Proposal for an additional
Extra **L**ow **EN**ergy **A**ntiproton ring: **ELENA**
after the present **A**ntiproton **D**ecelerator: **AD**

A Letter of Intent from the AD-community.

1. Motivation for further deceleration of the $\bar{p}$ beam from the AD/CERN

The Antiproton Decelerator (AD) at CERN, in operation since the year 2000 has led to enormous production rates of cold antihydrogen, which received great acknowledgements in the scientific community as well as in the public media. Thus CERN provides a facility which is unique in the world, which leads to fundamental and new physics, and which is very productive despite a rather inefficient way of getting slow antiprotons. The efficiency could be largely improved if a further deceleration and cooling storage ring would be installed between the AD and the experiments.
Such an improvement is needed to enhance the productivity and the availability of the unique user facility AD at CERN with its great scientific potential.

1.1. Past

During the first phase of the operation of AD three experiments were sharing the available beam time equally. Later a forth experiment joined the activities.
All experiments worked very successfully.
Two collaborations (ATHENA and ATRAP) are pursuing the long–term goal of a precise test of possible differences in physical observables between antihydrogen and hydrogen, and have thus far succeeded in the observation of very promising production rates of cold antihydrogen atoms.
ATHENA published the hadronic annihilation signature whereas the detection scheme adopted by ATRAP used atomic physics techniques to field ionize and detect the antihydrogen atoms produced. Further progress has been made by the collaborations in determining additional parameters of both the antihydrogen atoms produced and the antiproton and positron plasmas used to create the antimatter atoms. The very ambitious goals of stringent CPT–invariance tests seems achievable.
The ASACUSA collaboration aims for the spectroscopy of $\bar{p}$ He^+ bound states and the ultimate test of the three–body quantum theory. There obviously is a strong interplay between the development of three-body QED theory and better experimental precision, improving our understanding of fundamental physics. This collaboration has more recently proposed spectroscopic investigations of antihydrogen as well.
The ACE collaboration studies the relative biological effectiveness and peripheral damage of antiproton annihilation in tissue.

The first phase with beam during about five months each year in 2000 to 2003 was very effective thanks to good performance of AD and the steady improvement of the experiments. The efforts of the CERN-PS division and the three collaborations is demonstrated by some 30 publications in refereed journals *(NIM, Phys. Rev. Lett.,* *Phys. Lett., Phys. Rev. A, Eur. Phys. J. D, Physics Reports and Nature)*, numerous publications of subgroups of each collaboration, many presentations at international and national conferences, colloquia and seminars, high quality education of more than 12 PhD and more than 18 diploma students, and a large impressive interest of the public by articles and interviews for news papers, radio–, and TV–broadcast stations.

In summary: Without any doubt the physics performed at the AD is fundamental, highly acknowledged, and very much recognized.

1.2. Present

The individual collaborations working presently at the AD are preparing themselves for a fruitful continuation of precise measurements of fundamental questions of physics. Techniques have been, and will continue to be, developed which are by no means standard and always at the frontier of technology. Though further progress is certain, it is obvious that the final ambitious goals of physics envisaged by the collaborations can not be finished during this year of AD operation. Thus, for a successful achievement of the scientific goals at the AD in the years after the break in the production of antiprotons from November 2004 to May 2006 improvements can be made.
For future operations an essential consideration is the more effective use of the costly antiprotons. Until now, for the two experiments ATHENA and ATRAP the deceleration of antiprotons is done via the three following steps:

- deceleration in the AD machine from 3.5 GeV/c down to 0.1 GeV/c,
- degrading by a foil from 5 MeV kinetic energy down to a few keV,
- electron and positron cooling of the particles trapped to meV energies.

The drawback of this procedure is the rather large increase of the divergence and the momentum spread and, related to that, the high loss rate of the antiprotons when being degraded by a foil, which limits the capture efficiency to about 10^{-4}. Here a significant improvement is essential and can be done by a decelerating storage ring which lowers the beam from presently 5 MeV to 100 keV.

In fact, ASACUSA is using a D–RFQ for additional deceleration of the AD $\bar{p}$'s. However, the divergence of the resulting low energy beam is so large that trapping is problematic and distribution to experiments disadvantageous, limiting the effectiveness of this scheme.

1.3. Future

An additional deceleration and cooling ring after the AD would allow for improved efficiency by up to three orders of magnitude resulting in the following advantages:

- the capture rate of $\bar{p}$'s will be drastically improved,
- the density of the captured $\bar{p}$'s will increase significantly,
- the antihydrogen production rate in a given time will improve,
- optimization procedures for the production yield can be done much faster,

- the possibility of trapping neutral antiatoms will be greatly enhanced,
- the precision of the measurements will increase,
- given the advantage of much faster turn around times, additional users might participate in the use of the $\bar{p}$ beam.

The installation of a further deceleration and cooling ring is certainly clear progress beyond the state–of–the–art and would allow for new developments of innovative research done at the European antiproton facility AD/CERN.

