Proposal to the CERN SPSC

ELENA:

An Upgrade to the Antiproton Decelerator

from the AD User Community*:

J. Alsner, G.B. Andresen, A. Angelopoulos, D. Barna, N. Bassler, A.S. Belov, W. Bertsche,
G.-J. Beyer, G.Bonomi, J.S. Borbely, I. Boscolo, S. Böttner, P.D. Bowe, N. Brambilla,
J. Bremer, R.S. Brusa, E. Butler, V. M. Byakov, L. Cabaret, C. Canali, C. Carraro,
F. Castelli, C.L. Cesar, S. Chapman, M. Charlton, S. Cialdi, D. Comparat, G. Consolati,
M. Corradini, F. Curreli, L. Dassa, A. Dax, J. DeMarco, N. Djurelov, H. Dølrath, M. Doser,
G. Drobychev, A. Dudarev, A. Dupasquier, T. Eisel, Y. Enomoto, D. Fabris, B. Fahimian,
J. Fajans, S. Federmann, R. Ferragut, G. Ferrari, A. Fisher, P. Folegati, A. Fontana,
L. Formaro, S. Friedreich, M.C. Fujiwara, G. Gabrielse, A. Gervasini, M.C. George,
M. Giammarchi, D.R. Gill, S. N. Gninenko, G. Gribakin, D. Grzonka, D. Hajdukovic,
J.S. Hangst, W.N. Hardy, O. Hartley, F. Haug, R.S. Hayano, M.E. Hayden, R. Herrmann,
E.A. Hessels, R. Heyne, H. Higaki, S.D. Hogan, M. Holzscheiter, M. Hori, D. Horváth,
A.J. Humphries, C.A. Hunniford, R. Hydomako, H. Imao, K. Iwamoto, O. Jäkle,
L.V. Joergensen, B. Juhasz, F.J. Kaiser, Y. Kanai, I. Kantemiris, J. Kavanagh,
A. Kellerbauer, R. Keyes, K. Kira, H. Knudsen, T. Kobayashi, D. Kolbe, A. Koglbauer,
W.S. Kolthammer, S. Kovacevic, D. Krasnicky, H-P E. Kristiansen, L. Kurchaninov,
N. Kuroda, V. Lagomarsino, R. Lambo, P. Larochelle, M. Leali, F. Leveraro, E. Lodi Rizzini,
M. Lunardon, M. Lund, N. Madsen, G. Manuzio, S. Mariazzi, V. Mascagna, O. Massiczek,
Y. Matsuda, V. A. Matveev, W. McBride, R. McConnell, R.W. McCullough, F. Merkt,
K. Michishio, R. Miralbell, S.P. Møller, A. Mohri,S. Moretto, C. Morhard, A. Müller,
Y. Nagata, G. Nebbia, P. Nedelec, T. Ninikowski, P. Nolan, M. Oberthaler, W. Oelert,
K. Olchanski, A. Olin, J. Overgaard, D. Perini, S. Pesente, J. Petersen, V. Petracek,
W. Pirkl, A. Povilus, M. Prevedelli, P. Pusa, F. Quasso, I.Y. Al-Qaradawi, O. Ratib,
C. Riccardi, P. Richerme, F. Robicheaux, O. Rohne, A. Rotondi, H. Saitoh, H. Sandaker
E. Sarid, G. Schettino, M. Scheid, T. Sefzick, S. Sellner, D. Sillou, D.M. Silveira,
P. Somkuti, A. Sótér, M. Spacek, A. Speck, S. Stapnes, R. Steinborn, S. V. Stepanov,
J.W. Storey, C.H. Storry, H.H. Stroke, S. Tegami, G. Testera, R.I. Thompson, D. Timson,
G. Tino, K. Todoroki, K. Tökési, H.A. Torii, D. Trezzi, A. V. Turbabin, A. V. Turbabin,
U. Uggerhøj, K. Umlaub, R. Vaccarone, A. Vairo, V.L. Varentsov, L. Venturelli, G. Viesti,
F. Villa, S. Vranjes, H.R.J.Walters, J. Walz, U. Warring, M. Weel, C. Welsch, D.P. van der Werf,
E. Widmann, B. Wouters, J. Wrubel, J.S. Wurtele, Y. Yamazaki, Z. Yoshida, P. Zalán,
S. Zavatarelli, A. Zenoni, M. Zielinski, N. Zurlo, and D.S. Zvezhinskij.

*Allocations to the collaborations and Affiliations of the individual persons
are given in the Appendix

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Five Documents comprise this Proposal:

1. This document, which gives the overview and makes the case for the substantial technical advantage and impact of the ELENA upgrade to CERN's AD.

