ELENA: AN UPGRADE TO THE ANTI-PROTON DECELERATOR AT CERN

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1. The Scientific Case for the ELENA Upgrade of AD

There is a huge interest in the very compelling scientific case for anti-hydrogen and low-energy anti-proton physics. This case has been regularly reviewed and approved at several occasions. The scientific case was made most recently at the Workshop on “New Opportunities in the Physics Landscape at CERN”\(^1\) in May 2009. The summary report\(^2\) for this workshop is present here as a short list of key points:

1.1. **Physics Motivation**

- Many predictions of the established Standard–Model and General–Relativity remain experimentally unverified in the anti-matter regime.
- Specific Standard-Model-Extensions govern a large set of the emerging effects relevant for low-energy anti-matter experiments.
- Searches for new interactions can be carried out by studying discrete symmetries such as CPT.
- The prospects of performing spectroscopic investigations of anti-hydrogen opens the possibility for CPT tests more stringent than ever done before.
• Anti-hydrogen is particularly well suited to determine the gravitational force on anti-matter 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.

1.2. Existing Experiments

• AD-2 (ATRAP) has demonstrated the production of anti-hydrogen 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 laser light needed for further cooling and for the precise spectroscopy.
• AD-3 (ASACUSA) performs precision spectroscopy of anti-protonic Helium atoms, testing CPT invariance and contributing to the CODATA fundamental physics constants. Measurements of the ground-state hyperfine splitting of anti-hydrogen are foreseen with a “cusp trap” or a super-conducting Paul trap followed by a Rabi-type atomic beam line.
• AD-4 (ACE) follows an ambitious aim of contributing to cancer therapy. The availability of ultra-low-energy anti-protons would provide the possibility to perform nano-dosimetry and biological studies on the cellular level.
• AD-5 (ALPHA) is working to demonstrate trapping of anti-hydrogen atoms in a magnetic multipole trap. The long term goal of this work is a spectroscopic comparison of hydrogen and anti-hydrogen. The apparatus will be modified and expanded to perform increasingly precise microwave and laser spectroscopy of anti-hydrogen.

1.3. New Experiments

• AD-6 (AEGIS) intends to measure the gravitational interaction of anti-hydrogen with a precision of 1 %. The experiment has been approved and the installation of the apparatus will happen during the upcoming years.
• Proposal by the PAX collaboration for: “Measurement of the spin-dependence of the proton – anti-proton interaction at the AD-ring”.³
• Letter of Intent for: “A measurement of the acceleration of anti-hydrogen in the gravity field of the Earth”.⁴
• “Double-strangeness production with anti-protons at the AD-ring”.⁵
• “Anti-protonic atom X-ray studies from selected elements with low Z”.⁶

2. The Technical Case for the ELENA Addition to AD

The figure of merit for the anti-protons available to the AD experimental program is the number of cold anti-protons that can be accumulated within a trap per pulse of anti-protons delivered from the AD. There is now enough experimental experience with slowing down, decelerating, trapping and cooling anti-protons to reliably estimate the very substantial improvement of a factor of 10 to 100, depending upon the experiment the ELENA upgrade to the AD would provide.
2.1. Current Accumulation of Cold Anti-Protons

The methods for accumulating cold anti-protons in traps were developed at CERN by the TRAP collaboration. Anti-protons from LEAR were slowed by passing them through thin metal degraders, captured in a Penning trap formed by the rapid application of kV potentials within a strong magnetic field, and cooled by collisions with cold, trapped electrons till they were in thermal equilibrium with the surrounding liquid He temperature at 4.2 K. These trapped anti-protons, with an average energy of only 0.3 meV, were thus more than $10^{10}$ times lower in energy than on ejection from LEAR.

