency range of 600 MHz to 1.8 GHz (-3dB). The variation of phase from the mean delay is very flat in the pass band (±5°). This and the smooth role-off of gain at the lower and upper limits of the pass band is essential for efficient cooling. Any signal fed back at the edges of the band and out-of-band with the wrong phase will counteract cooling and lead to hidden heating. During operation in 2021 several amplifiers showed repeated issues and needed to be disabled. When possible, pairs of amplifiers feeding opposing parts of the structure are disabled to keep the kicks as homogeneous as possible. With the recovering of more spare amplifiers it is expected to start 2022 operation with all 48 amplifiers fully operational. Additional interlocks have been added to protect against the case of compromised water cooling for both the final 100 W amplifiers and their drivers.

Kickers

During the dismantling of the installation at the start of LS2 in 2018 all RF lines connecting amplifiers to the kicker tanks as well as the matching of the loads in the kicker tank have been checked by RF time domain reflectometry. Figure 2 shows as an example a typical measurement in-situ on one of the lines with the end reflection of -17.7 dB representing the matching of the load. A faint DC current is used to detect the presence of the loads and interlock the RF power. The circulator which protects the amplifier from reflected power was removed for these measurements. Visible in the measurement are also imperfections on the line by the discs supporting the inner conductor and reflections from joints and connectors. All reflections are below -25 dB. A number of bad contacts with higher reflection were identified and corrected as part of the program during LS2.

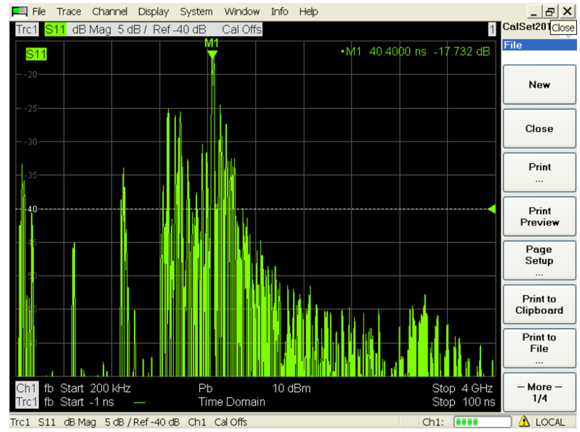

Figure 2: RF reflectometry on an RF line connecting the power amplifier to the kicker tank.

Controls

Controls is provided by a PLC system that was also upgraded to a more modern version during LS2. It will allow for the future to add more remote control functionality. This system needed commissioning of all its newly wired hardware, and the different layers of the control system in parallel to RF measurements and commissioning.

Optical Delay Notch filter and Automizing of the Hardware Transfer Function (HTF) Measurement

The optical delay line notch filter had been tested successfully pre-LS2 [9] and was recommissioned with an add on to monitor and adjust its transfer function automatically. In segments of the AD cycle without beam a network analyzer sweeps in frequency to verify the transfer function of the longitudinal branch, checking the position of notches and applies a correction if a deviation is noticed by the system. Once commissioned at 3.57 GeV/c the optical notch became the operational system and provided excellent stability over the year. It is now planned to extend the system to 2 GeV/c and to evolve the transfer function measurements towards also automatically measuring beam transfer functions.

Figure 3 as an example shows how over a period of ~four weeks the system kept the notch frequency of the 1000th revolution harmonic in the longitudinal cooling branch at 3.57 GeV/c within 2.5 kHz of the target frequency of 1.589411 GHz. The variation of programmed delay required to keep the stability in this one month period was 10 ps approximately and the notch depth remained better than -30 dB on average.