2. The most recent case for the importance and richness of the scientific program at the AD is in the report on the May 2009 workshop: "**New Opportunities in the Physics Landscape at CERN**" convened by CERN's Director General and the Research Director to consider the prospects for future non-LHC physics at CERN. A copy of this report, written by H. Abramowicz, is given in the first part of the Appendix.

3. "**ELENA - a Preliminary Cost and Feasibility Study**,"
   M.-E. Angoletta, M. Barnes, A. Beuret, P. Belochitskii, J. Borburgh,
   P. Bourquin, M. Buzio, D. Cornuet, T. Eriksson, T. Fowler, M. Hori,
   E. Mahner, S. Maury, D. Möhl, J. Monteiro, S. Pasinelli, F. Pedersen,
   U. Raich, L. Soby, P. Strubin, G. Tranquille, and T. Zickler.
   A copy of this report is given in the second part of the Appendix.

4. A list of approved experiments at the AD with their members and affiliations is presented in the third part of the Appendix.

5. A letter from Prof. Swapan Chattopadhyay of the Cockcroft Institute expressing his strong interest in participating in the construction of ELENA.

1 Overview

CERN has a splendid tradition of pursuing fundamental physics on a variety of energy scales. For antiprotons, CERN famously produced the high-energy SPS beam, but also the world's only and unique sources of low-energy antiprotons – first the Low Energy Antiproton Ring (LEAR) and now the Antiproton Decelerator (AD). LEAR and the AD led to widely recognized scientific successes that include:

- the trapping, cooling and accumulation of extremely cold antiprotons, more than 10^{10} times lower in energy than the LEAR and AD antiprotons
- the most precise comparison of the charge-to-mass ratios for the antiproton and proton, resulting in the most stringent test 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 further proposals are under consideration. Thus, 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.

It is now possible to consider more rapid progress and much higher measurement precision by upgrading the AD to increase and optimize the number of cold antiprotons that can be trapped and accumulated. To achieve this the construction of the **E**xtra **L**ow **EN**ergy **A**ntiprotons (ELENA) upgrade to the AD is proposed. 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 ELENA upgrade will not only enable higher quality low-energy antihydrogen physics at CERN over the next decade, it will also be an accelerator test platform of 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 [1], a facility that is being planned in response to the ever-increasing interest in low-energy antiproton physics. ELENA will provide vital experience and methods for the design and operation of such future facilities. However, at least during the next decade there is no alternative low-energy antiproton source for physics to be done now.

2 The Scientific Case for the ELENA Upgrade

There is a huge interest in the very compelling scientific case for antihydrogen and low-energy antiproton physics. This case has been regularly reviewed and approved by the SPSC and the CERN management. The scientific case was made most recently at the Workshop on "New Opportunities in the Physics Landscape at CERN" [2] that the Director General and the Research Director convened in May of 2009. The summary report [3] for this workshop, just issued at CERN, is submitted as part of this proposal. Nevertheless, we present here a short list of key points from this report:

2.1 Physics Motivation

- 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 effects relevant for low-energy antimatter experiments.
- Searches for new interactions can be carried out by studying discrete symmetries such as CPT.
- The prospects of performing spectroscopic investigations of antihydrogen opens the possibility for CPT tests more stringent than ever done before.
- 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.

2.2 Existing Experiments

- 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 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) follows an ambitious aim 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) is working to demonstrate trapping of antihydrogen atoms in a magnetic multipole trap. The long term goal of this work is a spectroscopic comparison of hydrogen and antihydrogen The apparatus will be modified and expanded to perform increasingly precise microwave and laser spectroscopy of antihydrogen.

2.3 New Experiments

- AD-6 (AEGIS) intends to measure the gravitational interaction of antihydrogen with a precision of 1 %. The experiment has been approved and the installation of the apparatus will happen during the next two years.
- Proposal by the PAX collaboration for: “Measurement of the spin-dependence of the proton-antiproton interaction at the AD-ring” [4].
- Letter of Intent for: “A measurement of the acceleration of antihydrogen in the gravity field of the Earth” [5].
- Letter of Intent for: “Double-strangeness production with antiprotons at the AD-ring” [6].
- Letter of Intent for: “Antiprotonic atom X-ray studies at AD from selected elements with low Z” [7].

3 The Technical Case for the ELENA Upgrade

The figure of merit for the antiprotons available to much of the approved and contemplated AD experimental program is the number of cold antiprotons that can be accumulated within a trap per pulse of antiprotons delivered from the AD. There is now enough experimental experience with slowing down, decelerating, trapping and cooling antiprotons to easily and reliably estimate the very substantial improvement in this figure of merit that the ELENA upgrade to the AD would provide. This section contrasts the number of cold antiprotons that have been accumulated per AD antiproton pulse, with the dramatically larger number that the ELENA upgrade will make possible – a substantial improvement by a factor of 10 to 100, depending upon the experiment. This section is complete, even though it is short, because the numbers and efficiencies provided are based upon experimental demonstrations that are beyond dispute.