1.4. Fundamental Physics

A deep insight to our understanding of physics properties and laws have been given by the studies of invariances of discrete symmetries.
Four fundamental interactions (gravity, weak interaction, electromagnetism, and strong interaction) are known and a major goal in physics is to find a unified quantum field theory which provides a description of all the four fundamental forces.

Physics is an experimental science and experimental tests have made physicists abandon earlier assumptions for example, the invariance under P and under CP transformations. The current assumption that reality is invariant under CPT transformation is based in large parts upon the success of quantum field theories. These are invariant under CPT as long as reasonable assumptions for causality, locality, and Lorentz–invariance are made. Gravity has not yet fit into a quantum field theory but theoretical investigations of possible CPT–violations are appearing in the context of the new approach of string theory. Any deviation from an absolute CPT–invariance would indicate new physics. Until now, in most cases differences in masses, charges, lifetimes, and magnetic moments of particles and their anti–particles have been compared and upper limits set. An improved CPT test is a very important motivation for experiments which compare antihydrogen and hydrogen when long term goals of experiments at the AD are realized, since it is eventually more stringent than any existing test with leptons and baryons only.
The question to which level CPT as well as Lorentz invariance hold in atomic systems will be tackled with the experiments proposed at the AD of CERN. Here the tools are the measurements of optical– and microwave transitions in antihydrogen to be compared to those from the hydrogen atom.
For precision measurements with antihydrogen the experimental statistics is an important factor which only can be improved by a high efficiency of the antiproton capture rate which in turn depends on the cooling of the antiproton beam. Here the suggested development of a further decelerator is the essential component. Effectively, the suggested storage ring will strengthen the present $\bar{p}$–source and will improve the precision of the exciting, innovative physics. It will help especially when using precise laser spectroscopy to probe for any tiny differences between antihydrogen and hydrogen. It will be a solid ground for precision physics, new understanding, fruitful developments and extremely good education for young scientists for research, teaching and industry.

2. Further deceleration of AD $\bar{p}$'s by an Extra Low ENergy Antiproton ring (ELENA)

An extra low energy ring for $\bar{p}$ deceleration from the AD to an energy of 100 keV is proposed. The envisaged layout of the ELENA ring is such that it would fit into the present AD hall.
The main features of ELENA are:

- A compact machine with a circumference of less than 20 meters.
- Energy range from 5.3 MeV (present AD extraction energy) down to 100 keV.
- The cycle length is much shorter than the AD cycle.
- An electron cooler to maintain small transverse and longitudinal emittances for the $\bar{p}$'s.
- An ultra low vacuum of few 10^{-12} Torr.
- The beam lifetime at 100 keV is longer than 10 seconds.
- The ring would fit inside the existing AD hall.
- The commissioning can be done without disturbing the present AD operation. A dedicated 100 keV proton source can be used to optimize ring parameters.
- Fast extraction is foreseen.
- Slow extraction, necessary for a certain type of experiments, could be envisaged depending on the users requirement.

Special challenges are to maintain high intensity in view of the space charge limitations, construction of the electron gun for the electron cooler with low transverse and longitudinal temperatures in the energy range from 500 eV to 55 eV, $\bar{p}$ beam diagnostics at low energies and intensity.
Machine configuration features are as follows:

- A simple lattice with four 90 degrees combined function magnets to minimize the circumference and the cost of the magnet system.
- One long straight section for beam injection and extraction, the other one for electron cooling.
- The two short straight sections for RF, diagnostics, and correction elements.
- A circumference as small as possible to minimize space requirements in the AD hall.
- The AD experimental areas keep in their present locations.

Figure 1 shows the layout of the proposed ELENA ring, and Figure 2 shows its location inside of AD hall.