These same methods are used with the AD anti-protons by ATRAP and ALPHA to produce anti-hydrogen, and AEGIS proposes to do so as well. ASACUSA also uses these methods with a modification to be described. In the early days of the AD, up to $2 \times 10^4$ anti-protons were captured and cooled from an AD pulse of $3 \times 10^7$ anti-protons, i.e. with an efficiency of only $8 \times 10^{-4}$. A pulse of anti-protons is delivered by the AD approximately every 100 seconds. Anti-protons can be added to the trap from successive pulses of AD anti-protons; this accumulation of trapped and cooled anti-protons is often referred to as “stacking”.

Recent improvements made it possible to increase the number of anti-protons accumulated per AD pulse by about a factor of 5 so that now up to $1.3 \times 10^5$ anti-protons are accumulated from an AD pulse and transferred into a 1 Tesla trapping field, giving a total efficiency of $4 \times 10^{-3}$. In 15 minutes, more than 1 million anti-protons can be stacked into a trap for an experiment without the ELENA upgrade. These numbers give the scale of what is now possible for the ATRAP and ALPHA collaborations that rely entirely upon these methods, and what can be expected by the AEGIS collaboration.

The ASACUSA collaboration also uses these methods, but with a radio-frequency quadrupole decelerator (RFQD) and a much thinner (1.2 µm) plastic foil replacing the thin metal degrader. The 12 meters of anti-proton beam path required to install an RFQD and its associated beam line elements, as well as its high construction cost keeps this option from being used by experiments at other locations at the AD.

The RFQD decelerates the 5.3 MeV anti-protons from the AD down to 50 - 120 keV, and the thin plastic foil slows the anti-protons to the required energy (< 10 keV) for trapping. It is important to note that of the $2 \times 10^7$ anti-protons extracted from the AD every minute, the RFQD decelerates 25% ($5 \times 10^6$), whereas most of the anti-protons ($1.5 \times 10^7$) miss the longitudinal acceptance of the RFQD and do not get decelerated or trapped. More anti-protons ($\sim 3.5 \times 10^6$) are lost during the deceleration in the foil or in the first few seconds after closing the trap, so that ultimately around $10^6$ anti-protons are cooled and accumulated per AD pulse.

On average, this corresponds to a net efficiency of $\sim 5 \times 10^{-2}$ ($10^6/2 \times 10^7$). The RFQD thus makes it possible to accumulate $\sim 10 \pm 2$ times more anti-protons in a trap per AD pulse than what is currently being achieved using a degrader with no
RFQD. To some extent these numbers are subject to the day to day performance of the different equipments.

Though the construction of the RFQD was a substantial step forward, for several reasons, based on experiences by the ASACUSA collaboration during the operation of the RFQD over the last decade, this type of decelerator is not an appropriate AD upgrade, since:

(i) The ELENA ring with multi-bunch extraction would provide $\sim 100$ times more anti-protons in a trap per AD cycle, compared to $\sim 10$ more for the current RFQD.

(ii) No cooling of the anti-proton beam is possible during deceleration of the beam in an RFQD. The quality of the slowed 100 keV anti-proton beam is thus determined by the beam quality of the 5.3 MeV input beam. Measurements have shown that the emittance of the ASACUSA RFQD beam at 63 keV is extremely large (around $100 \pi \text{ mm mrad}$); ASACUSA now suffers from high beam losses when using an achromatic spectrometer to transport this beam with a typical diameter of 40-50 mm over a distance of 4 meters. Based on this experience, it would seem extremely difficult to distribute such a beam to other experiments.

(iii) The input acceptance of the RFQD is small - the design value of the ASACUSA RFQD was $10 \pi \text{ mm mrad}$, but experiments have shown that the highest beam quality needed for efficient anti-proton trapping is achieved for only the central $< 1 \pi \text{ mm mrad}$ part, which is much more demanding than the design specifications of the AD. In practice it was difficult to achieve and maintain this optimum performance without frequent and time-consuming tuning of the AD electron cooler and beam transport lines, and so the ASACUSA RFQD beam is strongly perturbed by any small changes in the beam quality of the AD.

(iv) Anti-protons trapped right at the output of the RFQD can be cooled and extracted to other experiments, in principle, but only with a low duty cycle and consequently a much lower effective efficiency so far.

