ELENA (Extra Low ENergy Antiproton): from commissioning to operation

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On behalf of the operation and commissioning teams with special thanks to D. Gamba, C. Carli and Y. Dutheil
Outlines

- Introduction
- Beam commissioning timeline
- Operation overview
- Beam performances of the first physics run

The CERN accelerator complex
Antiprotons are produced by the 26 GeV proton beam from CERN PS impacting an irridium target.

3.5 \times 10^7 antiprotons at 3.5 GeV/c are captured in AD (Antiproton Decelerator).

Antiproton deceleration to 100 MeV/c in AD.

5 experiments connected to AD up to end of 2018.

ELENA project approved in 2011 to increase the capture efficiency of the traps operated by experiments.

- further deceleration from 5.3 MeV down to 100 keV kinetic energy.
- Small 30.4 m circumference synchrotron connected after AD to decelerate antiprotons from 5.3 MeV to 100 keV
- Magnetic elements in the ring and electrostatic ones in the transfer lines:
  - 125 m of beam lines to deliver beam to 8 different users
- Local 100 keV H\(^{-}\) ion source:
  - Instrumental for commissioning of the transfer lines
- Electron cooling to preserve low transverse and longitudinal emittances during deceleration
- Available intensity distributed into 4 bunches sent to up to 4 experiments
Commissioning timeline:

- **2016**: 
  - Mid November: First injection of H⁻

- **2017**: 
  - June: First pbars injection
  - August: Pbars circulating

- **2018**: 
  - Mid November: First injection of H⁻
  - 22/05/2018: First pbars at 100 keV
  - 20/07/2018: 1st Pbar beam observed at entrance of Gbar

- **2019**: 
  - CERN Long Shutdown 2: No antiproton
  - Installation of new transfer lines

- **2020**: 
  - Decision to connect all users to ELENA
  - Beam commissioning of transfer lines

- **2021**: 
  - 28th August 2021: Start of first physics run

ELENA planning adjusted to general CERN planning
A closer look at 2018 beam commissioning

- Commissioning plan with alternance of H- and pbars:
  - 3 pbar shift/week planned till end of July
  - Setting-up of accelerating/decelerating H- cycle

- Progress with ELENA despite issues with beam(s) availability:
  - 65% machine availability for AD affecting physics as well as ELENA commissioning with antiprotons (pbars)
  - H- operation compromised due to several breakdowns of the source High Voltage isolation transformer

- ELENA start-up end of April – equipped with electron cooler
  - 22/05: first beam observed at 100 keV after tune corrections throughout the cycle
  - 2/7: first signs of effect of electron cooling, first in longitudinal and transverse planes a couple of weeks later
  - 20/7: first antiprotons received by the first user of ELENA

- Reasonable deceleration efficiency (~45%), beam survival at 100 keV and transfer to GBAR obtained the last week of the run:
  => Decision confirmed to connect all users to ELENA
During LS2: Installation of new extraction lines

- Installation of new beam lines to transport and distribute bunches to every experimental area:
  - 239 electrostatic elements, almost 500 power converters
  - Fast deflector proved capable of deflecting single bunch with rise & fall time < 1us
  - More than 40 beam profile monitors:
    - Partially interceptive micro-wire grids for measurement of the beam size and position
    - The comprehensive coverage of the lines was critical for commissioning
- Complex timing system to distribute available bunches to up to four experiments in the same cycle

Fast deflector plus static deflector to channel a single bunch towards a different line

Example of a horizontal profile taken just after extraction
2020-2021: Extraction lines beam commissioning

- Characterization of beam profile monitors:
  - Found several wires in several monitors not working, but overall quality sufficient for commissioning
- Modelling and commissioning
  - Extensive modelling of the optical effects of the electrostatic devices during the design using tracking tools
  - Systematic optical characterisation of the beam delivered to every line was done during commissioning
  - No rematching as measured optics found close to design

Comparison at the end of the longest line of a tracking-based model from 2015 and a measurement taken in 2021 agree within 20% without corrections
Operation overview: pbars cycle

