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ELENA - FROM COMMISSIONING TO OPERATION

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Abstract

In 2021 the Extra Low ENergy Antiproton ring (ELENA) moved from commissioning into the physics production phase providing 100 keV antiprotons to the newly connected experiments paving the way to an improved trapping efficiency by one to two orders of magnitude compared to the AD era. After recalling the major work undertaken during the CERN Long Shutdown 2 (2019-2020) in the antiproton deceleration complex, details will be given on the ELENA ring and new electrostatic transfer line beam commissioning using an ion source. Subsequently, the progress from commissioning with ions to operation with antiprotons will be described with emphasis on the achieved beam performance.

INTRODUCTION

The Extra Low ENergy Antiproton ring (ELENA) is the new baby of the CERN Antimatter Factory complex. The small 30.4 m circumference synchrotron is complementing the 20 years old Antiproton Decelerator (AD) to further decelerate the antiprotons from 5.3 MeV kinetic energy down to 100 keV. The lower energy will allow for increased antiproton trapping efficiency in the experiments by up to two orders of magnitude, which was typically less than 1 % with the beam from AD. ELENA allows up to four bunches of equal intensity and emittance to be produced, which can be distributed to four different experiments at the same time. In the first phase of the project [1], the commissioning of the ring and a short transfer line was done successfully using a local ion source providing 100 keV H^- ions, as well as antiprotons coming from AD. At the end of 2018, just before the start of Long Shutdown 2 (LS2), decelerated beams with characteristics close to the design values were delivered to the first connected experiment (GBAR). Based on these results, the decision was taken to dismantle the old magnetic transfer lines from AD and to connect all the experiments to ELENA with new electro-static lines. Despite the unavailability of antiprotons during the LS2 (2019-2020), the ELENA ring could still be operated with beam from the local ion source, allowing the commissioning of the new transfer lines as well as the optimization of beam performance, including e-cooling.

BEAM COMMISSIONING OVERVIEW

The beam commissioning started mid-November 2016 with the injection into the ELENA ring of a 100 keV H^- ion beam coming from the local source through an electrostatic line. A few days later, beam was circulating for a few hundred turns. Due to the breakdown of the ion source isolation transformer, beam commissioning was stopped and resumed

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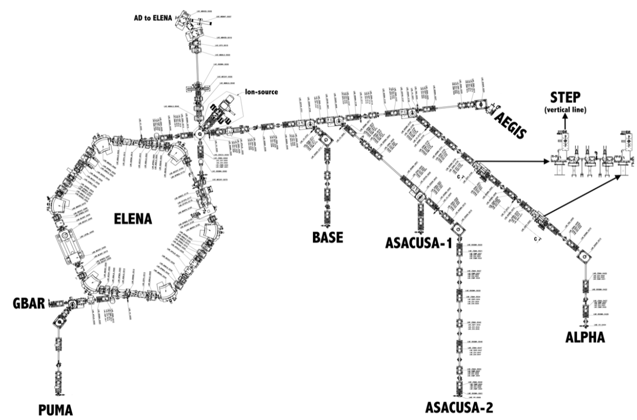

Figure 1: Layout of the ELENA ring and transfer lines.

only in March 2017 with the source operated at 85 keV to minimize the risk of further breakdowns. ELENA commissioning with H^- was inefficient due to erratic injections, later traced back to strong fluctuations of the beam generated by the source. Thus, starting in June 2017, ELENA was also commissioned with antiprotons using typically three eight hours periods per week of AD beam time. The first antiprotons circulated in ELENA in August 2017. At the end of 2017, bunch to bucket transfer was operational and antiproton beams were decelerated almost to 100 keV.

Beam operation stopped again for a few months to complete the ELENA ring with the installation of its electron cooler. ELENA commissioning resumed end of April 2018. 2018 was an unfortunate year for AD with only 65% machine availability, affecting the physics run but also ELENA beam commissioning. Commissioning with the H^- ion beam was also perturbed by several breakdowns of the source which was not available from September onwards. End of May 2018, first antiproton beam was observed at 100 keV after tune and orbit corrections along the cycle, without beam cooling. Setting-up and conditioning of the e-cooler started end of May, and clear signs of longitudinal and transverse cooling at both energies were measured in July. Antiproton beam was observed at the entrance of the GBAR decelerator experiment at the end of July 2018. The remainder of the run was used to further commission many sub-systems (RF, beam instrumentation, electron cooler) and optimize the beam parameters to allow for a decision to be taken on the connection of all users to ELENA. Despite the little beam time available and issues with the ion source, by the end of 2018 it was possible to achieve beam parameters before extraction reasonably close to the design values [2].