(v) At the AD hall there is no room for a single RFQ decelerator that could be shared by all of the users, and certainly not for an RFQ decelerator for every experiment.

There is a clear consensus among the AD experiments that an RFQD is not the upgrade path for the AD. The ASACUSA collaboration has probed the limits of the AD followed by an RFQD technology in the last decade, such that further large improvements in the number of trapped anti-protons can only be achieved using a cooled anti-proton beam from ELENA.

2.2. ELENA Optimized for Trapped Anti-Protons

ELENA is a small circular decelerator which slows the AD anti-protons to 100 keV, cools them via integrated electron cooling, and delivers the anti-protons to the various experiments via electrostatic beam lines.
ELENA is clearly the best known upgrade option for the AD. Its attractive features include:

(i) The input acceptance of ELENA matches well the AD emittance, as needed for routine operation of a general facility.
(ii) Electron-cooling within ELENA will produce an anti-proton beam quality that makes it possible to distribute pulses of 100 keV anti-protons to the experiments through electrostatic beam lines.
(iii) ELENA can be located within the existing AD hall without requiring the expensive relocation of the experimental areas.

Each of these points are discussed in detail in the ELENA feasibility study. The AD and ELENA will deliver well-cooled pulses of $2.5 \times 10^7$ anti-protons to the experiments through electrostatic beam lines. These beam lines will be shielded to minimize the effect of the stray fields from the solenoids used by the experiments. About half of the anti-protons sent to the experiments are expected to pass through extremely thin vacuum windows located at each of the experiments, to separate the AD/ELENA vacuum from the much higher vacuum needed within the anti-proton traps. The result is that it should be possible to trap approximately $10^7$ anti-protons from one pulse, or about 30% of the $3 \times 10^7$ AD anti-protons.

The ELENA upgrade to the AD thus promises a very large increase in the number of cold anti-protons that can be accumulated in traps. Compared to AD anti-protons slowed entirely within a degrader, the ELENA upgrade would result in more trapped anti-protons per AD pulse by about a factor of 100. Compared to AD anti-protons slowed using an RFQD, the ELENA upgrade to the AD would result in more trapped anti-protons per AD pulse by a factor of $\sim 10$, see the previous section 2.1. In addition an improved duty cycle is expected, leading to an even larger enhancement.

ELENA will increase the trapping efficiency to the point where it is important to be able to divide AD pulses between experiments, or to direct each pulse of AD/ELENA anti-protons to a different experiment. For example, while one experiment is using its anti-protons (cooling them, manipulating them, forming anti-hydrogen from them, ramping traps, etc.), another can be accumulating its anti-protons. The electrostatic beam lines are compatible with rapid and stable switching of anti-protons from one experiment to another. ELENA has also been designed to divide a pulse of AD anti-protons into four bunches that can be sent to up to four different experiments before the next AD pulse of anti-protons arrives.

The capability to provide higher energy beams to experiments, if so requested (i.e. by ACE), would not be affected by the ELENA upgrade.

3. Conclusions

A careful study of ELENA has resulted in a clear consensus in the low-energy anti-proton community that the ELENA upgrade to the AD is the reasonable and very attractive way forward. There is also a clear consensus upon the design parameters.
for ELENA as described in the feasibility study\(^{15}\) along with the present discussion of the advantage and importance of the upgrade. Thanks to CERN’s unique past (LEAR) and present (AD) low-energy anti-proton facilities, there is an important and flourishing scientific program that requires more anti-protons than AD can provide today. There are not enough anti-protons for the scientific program that is already approved at CERN. The recent workshop\(^1\) showed clearly that there are many additional proposals that are worthy of careful consideration.

The low-energy anti-hydrogen and anti-proton community at CERN’s AD has reached a clear consensus upon the ELENA upgrade to the AD. Many more cold anti-protons will enable already approved experiments to make more rapid progress and to achieve much more sensitive and precise results. With more anti-protons available and with an efficient beam sharing, more experiments can be accommodated.

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References

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