Extra Low ENergy Antiproton ring ELENA: From the Conception to the Implementation Phase

IPAC 2014

17th June 2014

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- Introduction
  - Antiproton Decelerator
  - Efficiency for experiments at present without ELENA and with ELENA
- ELENA Overview and Layout
- Selected Features and Issues
- Beam Parameter
- Conclusions, Status and Outlook
Introduction: Antiproton Decelerator AD – a unique facility providing 5.3 MeV antiprotons

1. Antiproton Production
2. Injection at 3.5 GeV/c
3. Deceleration and Cooling (3.5 - 0.1 GeV/c)
4. Extraction (3 \times 10^7 in <300 ns)

- \sim 1.5 \times 10^{13} protons (26 GeV) on target
- \sim 3.5 \times 10^7 antiprotons captured in AD
  - Acceptances 200 \mu m and \pm 30 \times 10^{-3}
- Deceleration to the lowest energy 5.3 MeV reachable “safely” (limited by mag. Fields?)
- Stochastic and electron cooling at four different energies
- \sim 3 \times 10^7 antiprotons extracted per cycle
  - Dense core containing \sim 70% within <1 \mu m, often tails up to 10 \mu m
  - Longitudinal before bunch rotation 95% within 10^{-4} and 400 ns
- Cycle length about 100 s

Sketch of the present AD – circumference 182 m
- In addition experiment AEGIS installed
- Experiment BASE being installed
- Gbar approved to receive beam from ELENA
**Introduction:** Efficiency for capturing antiprotons in traps without and with ELENA

**Present situation with AD alone:**
- Most experiments slow antiprotons down by “degrader”
  - => very inefficient – most (>99%) antiprotons lost
  - (one experiment uses an RFQ for deceleration with higher efficiency)

**Future situation with AD and ELENA decelerating to 100 keV:**
- thinner “degrader” and increased trapping efficiency
  - (some experiments use other means to decelerate the beam)
- Intensity shared by four exp’s allows longer periods with beam
Deceleration of antiprotons from 5.3 MeV to 100 keV to improve efficiency of experiments

- Circumference 30.4 m (1/6 the size of the AD)
  - Fits in available space in AD hall and allows installing all equipment without particular efforts
  - Lowest average field (beam rigidity over average radius) $Bp/R = 94 \text{ G}$ (smaller than for AD 115 G)

Wideband RF cavity

Scanner to measure emittances (destructive)

Electron Cooler and compensation solenoids

Extraction towards existing experiments (with fast electrostatic deflector)

Line from H⁻ and proton source for commissioning

Injection with magnetic septum (≈300 mrad) and kicker (84 mrad)

High sensitivity magnetic pick-up for Schottky diagnostic (intensity) and LLRF

Extraction towards new exp. zone

Quadruopoles

Extra Low ENergy Antiproton ring ELENA
ELENA Overview and Layout

- ELENA in AD hall with existing (AD experiments) and new experimental area
  - Cost effective with short transfer line from AD and no relocation of existing experiments
  - New (small) building to house equipment now at location, where ELENA will be installed
ELENA Overview and Layout

- **Transfer line (magnetic) from AD**
- **External source for commissioning**
- **Electro-static line towards existing experimental area**
- **Extraction towards new experimental area**
Selected Features and Issues

- **Energy Range**
  - Machine operated at an unusually low energy for a synchrotron (down to 100 keV!)
  - Many points below a consequence of the low energy

- **Lattice**
  - **Constraints**
    - Long straight section with small dispersion for electron cooling
    - Geometry in AD hall (location of injection and two extractions)
  - Many geometries and quadrupole locations investigated
  - Hexagonal shape and optics with periodicity two
  - Tunes: $Q_x \approx 2.3$, $Q_y \approx 1.3$ (e.g. $Q_x = 2.23$, $Q_y = 1.23$)
  - Acceptances: about 75 μm (depends on working point)
Selected Features and Issues

- Electron cooling
  - Applied at an intermediate plateau at 35 MeV/c and the final energy 100 keV
  - To reduce losses during deceleration after 1st cooling plateau and generate bright bunches for experiments
  - Electron beam expansion by factor 10 to reduce its temperature
  - Bunched beam cooling at 100 keV to reduce momentum spread of short bunches requested by experiments
  - Perturbations of magnetic system on circulating beam under study

- Expected main performance limitation: Intra Beam Scattering IBS
  - Determines beam parameters with cooling (equilibrium between the two processes)