During LS2, beam commissioning was interrupted for the time required to install the new electrostatic transfer lines and to consolidate the local ion source. Achieving reliable

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operation with the H^- ion source during the period when antiprotons were not available was crucial for the commissioning of the new transfer lines and the preparation of the ELENA ring after the LS2. The main purpose of beam activities beginning of 2021 was to test the newly installed electrostatic transfer lines. Very quickly, beam was steered to the last profile monitor in front of the hand-over points of all the experiments, first to ALPHA, the longest line, followed by BASE, ASACUSA1 and 2, and finally AEGIS. Beam properties have been extensively measured using quadrupole scans. No major issues have been encountered and the theoretical optics along the transfer lines have been found sufficiently close to the design such that no re-matching was required [3]. Furthermore, this period without antiprotons could be used to extensively test the automatic beam distribution system, sending up to four available bunches at extraction to four different experiments with the help of fast deflectors rising during the gap between consecutive bunches. In addition to the transfer line commissioning, many tests to better understand the ELENA ring, including e-cooling, could be carried out with H^- ions, allowing the preparation of the antiproton deceleration cycle. Typical examples include investigations on magnetic hysteresis and remanence effects, optimization of the working point and setting-up of the Low Level RF (LLRF) system with deceleration on different harmonic numbers. The possibility of using H^- for the setup and optimization of e-cooling in ELENA allowed to the time needed to re-commission ELENA with antiprotons to be minimized.

The first proton beam for antiproton production after LS2 was delivered by the PS at the end of June 2021. In the following weeks, the AD operation was restored. The first antiproton beam was delivered to ELENA mid August 2021 and 100 keV pbar beams were delivered to the experiments for physics on August 23^{rd}, as scheduled. During this short period only minor adjustment of the machine cycle prepared in advance with the H^- cycle were necessary to decelerate and cool antiprotons, demonstrating that the local source can be used for optics and cooling studies in ELENA without the need of pbars.

OPERATION OVERVIEW

The antiproton deceleration cycle is typically 13 s long, as shown in Fig.2, much shorter than the AD cycle which is more than 110 s long. This allows interleaved operation of the H^- ion cycle for machine studies in between the antiproton cycle for physics production.

A single bunch of antiprotons is injected from AD at 100 MeV/c in an ELENA RF bucket and is immediately decelerated to the intermediate plateau at 35 MeV/c where the beam is de-bunched for the first electron cooling to reduce the beam emittances. At the end of the plateau, the beam is re-bunched on harmonic 4 and decelerated to the extraction energy plateau at 13.7 MeV/c where it is again de-bunched and cooled. The beam is finally re-bunched and extracted towards the experiments in one turn. By design, the re-bunching is done on harmonic 4 and the electron cooler is kept ON for "bunched beam cooling" in order to obtain four short bunches with sufficiently low momentum spread.

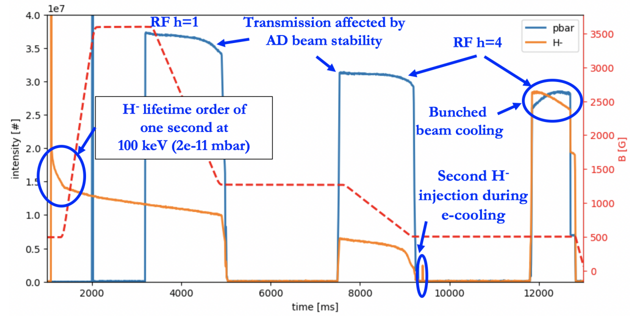

Figure 2: ELENA antiproton deceleration cycle (dash red) with H^- (orange) and pbar (blue) beam intensity.

At the end of the 2021 run, bunch rotation before extraction was also implemented to further reduce the bunch length on request of the GBAR experiment. As the resulting larger energy spread was detrimental for another experiment (ALPHA), bunch rotation has been removed for the beginning of the 2022 physics run. As the conflicting requirements are from experiments connected to different extraction lines, tests are on-going to delay the fast deflector pulse toward LNE50 (line to GBAR and PUMA) and implement the bunch rotation until after the extraction toward LNE00 (serving ALPHA, AEGIS, BASE, ASACUSA1/2 and STEP).

After LS2, all experiments previously using antiprotons from AD were connected to ELENA and two new experiments (STEP and PUMA) are being installed in 2022. As ELENA, by design, can provide up to four bunches to different users in the same cycle, the beam time distribution between the users has changed. Up to LS2, beam from AD was delivered to one user at a time for a period of 8 hours per day with a rotation between the five experiments operating at that time following a predefined planning. In the ELENA physics era, users can request beam any time. The automatic beam distribution system named Beam Request Server (BRS) is handling the requests and ensures a fair distribution in case more than four users are requesting beam for the same cycle, as was the case already at the end of 2021. Following the first experience with ELENA exploitation, the BRS logic was improved to avoid sending multiple bunches to the same users which could happen in case fast deflectors are not operational. The fish bone structure of the ELENA transfer lines combined with the new beam time sharing scheme, however, reinforce the dependencies of various user on each others.