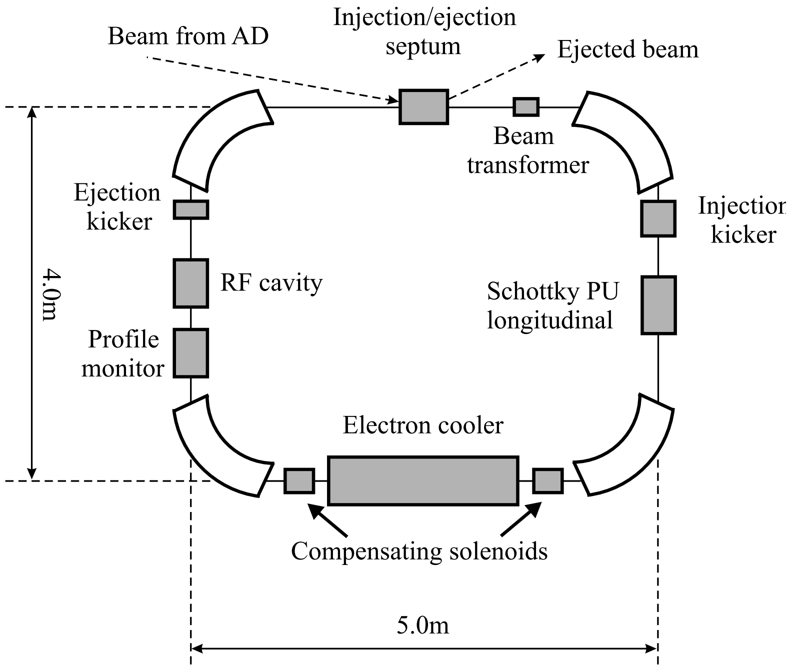

Figure 1. *Layout of the ELENA ring.*

2.1. ELENA main parameters

Energy range, MeV	5.3 - 0.1
Circumference, m	16.7
Working point	1.64 / 1.62
Emittances at 100 keV, π mm mrad	5 / 5
Intensity limitations due to space charge	1.7×10^{7}
Maximal incoherent tune shift	0.10
Bunch length at 100 keV, m / ns	1.3 / 300
Multiple scattering blow up rate for	
3×10^{-12} Torr (N_2 equiv.), $\pi mm\ mrad/s$	0.5
IBS blow up times, s ($\Delta p/p = 2\ 10^{-3}$)	3.2 /-30.6 / 3.9

2.2. Necessary changes in the AD hall

Only minor changes has to be made in the layout of the AD hall:

- Some rearrangement of the shielding
- The water distribution circuits have to be modified.
- One of the wooden barracks on the ground floor has to be moved to available space elsewhere in the hall.

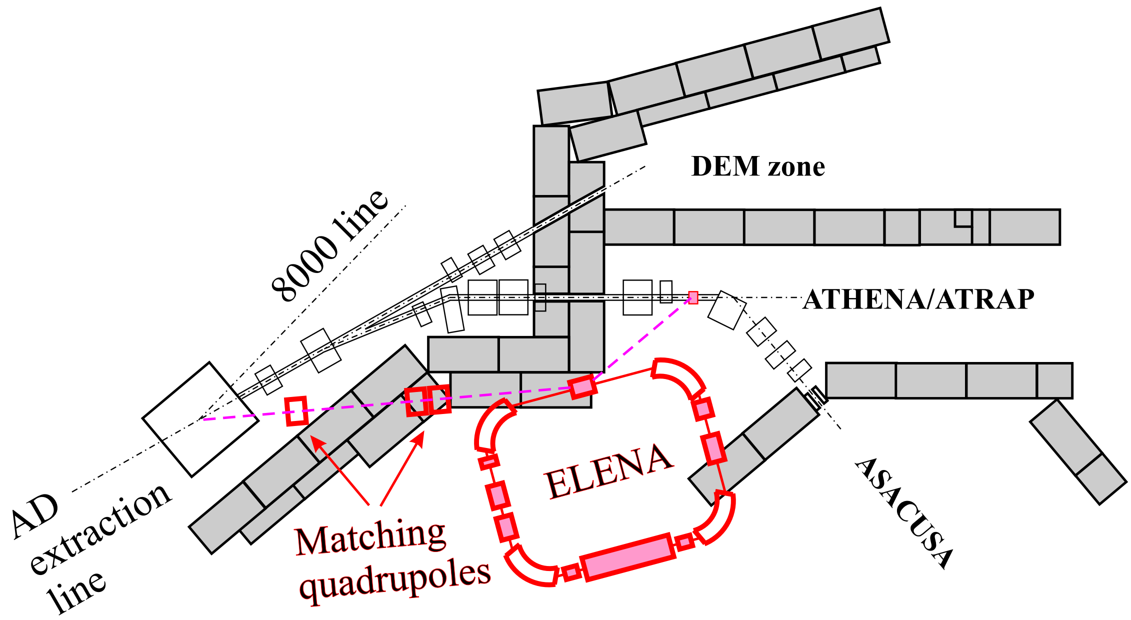

Figure 2. *Suggested location of the ELENA ring inside the AD-Hall.*

- A small part of the ASACUSA experimental area is needed, which however, is acceptable.
- To match the lattice functions, two or three quadrupoles have to be added in the injection line.

3. Conclusion

A further deceleration and cooling ring between AD and the experiments will increase the phase space density at 100 keV by several orders of magnitude. This would raise the efficiency of the antiproton/antihydrogen program at CERN by a very large factor.

A small machine for such purpose is feasible. The main challenges for such a project of deceleration to very low energies like ultra low vacuum and effective electron cooling can be managed. The long time discussed idea of beam deceleration at very low energies by electron cooling could be implemented. ELENA can be located inside the AD hall without large modifications. Assembly and commissioning of ELENA can be done without disturbing the current AD operation. The experience gained at existing low-energy storage rings such as AD (CERN), ASTRID (Aarhus), and CRYRING (Stockholm) can be exploited in the design and construction of ELENA. Some of this experience exists within the AD user community.

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Acknowledgment:
We would like to thank *T. Eriksson, D. Moehl, F. Pedersen, G. Tranquille* for many helpful and fruitful discussions. Their enthusiasm is greatly acknowledged.

CERN, 15.07.2004