### Table: Beam Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum (MeV/c)</td>
<td>35</td>
<td>13.7</td>
</tr>
<tr>
<td>Relativistic $\beta$</td>
<td>0.037</td>
<td>0.015</td>
</tr>
<tr>
<td>Electron beam energy (eV)</td>
<td>355</td>
<td>55</td>
</tr>
<tr>
<td>Electron current (mA)</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>Electron beam density ($10^{12} \text{ m}^{-3}$)</td>
<td>2.8</td>
<td>1.4</td>
</tr>
<tr>
<td>Field at gun (Gauss)</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Field at cooling section (Gauss)</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Expansion factor</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Cathode radius (mm)</td>
<td>7.9</td>
<td></td>
</tr>
<tr>
<td>Electron beam radius (mm)</td>
<td>25</td>
<td></td>
</tr>
</tbody>
</table>
Selected Features and Issues

- Rest gas interactions and vacuum system
  - 3 $10^{-12}$ Torr nominal pressure - fully baked machine with NEGs wherever possible
  - Interactions of beam with rest gas to be evaluated with care (see TUPRI028, MOPRO036) and not a dominant performance limitation

- Beam diagnostics with very low intensities and energy
  - E.g.: Beam currents down to well below 1 μA far beyond reach standard slow BCTs
    - Intensity of coasting beam measured with Schottky diagnostics

- Magnets with very low fields (see TUPRO106)
  - “Thinning” (mixing of stainless steel and magnetic laminations) for bending magnets and possibly for other small magnets, steerers without magnetic yoke
  - Careful magnetic measurement with pre-series magnets

- Electrostatic transfer lines to experiments (see MOPRI101)
  - Cost effective at very low energies, easier for shielding against magnetic stray fields

- RF system with modest voltages, but very large dynamic range

- Direct space charge defocusing a possible limitation despite very low intensity (and 300 ns long bunches)
  - Split available intensity to several (baseline four) bunches to mitigate

- Commissioning with external H⁻ and proton source (and electrostatic acceleration to 100 keV)
  - Higher repetition rate but start commissioning at the difficult low energy part of the cycle
Expected Magnetic Cycle

- Ramps
  - Blow-up due to IBS must remain acceptable (fast ramp)
  - Perturbation of optics due to Eddy currents must remain acceptable (slow ramp)
- Plateaus with electron cooling
  - Duration taken from simulations of cooling
- ELENA cycle expected to last about 25 s, but repetition rate slower (beam from AD about every 100 s)
ELENA Beam Parameters
Present best guess combining different Sources

<table>
<thead>
<tr>
<th>Step in cycle</th>
<th>$\varepsilon_L$ (meVs)</th>
<th>$\sigma_p/p$ ($10^{-3}$)</th>
<th>$\sigma_E$ (keV)</th>
<th>$\sigma_T$ (ns)</th>
<th>$\varepsilon_{H,rms}$ ($\mu$m)</th>
<th>$\varepsilon_{V,rms}$ ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection$^+,$a)</td>
<td>3.5</td>
<td>0.25</td>
<td>2.8</td>
<td>98</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Start 1$^{st}$ ramp$^+,$b)</td>
<td>3.5</td>
<td>0.49</td>
<td>5</td>
<td>53</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>End 1$^{st}$ rampc)</td>
<td>3.5</td>
<td>1.4</td>
<td>1.8</td>
<td>150</td>
<td>1.8</td>
<td>1.1</td>
</tr>
<tr>
<td>Start plateau 35 MeV/c$^d$</td>
<td>5.2</td>
<td>0.46</td>
<td>0.6</td>
<td>coasting</td>
<td>1.8</td>
<td>1.1</td>
</tr>
<tr>
<td>End plateau 35 MeV/c$^e$</td>
<td>1.7</td>
<td>0.15</td>
<td>0.20</td>
<td>coasting</td>
<td>0.45</td>
<td>0.42</td>
</tr>
<tr>
<td>Start 2$^{nd}$ ramp$^d$</td>
<td>2.5</td>
<td>0.84</td>
<td>1.1</td>
<td>180</td>
<td>0.45</td>
<td>0.42</td>
</tr>
<tr>
<td>End 2$^{nd}$ rampc)</td>
<td>2.4</td>
<td>2.1</td>
<td>0.42</td>
<td>455</td>
<td>2.2</td>
<td>2.5</td>
</tr>
<tr>
<td>Start plateau 100 keV$^d$</td>
<td>3.2</td>
<td>0.46</td>
<td>.092</td>
<td>coasting</td>
<td>2.2</td>
<td>2.5</td>
</tr>
<tr>
<td>Cooled coasting 100 keV$^e$</td>
<td>1.1</td>
<td>0.25</td>
<td>.050</td>
<td>coasting</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Cooled bunched 100 keV$^f$</td>
<td>4 x 0.12</td>
<td>0.60</td>
<td>.120</td>
<td>75</td>
<td>1.2</td>
<td>0.75</td>
</tr>
</tbody>
</table>

