Name: Joel Fajans
Authors: ELENA Collaboration
J. Fajans, G. Gabrielse,
F. Robicheaux, A. Sessler,
J. Wurtele,
Principle U.S. Investigators
Institutions: Auburn, U.C. Berkeley,
Harvard, LBNL,
Principle U.S. Institutions
Working Group: Discovery Science

# Discovery Science with Low Energy Antiproton Sources: The ELENA Upgrade

**Overview**: The Antiproton Decelerator (AD) at CERN has been the site of much exciting research in recent years. In this white paper, we discuss a significant upgrade to the AD, the Extra Low ENergy Antiprotons (ELENA), which will dramatically improve the opportunities for fundamental science.

CERN has long had a tradition of pursuing fundamental physics on a variety of energy scales. Much work at CERN has been with antiprotons. In addition to the high-energy SPS beam, CERN has developed the world's only sources of low-energy antiprotons: first, the Low Energy Antiproton Ring (LEAR) and now the Antiproton Decelerator (AD). LEAR and the AD led to many widely recognized scientific advances including:

- The trapping, cooling and accumulation of extremely cold antiprotons. Energies ten orders of magnitude lower than in LEAR or in the AD have been achieved.
- The most precise comparisons of the charge-to-mass ratios for antiprotons and protons, resulting in the most stringent tests of CPT invariance with baryons.
- Some of the most precise studies of CP violation.
- The observation and laser spectroscopy of metastable antiprotonic Helium atoms.
- The first observations of fast and slow antihydrogen atoms.

The scientific demand for low-energy antiprotons at the AD continues to grow. By now there are four experiments running at the AD, a fifth one is approved, and several additional proposals are under consideration. CERN's unique Antiproton Decelerator can no longer provide the number of antiprotons needed. As antihydrogen studies evolve into antihydrogen spectroscopy and gravitational measurements, the shortage will become even more acute. The ELENA upgrade to the AD will increase and optimize the number of cold antiprotons that can be trapped and accumulated. This will dramatically increase the rate of progress and enable much higher measurement precision measurements. This White Paper presents a summary of the construction of the ELENA upgrade to the AD. This upgrade involves the addition of a small storage ring and electrostatic beam lines whose design parameters have been carefully studied and agreed upon over several years. The technical risk is low, the cost is quite modest, and the scientific payoff is high.

The ELENA upgrade will (1) enable higher quality low-energy antihydrogen physics at CERN over the next decade, and (2) serve as an accelerator test platform for use in developing the methods needed for future generations of low-energy facilities. In a decade, a new generation of low-energy antiproton sources may start with FLAIR [GSI], a planned dedicated low-energy antiproton source, at JPARC [Japan] or, perhaps, as a future component of Project X [FNAL]. ELENA will provide vital experience and methods for the design and operation of such future facilities. For the next decade, however, there is no alternative low-energy antiproton source for physics. This is a unique opportunity.

**Scientific Case:** There is a huge interest in antihydrogen and low-energy antiproton physics. The scientific justification for this physics has been regularly reviewed and approved, for instance, by CERN's SPSC and management. The scientific case was made most recently at the Workshop on "New Opportunities in the Physics Landscape at CERN." The key points from the summary report of this workshop on the physics motivation for ELENA include:

- Many predictions of the established Standard–Model and General–Relativity remain experimentally unverified in the antimatter regime.
- Specific Standard-Model-Extensions govern a large set of the emerging sectors relevant for low-energy antimatter experiments. Searches for new interactions can be carried out by studying discrete symmetries such as CPT. Spectroscopic investigations of antihydrogen could result in the most stringent CPT tests ever.
- Antihydrogen is particularly well suited to determine the gravitational force on antimatter and examine the weak equivalence principle.
- Pioneering experiments have led to precise values and accurate tests and contributed to the NIST adjustments of fundamental constants.

The current User Community of the AD, which would be the first to benefit from ELENA, includes strong US participation. ATRAP has a US PI, and ALPHA has significant US participation.

- AD-2(ATRAP) has demonstrated the production of antihydrogen in a Penning-Ioffe trap, and makes continued progress towards trapping using 1.2 K plasmas. A new Ioffe trap is under construction. A Lyman-α source is starting to produce the laser light needed for further cooling and for the precise spectroscopy.

- AD-3(ASACUSA) performs precision spectroscopy of antiprotonic Helium atoms, testing CPT invariance and contributing to the CODATA fundamental physics constants. Measurements of the ground-state hyperfine splitting of antihydrogen are foreseen with a "cusp trap" or a super-conducting Paul trap followed by a Rabi-type atomic beam line.

- AD-4(ACE) has the ambitious goal of contributing to cancer therapy. The availability of ultra-low-energy antiprotons would provide the possibility to perform nano-dosimetry and biological studies on the cellular level.

- AD-5 (ALPHA) has performed the first ever searches for trapped antihydrogen in a Penning-Ioffe trap. The long term goal of this work is a spectroscopic comparison of hydrogen and antihydrogen. Their apparatus will be modified and expanded to perform increasingly precise microwave and laser spectroscopy of antihydrogen.

• In addition to the currently operating experiments, several more experiments at the AD have been proposed or approved.

**Project Description:** ELENA is envisioned to be a small circular decelerator which slows the AD antiprotons to 100 keV, cools them via integrated electron cooling, and then delivers the antiprotons to the various experiments via electrostatic beam lines. ELENA is, to date, the best upgrade option for the AD. The ELENA Proposal describes its key features, which include:

- The ELENA input acceptance matches AD emittance, as is needed for routine operation of a general facility.
- Electron-cooling within ELENA will produce a 100keV antiproton beam of sufficiently high quality that it can be distributed to experiments with electrostatic beam lines.
- ELENA can be located within the existing AD hall without requiring the expensive relocation of experimental areas.