START-UP WITH BEAM

Following verification of all hardware transfer functions the beam time required for bringing back the system in operation was spread over three weeks in Summer 2021. The principle challenge was to find back the correct settings for the delay, matching time of flight between pick-up and kicker. This can done by measuring beam transfer functions

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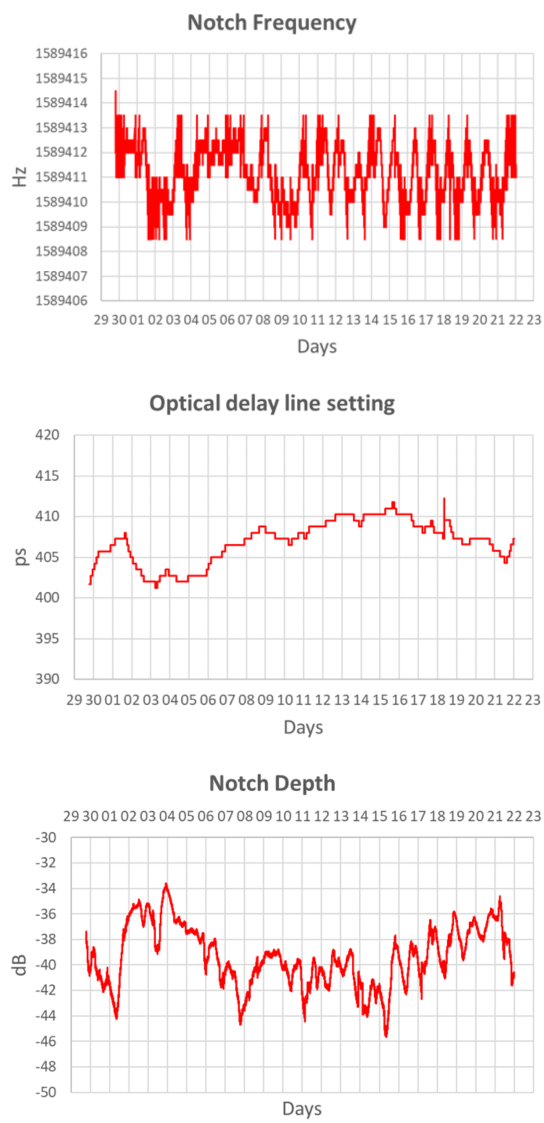

Figure 3: Notch frequency at 1000th harmonic, notch depth and programmed delay to keep stability over a period of ~four weeks from 29.09.2021 to 23.10.2021.

in multiple narrow bands each covering a few revolution harmonics. In order to get clean measurements additional low-noise pre-amplifiers were used at the network analyzer input. The cooling loops can be remotely opened to do the measurement following a calibration of the signal cables from the AD control room to the installation. The amplitude response over the frequency range of interest shows that the overall system has gain between 900 MHz and 1.8 GHz at 3.57 GeV/c with -3 dB points at approximately 1.1 GHz and 1.5 GHz. The complex response can be displayed as Nyquist plot. Here the relevant circles must be oriented towards the negative real axis for stability of the closed loop that also corresponds to optimum damping [5].

The measurements in the longitudinal plane are carried out with the long line of the notch filter disabled and only the short direct signal path left in place. Figure 4 shows an example of the plots used to adjust the delay in the horizontal plane. The top plot shows the amplitude response with significant contributions at the revolution harmonics in addition to the response at the betatron frequencies. A frame of 5 MHz width is shown covering four revolution harmonics with six betatron sidebands. The unwanted signal at the revolution harmonics is due to the imperfect cancellation in the hybrid of the orbit component and its excitation by asymmetries. Improvements are possible by ensuring that only transverse motion is excited and by making the hardware adjustable to achieve a better suppression of the orbit. The beam orbit itself must be kept within the homogeneous field region and should ideally be physically centered in the structures both of the pick-ups and kickers. The Nyquist plot shows the correct orientation of circles of the betatron side bands. For the case that the undesired longitudinal response has a wrong orientation, there will be a contribution that heats the beam longitudinally. This is a general observation that in the sequence of setting-up first the longitudinal system must be commissioned as it is needed to counteract the longitudinal heating introduced by the transverse systems.