- Operational deceleration cycle is 13 s long:
  - Injection pbars from AD at 100 MeV/c
  - Deceleration to 35 MeV/c on RF h=1,
  - Electron cooling of debunched beam at 35 MeV/c
  - Re-bunching and deceleration to 13.7 MeV/c on h=4
  - Electron cooling of debunched beam at 13.7 MeV/c
  - Re-bunching on h=4 with e-cooling on

Cycle optimized using mimic cycle with H⁻ ion beam, including the e-cooling setting-up in 2020-2021
Operation overview: operation mode

- ELENA cycle short compared to AD cycle (~2min)
  - H- cycles possible between antiproton cycle

- New mode of operation with respect to pre-LS2 time:
  - Four bunches per cycle sent to up to 4 users

- The extra low energy of the beam makes it very sensitive to stray magnetic fields:
  - Stray field generated by the AEGIS experiment caused large distortions of the trajectory in ALPHA

1 G.m of transverse integrated magnetic field induces a deviation of around 2 mrad
Beam performance: delivered pbars

- ELENA deceleration efficiency and delivered bunch intensities well above design values (despite lower intensity from AD than 2018):
  - Uncertainty (of 10-15%) on calibration/signal treatment of instruments (measurement with optimistic calibration)
  - Profile monitors are semi-interceptive device (about 10 % beam loss per monitor)

![Deceleration efficiency and ejected intensity histograms](image)

Excellent reliability! Most of what is injected is always decelerated!

Due to SEM in the beam upstream the measurement
Beam performance: extracted antiproton parameters

- Energy spread and bunch length within or better than design
  - Bunch length could be further reduced with bunch rotation at expense of energy spread
- Typical emittances of 2 \( \mu \text{m rms} \) are about factor 2 larger than design (factor \( \sim 2 \) better than 2018 estimate!)
  - Working on adjusting the length of bunched beam cooling before extraction in ELENA to get smaller emittance
  - We observed clear emittance-intensity dependance to be investigated

=> Overall reached close to nominal beam characteristics
# Beam parameters summary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>design</th>
<th>Achieved in 2021</th>
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<tbody>
<tr>
<td>$Q_x/Q_y$</td>
<td>~2.3/~1.3</td>
<td>2.37/1.85</td>
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<tr>
<td>Cycle duration [s]</td>
<td>20</td>
<td>13</td>
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<tr>
<td>Injected intensity [pbars]</td>
<td>3e7</td>
<td>&gt;3.2e7</td>
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<tr>
<td>Deceleration efficiency [%]</td>
<td>60</td>
<td>85</td>
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<tr>
<td>Extracted bunches</td>
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<td>4</td>
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<tr>
<td>Bunch population [pbars]</td>
<td>4.5e6</td>
<td>&gt;6e6</td>
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<tr>
<td>$Δp/p_0$</td>
<td>5e-4</td>
<td>4.5e-4</td>
</tr>
<tr>
<td>Bunch length (rms) [ns]</td>
<td>75</td>
<td>&lt;75</td>
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<tr>
<td>Transverse emittances x/y [$\mu$m]</td>
<td>1.2/0.75</td>
<td>~2/~2</td>
</tr>
</tbody>
</table>
ELENA and its new transfer lines have been successfully commissioned during summer 2021
- From autumn 2021 new era for antimatter physics with 100 keV antiproton beams delivered to all experiments

Beam characteristics very close to design values:
- Easy to get shorter bunches than design, but transverse emittances still a factor 2 bigger than nominal
- Higher intensities than design in ELENA

Extremely useful first run in 2021 for both operation and users:
- Experience gained on operation with 4 bunches available on demand at any time to any experiments
- Experience during the commissioning strongly validated the early choice of using electrostatic devices only for the transfer lines
- Pretty good orbit stability of beam delivery in transfer lines:
  • Still strong impact of experiment magnetic fields when switching on/off
- H⁻ source operation very useful for ELENA and transfer line set-up, but also for experiment setup/optimization (higher repetition rate)
Thank you