The ELENA Proposal provides an estimate of how much the antiproton trapping efficiency can be expected to improve after the upgrade. The AD and ELENA will deliver well-cooled pulses of $2.5\times10^7$ antiprotons to the experiments through electrostatic beam lines. About half of these antiprotons will survive passage through the extremely thin vacuum windows located at each of the experiments which separate the AD/ELENA vacuum from the much higher vacuum needed within the experiments. Thus, it should be possible to trap approximately $10^7$ antiprotons from one pulse, or about 30% of the $3\times10^7$ AD antiprotons. This is ~100 greater that the number of antiprotons current trapped using degraders, and ~10 greater than the number trapped with an RFQD. The projected ability to steer the beam on successive shots between the various experiments will further enhance the effective beam usage.

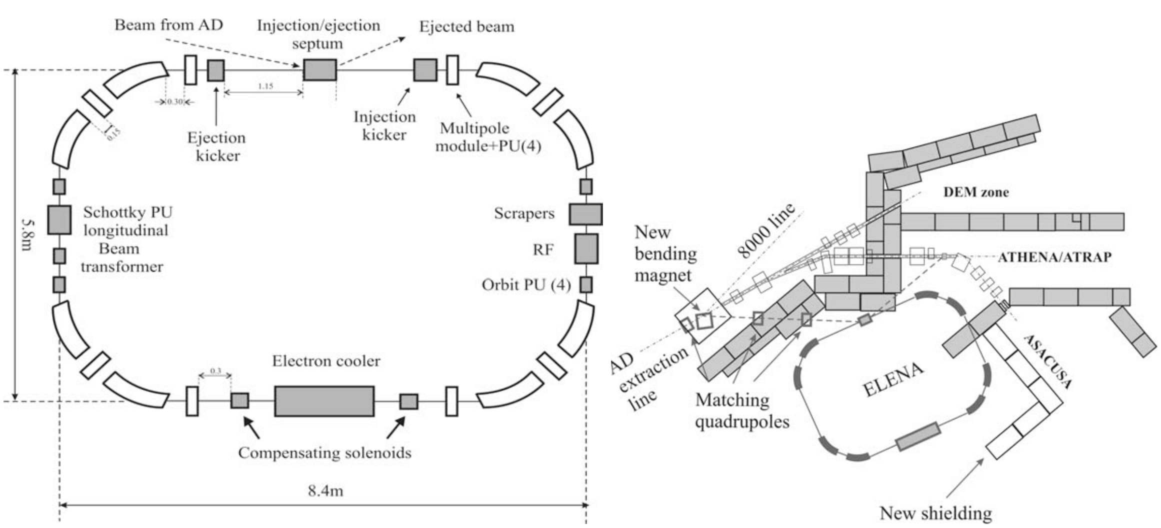


**Figure 1.** The layout of ELENA (l) and ELENA in the AD Experimental Hall (r). From [2].

**Accelerator physics and training at ELENA:** ELENA provides the opportunity for interesting and important accelerator physics studies on the challenges involved in obtaining a very low phase space volume as the beam energy is reduced in a compact ring. These challenges include:

- Intensity limit to low-energy bunch compression: The space-charge limit in "normal" synchrotrons is well understood. However, in ELENA the deceleration reaches energies that are orders of magnitude lower than this. The short (e.g. 1 meter or less) bunches needed to fill traps are generated by rotation of longer bunches in phase space in a very short time (less than a millisecond). Near the end of this process, just prior to ejection, space charge effects are strongest and the size of the resulting transverse tune shifts that can be tolerated set the fundamental intensity limit. ELENA offers the capability and opportunity to investigate these instabilities and limits, along with those from longitudinal instabilities.
- Instrumentation for low energies and intensities: Non-destructive Schottky beam-noise diagnostics must be developed to monitor these unusual particle beams. These diagnostics will be based upon what has been learned at the AD and other storage rings, but must be modified to deal with energies and intensities that are lower by one or two orders of magnitude.
- Vacuum requirements at low-energy: The blow-up and lifetime of low-energy beams, due to multiple (small angle) and single (large angle) scattering of the antiprotons on the residual gas, is estimated to require a vacuum of approximately $10^{-12}$ mb. ELENA offers the opportunity to produce and investigate beams at pressures for which there is limited experience.
- Electron cooling: The very special requirements for electron cooling at and below 40MeV/c (detailed in the ELENA feasibility report) will be tested in ELENA.

**Summary**: Our ability to investigate the potentially revolutionary physics of low energy antiprotons and antihydrogen would be greatly enhanced by the construction of ELENA. The demand for low energy antiprotons at the AD will increase in immediate future, and will be beyond what CERN can supply. Currently, there are no alternative antiproton facilities for the discovery science experiments of our thriving low-energy physics community. Future low energy antiproton sources, like FLAIR, JPARC, and Project X will benefit from the experience gained on ELENA.

References:

[1] ELENA Proposal to the CERN SPS : http://cdsweb.cern.ch/record/1206242/files/SPSC-P-338.pdf

[2] Workshop on "New Opportunities in the Physics Landscape at CERN" http://indico.cern.ch/getFile.py/access?resId=0&materialId=7&confId=51128

[3] Angoletta, M-E, et al., "ELENA, a preliminary cost and feasibility study," CERN-AB-2007-079.