As expected, perturbation of the beam transfer due to stray fields from the equipment belonging to experiments has been observed in 2021. For example, when the AEGIS experiment switched on its magnets, the transfer line to ALPHA needed a substantial re-steering.

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BEAM PERFORMANCE OF THE FIRST PHYSICS RUN

The ELENA beam performance was optimized during LS2 thanks to the reliable operation of the local H^- ion source. Optimization of the working point, measurement of the chromaticity, setting-up of the electron cooling and setting-up of the Low Level Radio Frequency (LLRF) gymnastics [4] were done with a higher repetition rate on a machine cycle mimicking the pbar one, first accelerating the H^- ions to 100 Mev/c before going through the same deceleration and cooling sequence as for antiprotons. The main parameters at extraction obtained at the end of the first physics run are summarized in Table 1.

Table 1: Design and Obtained Beam parameters at the end of 2021

Parameter	Design	Obtained
Q_x/Q_y	≈ 2.3/ ≈ 1.3	2.37/2.385
Cycle duration [s]	20	13
Injected intensity [pbars]	3e7	≈3.2e7
efficiency [%]	60	80
Extracted bunches [#]	4	4
Bunch population [pbars]	4.5e6	>6e6
$\Delta p/p_0$	5e-4	4.5e-4
bunch length (rms) [ns]	75	<75

The achieved transmission in ELENA was of the order of 80%, higher than the design value of 60% and the one achieved in 2018 of 50%. The bunch length at extraction is close to the design value, and can be further reduced if requested using the bunch rotation, at the expenses of energy spread. Transverse emittances measured in the transfer lines based on multi-profile acquisitions using partially intercepting micro-wire monitors installed in the lines were found a factor two higher than design values, Figure3. Reduction of the transverse emittance in relation with the performance of the e-cooler on ejection plateau is still under studies.

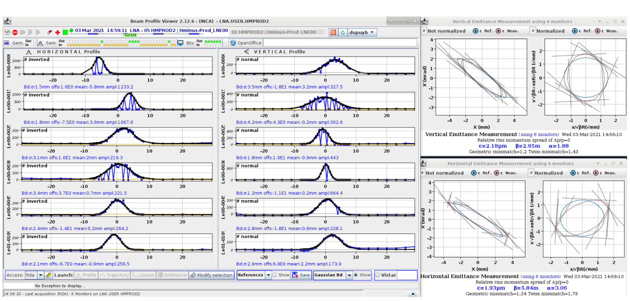

Figure 3: Transverse phase space reconstruction using measured beam sizes from subsequent profile monitors along a straight transfer line.

The bunch intensity in the ELENA ring is estimated by the LLRF system which works only when the beam is bunched and does not take into account the longitudinal distribution variations and therefore has a lower accuracy than the Beam Current Transformer (BCT) installed in the AD to ELENA transfer line. The extracted beam intensity is measured with a wide-band, low-noise, magnetic longitudinal pick-up installed in each transfer line. Both devices are presenting systematic calibration and measurement issues which are being investigated, giving an over-estimation of the bunch intensities. The typical distribution of single bunch intensities over 7 days of operation is shown in Fig.4. The discrepancy between the two lines, GBAR on one side and AEGIS, BASE,ASACUSA1/2 and ALPHA on the other side, are mainly to the systematic insertion of the semi-intercepting profile monitor in front of the intensity monitor in LNE50 (GBAR).

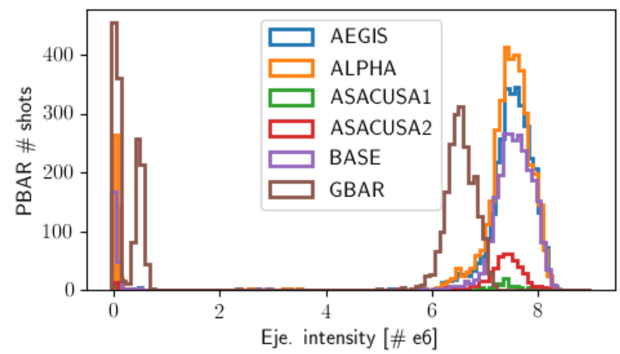

Figure 4: Typical distribution of extracted bunch intensity over a week of operation.

SUMMARY AND OUTLOOK

The ELENA beam commissioning started at the end of 2016 and was interleaved with operation and installation periods until successfully completed in August 2021 with the start of the first physics run with all experiments taking beam from ELENA. During and after LS2, ELENA commissioning profited from the possibility to inject H^- ions from a local source during periods when antiprotons were not available or in between the antiproton cycle for machine studies. During the CERN Long Shutdown 2, the newly installed electrostatic transfer lines from ELENA to the experiments could be commissioned to a large extend with the H^- ion beam and the deceleration cycle was optimized, allowing to start the first physics of ELENA on time with beam parameters close to design values, with the exception of the transverse emittances, where more studies are planned for the next run to possibly reduce them at extraction.

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