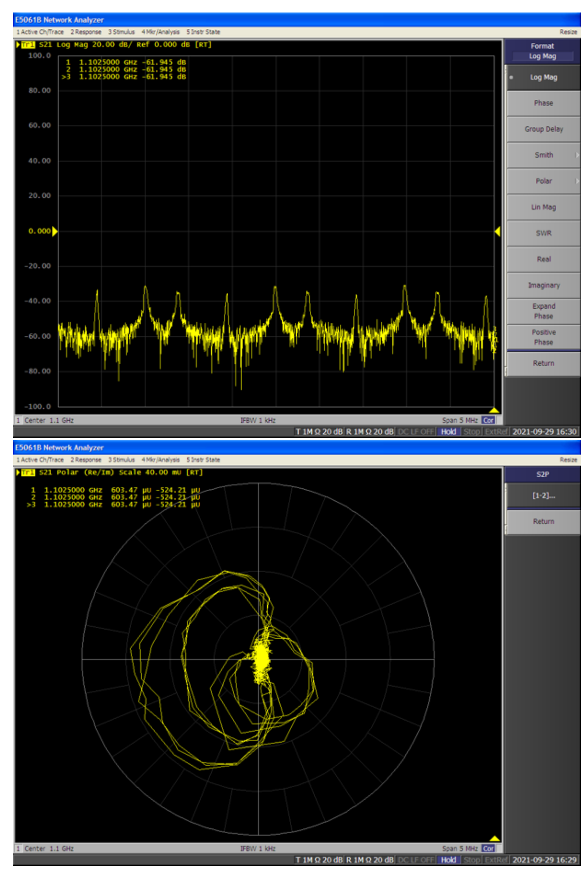

Figure 4: Beam transfer function in open loop, horizontal system at 3.57 GeV/c at 1.1 GHz.

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PERFORMANCE WITH BEAM

Longitudinal Plane

Figure 5 shows the longitudinal cooling achieved at 3.57 GeV/c on the left side and 2 GeV/c on the right side. Cooling in both cases was re-established and permitted deceleration of the beam to the next plateau. The good results at 3.57 GeV/c and the stability obtained with the described HTF monitoring and adjustment justifies to introduce this technology also to the cooling at 2 GeV/c as soon as the hardware will be ready.

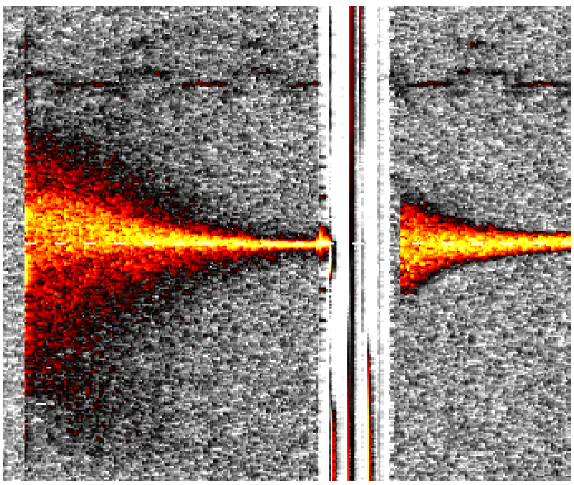

Figure 5: Stochastic Cooling at 3.57 GeV/c (left) and 2 GeV/c (right).

Transverse Cooling

Transverse Cooling is somewhat more demanding to setup as Schottky diagnostics is not available in AD for the transverse plane. The emittances before and after cooling can be measured by a scraper system to confirm by how much the emittances are reduced by the cooling. Without transverse cooling losses are also visible during deceleration and can serve as an observable for optimization.

Following recommissioning, cooling at 3.57 GeV/c in the horizontal plane was re-established faster than at 2 GeV/c with ~20-fold reduction in emittances from 230π mm mrad to 10π mm mrad (H-plane) and 12π mm mrad (V-plane). At 2 GeV/c the 2021 experience is that the system performs less well than before LS2 with emittances reduced in the H-plane from 18.5π mm mrad to 12.6π mm mrad and in the V-plane from 28.9π mm mrad to 15.8π mm mrad. These post-LS2 values cannot be readily be compared with pre-LS2 values due to changes in the scraper system and the analysis software used. Further studies are required to confirm the performance and to find the handles to improve in particular the cooling at 2 GeV/c.