3.1 Current accumulation of cold antiprotons

The methods for accumulating cold antiprotons in traps were developed at CERN by the TRAP collaboration [8]. Antiprotons 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 antiprotons, 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 AD antiprotons by ATRAP and ALPHA to produce antihydrogen, and AEGIS proposes to do so. ASACUSA also uses these methods with a modification to be described. In the early days of the AD, up to 2×10^4 antiprotons were captured and cooled from an AD pulse of 3×10^7 antiprotons, i.e. with an efficiency of only 8×10^{-4} [9]. (A pulse of antiprotons is delivered by the AD approximately every 100 seconds). Antiprotons can be added to the trap from successive pulses of AD antiprotons; this accumulation of trapped and cooled antiprotons is often referred to as "stacking" [9].

Recent improvements [10] made it possible to increase the number of antiprotons accumulated per AD pulse by about a factor of 5 so that now up to 1.3×10^5 antiprotons are accumulated from an AD pulse and transferred into a 1 Tesla trapping field, giving a total efficiency of 4×10^{-3}. In 15 minutes, more than 1 million antiprotons 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 [11] and ALPHA [12] collaborations that rely entirely upon these methods, and what can be expected by the AEGIS collaboration [13].

The ASACUSA collaboration [14] also uses these methods, but with a radiofrequency quadrupole decelerator (RFQD) and a much thinner (1.2 μm) plastic foil replacing the thin metal degrader [15]. The 12 meters of antiproton 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 in the AD.

The RFQD decelerates the 5.3 MeV antiprotons from the AD down to 50 - 120 keV, and the thin plastic foil slows the antiprotons to the required energy (< 10 keV) for trapping. It is important to note that of the $2{\times}10^7$ antiprotons extracted from the AD every minute, the RFQD decelerates 25% ($5{\times}10^6$), whereas most of the antiprotons ($1.5{\times}10^7$) miss the longitudinal acceptance of the RFQD and do not get decelerated or trapped. More antiprotons ($\sim 3.5{\times}10^6$) are lost during the deceleration in the foil or in the first few seconds after closing the trap, so that ultimately around 10^6 antiprotons are cooled and accumulated per AD pulse [15]. 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 antiprotons 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 equipment.

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.

1. The ELENA ring with multi-bunch extraction would provide ~ 100 times more antiprotons in a trap per AD cycle, compared to ~ 10 more for the current RFQD.
2. No cooling of the antiproton beam is possible during deceleration of the beam in an RFQD. The quality of the slowed 100 keV antiproton 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 π 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.
3. The input acceptance of the RFQD is small - the design value of the ASACUSA RFQD was 10 π mm mrad, but experiments have shown that the highest beam quality needed for efficient antiproton trapping is achieved for only the central < 1 π 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.
4. Antiprotons 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.
5. 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 four 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 antiprotons can only be achieved using a cooled antiproton beam from ELENA.

3.2 ELENA optimized for trapped antiprotons

ELENA is a small circular decelerator which slows the AD antiprotons to 100 keV, cools them via integrated electron cooling, and delivers the antiprotons to the various experiments via electrostatic beam lines.

ELENA is clearly the best known upgrade option for the AD. Its attractive features include:

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

Each of these points are discussed in detail in the ELENA feasibility study [16] submitted as part of this proposal.

From the ELENA feasibility study [16], and from the RFQD demonstration [17], it is easy to estimate the greatly improved antiproton trapping efficiency that can be expected after the upgrade. The AD and ELENA will deliver well-cooled pulses of 2.5×10^7 antiprotons 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 antiprotons 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 antiproton traps. The result is that it should be possible to trap approximately 10^7 antiprotons from one pulse, or about 30% of the 3×10^7AD antiprotons.

The ELENA upgrade to the AD thus promises a very large increase in the number of cold antiprotons that can be accumulated in traps. Compared to AD antiprotons slowed entirely within a degrader, the ELENA upgrade would result in more trapped antiprotons per AD pulse by about a factor of 100. Compared to AD antiprotons slowed using an RFQD, the ELENA upgrade to the AD would result in more trapped antiprotons per AD pulse by a factor of ~ 10, see the previous section 3.1. 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 antiprotons to a different experiment. For example, while one experiment is using its antiprotons (cooling them, manipulating them, forming antihydrogen from them, ramping traps, etc.), another can be accumulating its antiprotons. The electrostatic beam lines are compatible with rapid and stable switching of antiprotons from one experiment to another. ELENA has also been designed to divide a pulse of AD antiprotons into four bunches that can be sent to up to four different experiments before the next AD pulse of antiprotons 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.