$\varepsilon_{rms} = \sigma_\beta^2/\beta_T$ with $\sigma_\beta$ the rms betatron beam size and $\beta_T$ the Twiss betatron function

$+$) difficult to determine due to (i) dense core and long tails, (ii) variations with time

a) Typical values measured with AD – some reduction of long Emittance with bunched beam cooling
b) Increase of voltage from 16 V at transfer to 100 V on ramp
c) Simulations of IBS on ramp
d) Debunching/bunching with 50% blow-up (bunched with LHC def. $\varepsilon_L = 4\pi \sigma_E \sigma_T$, coasting $\varepsilon_L = 4 (2/\pi)^{1/2} \sigma_E T_{rev}$)

e) From ELENA technical meetings with presentations by G.Tranquille and P. Beloshitsky
New building adjacent to the AD hall

- New Building 393 completed in February ahead of schedule
  - Will house electronics (PFL) for AD and ELENA injection kicker
  - Storage space .. for experiments
- Infrastructure installation ongoing
Conclusions, Status and Outlook

- ELENA will be a small ring to further decelerate antiprotons from the AD
  - Electron cooling to reduce beam emittances and energy spread
  - Improvement for existing experiments and new types of experiments (e.g. gravitation)

- ELENA Machine to be built well known now
  - General Project Review last autumn
    - Concept of decelerator with electron cooling endorsed, no showstoppers identified
    - Many proposals for further studies and improvements
  - Technical Design Report TDR describing machine published

- Status and outlook
  - Moving from the conception to implementation phase
  - First contracts for equipment (magnets …) being signed
  - ELENA installation in 2nd half of 2015 and beginning 2016 followed by commissioning
  - Transfer line installation followed by commissioning during 1st half 2017
  - First physics run with 100 keV antiprotons from ELENA planned for 2nd half of 2017
Thanks for your attention!
## Basic ELENA Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic shape</td>
<td>Hexagonal</td>
<td>two long straights for injection and cooling</td>
</tr>
<tr>
<td>Periodicity</td>
<td>Two periods</td>
<td>neglecting the electron cooler</td>
</tr>
<tr>
<td>Circumference</td>
<td>30.4055 m</td>
<td>1/6 the AD</td>
</tr>
<tr>
<td>Max. beta functions $\beta_{H,\text{max}}/\beta_{V,\text{max}}$</td>
<td>$\approx 12 \text{ m}/\approx 6 \text{ m}$</td>
<td></td>
</tr>
<tr>
<td>Working point $Q_H/Q_V$</td>
<td>$\approx 2.3/\approx 1.3$</td>
<td>some tuning range to choose working point</td>
</tr>
<tr>
<td>Relativistic gamma at transition</td>
<td>$\approx 2$</td>
<td></td>
</tr>
<tr>
<td>Energy range</td>
<td>5.3 MeV – 100 keV</td>
<td></td>
</tr>
<tr>
<td>Momentum range</td>
<td>100 MeV/c – 13.7 MeV/c</td>
<td></td>
</tr>
<tr>
<td>Transverse acceptances</td>
<td>75 μm</td>
<td></td>
</tr>
<tr>
<td>Cycle length</td>
<td>&gt;25 s</td>
<td>deceleration and cooling</td>
</tr>
<tr>
<td>Repetition rate for pbar operation</td>
<td>$\approx 100$ s</td>
<td>limited by AD operation</td>
</tr>
<tr>
<td>Injected intensity</td>
<td>$3 \times 10^7$ antiprotons</td>
<td></td>
</tr>
<tr>
<td>Efficiency</td>
<td>60%</td>
<td>conservative guess</td>
</tr>
<tr>
<td>Parameter at ejection</td>
<td></td>
<td>with bunched beam cooling</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>4</td>
<td>baseline with four bunches</td>
</tr>
<tr>
<td>Bunch population</td>
<td>$0.45 \times 10^7$ pbars</td>
<td></td>
</tr>
<tr>
<td>Rel. mom. spread</td>
<td>$0.5 \times 10^{-3}$</td>
<td>Rms value</td>
</tr>
<tr>
<td>Bunch length</td>
<td>75 ns</td>
<td>Rms value</td>
</tr>
<tr>
<td>Hor. emittance</td>
<td>1.2 μm</td>
<td>Rms, physical</td>
</tr>
<tr>
<td>Vert. emittance</td>
<td>0.75 μm</td>
<td>Rms, physical</td>
</tr>
</tbody>
</table>