Transmission

Figure 6 shows the re-established AD cycle with the first two plateaus with stochastic cooling and the second two plateaus at 300 MeV/c and 100 MeV/c where electron cooling is used [10]. Losses remain prominent on the 3.57 GeV/c where the handover between bunch rotation system and stochastic cooling system deserves more scrutiny. Losses during re-capture and deceleration are very small and thanks also due to the excellent performance of the new digital LLRF system [11].

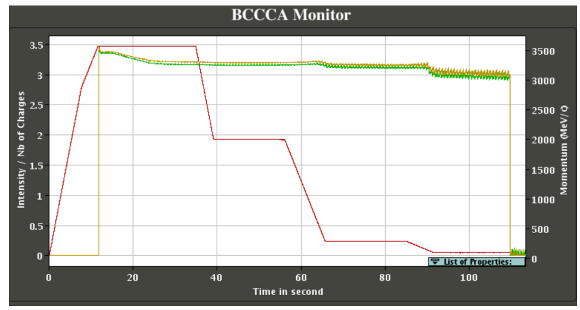

Figure 6: AD cycle with good transmission after LS2.

CONCLUSION

The stochastic cooling power system of AD was completely dismantled during the CERN long shutdown 2 (LS2) and required a substantial effort to recover an acceptable performance in 2021. A vacuum leak on the horizontal tank water cooling circuit was successfully repaired. The start-up with beam in Summer 2021 took longer than expected with settings for the delays that had to recovered from scratch without a well established procedure from past years. There remains margin to improve the performance of the transverse cooling at 2 GeV/c. The experience gained during the start-up will guide studies in the following years to better characterize the system and identify areas that need further improvement to boost performance in future years.

ACKNOWLEDGEMENT

The authors would like to thank their colleagues from SY-RF, BE-OP, TE-VSC, TE-MSC, EN-MME and EN-CV who have helped during the recommissioning of the system and the necessary repair and maintenance work and who have given advice during LS2.

REFERENCES

[1] 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.

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

[3] C. Dimopoulou, "Stochastic Cooling System for the Collector Ring at FAIR", *in proc. of COOL'21*, Novosibirsk, November 2021, paper S301, these conference.

[4] G. Zhu *et al.*, "Stochastic Cooling Pickup/Kicker Developments for the High-precision Spectrometer Ring in the HIAF Project at IMP", *IEEE Trans. Nucl. Sci.*, Vol. 68, No. 1, January 2021, pp. 9–20.

ISBN: 978-3-95450-243-1 ISSN: 2226-0374 doi:10.18429/JACoW-COOL2021-S302

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

[6] S. Albright, *private communication*, CERN, Geneva, 2021.

[7] M. E. Angoletta et al., "Experience with antiproton stacking at injection energy in CERN's AD, CERN-ACC-Note-2019-0025, CERN, Geneva, 2019.

[8] S. Albright, "A Method for Aligning the Phases of C10 Cavities in the AD", CERN-ACC-NOTE-2021-0026, CERN, Geneva, 2021.

[9] 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 (*COOL'19)*, Novosibirsk, Sep.2019 doi:10.18429/JACoW-COOL2019-MOY01

[10] D. Gamba *et al.*, "AD/ELENA electron cooling experience during and after CERNs Long Shutdown (LS2)", *in proc. of COOL'21*, Novosibirsk, November, 2021, paper S503, these conference.

[11] M. E. Angoletta *et al.*, "A New Digital Low-Level RF and Longitudinal Diagnostic System for CERN's AD", *in proc. of IPAC'19*, Melbourne, Australia, 2019, pp. 3966–3969. doi:10.18429/JACoW-IPAC2019-THPRB070