3.3 The future of antiproton physics

Through the years, first with LEAR, then with the AD, CERN has developed a unique low-energy antiproton research platform. The next step will be ELENA.
Looking to the future, it is clear that there will be an ever-increasing demand for low-energy antiprotons; in fact soon the demand might be beyond what CERN can supply and there will be need for a new source allowing for the ever-wider physics program. The science experiments and the thriving low-energy physics community can be expected to continue its steady progress over the next decade only at the AD - there is presently no alternative.

FLAIR [1], an addition to the substantial FAIR [18] facility that is being planned at the GSI in Germany, is just such a source as it will provide both low-energy ions and low-energy antiprotons. The FLAIR source, according to present design values [19], will have an advantage over the AD plus ELENA project, not so much by having a higher low-energy antiproton yield per time, but rather more through the desired possibility of slow extraction, providing a continuous beam needed by several suggested experiments. In addition, substantially more floor space will be available for experiments. The aspirations to make FLAIR an important addition to the activities with low-energy antiprotons will be at least a decade from now. Up to that time AD/ELENA will be the sole source for low-energy antiproton physics world wide.

Experiences at existing low-energy storage rings such as ASTRID (Aarhus), TSR (Heidelberg), CRYRING (Stockholm), and AD (CERN) will certainly help in the design, construction, and commissioning of ELENA. The subsequent FLAIR will undoubtedly also profit from this past experience as well as from the understanding that will come from operating ELENA.

3.4 Accelerator physics and training at ELENA

The "post-deceleration ring" that is ELENA provides the opportunity for interesting, important and manageable accelerator physics studies because of the challenges involved in realizing a very low phase space volume as the beam energy is reduced. Though being partly explored at the just mentioned low-energy storage rings, challenges remain to be solved, not least for the low-energy antiproton beams.

1. **Intensity limit to low-energy bunch compression:**
   The space-charge limit in "normal" synchrotrons is well understood. However, the ELENA post-deceleration is to energies that are orders of magnitude lower. Short (e.g. 1 meter) bunches are needed to fill traps, 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, the space charge effect is highest and the size of the resulting transverse tune shifts that can be tolerated set the fundamental intensity limit. ELENA offers the chance to investigate these instabilities and limits, along with those from longitudinal instabilities.

2. **Instrumentation for low energies and intensities:**
   Non-destructive Schottky beam-noise diagnostics must be developed to monitor the unusual particle beams, based upon what has been learned at the AD and

other storage rings, to deal with energies and intensities that are lower by one or two orders of magnitude.

3. **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.

4. **Design and shielding of beam transport lines:**
   The beam lines to the experiments for the low-energy beams will contain electrostatic rather than magnetic elements. ELENA provides the opportunity to experimentally test the design of these lines and their shielding against "ambient" magnetic fields in the hall.

5. **Electron cooling:**
   The very special requirements for electron cooling at and below 40 MeV/c (detailed in the ELENA feasibility report) will be tested in ELENA.

The operation of ELENA will provide invaluable opportunities for the development of methods that will be incorporated into the improved low-energy deceleration rings of the future, along with a useful accelerator physics training ground.

4 ELENA's Influence on the Experimental Progress

Here the influence on the expected progress for the different experiments is summarized. Some arguments will be valid for all experiments, some are rather specific to the individual case.

4.1 Significant Advantage of the ELENA Upgrade for ATRAP (AD-2)

The usage of the antiprotons from the AD by ATRAP is illustrated with a typical example. ATRAP starts its shift by steering and focusing the antiproton beam on its degrader target for about 15 minutes, where this time depends somewhat on the day to day conditions. Over the next 1.5 hours ATRAP first accepts about ten AD pulses to accumulate more than a million cold antiprotons in the trap which takes about 15 minutes. The rest of the time is spent for cooling and manipulating the antiprotons, transferring and positioning cold positrons, and using the antiprotons and positrons together to make one antihydrogen production experiment. If all goes perfectly, during one 8 hour shift five such antihydrogen trials can be made. ATRAP is thus currently able to use about 5 million antiprotons per day on average.

When a fourth experiment starts its operation, even fewer antiprotons per day will be available for ATRAP experiments since the AD beam will need to be split four ways on average rather than three. With equal sharing, each of the running experiments will thus only average a 6 hour shift per day, meaning that about 4 million trapped antiprotons per day will be available to ATRAP.

With the ELENA upgrade to the AD, the number of antiprotons available to ATRAP per day would go up dramatically. Consider a completely shared mode with four experiments running simultaneously for 24 hours. As detailed in Sec. 3.2, this means that ATRAP could accumulate 25 times as many antiprotons per AD pulse, and during the same antiproton accumulation time, compared to what is now possible. This is still much fewer antiprotons than the positrons and electrons we use in the trap for cooling and producing antihydrogen so our methods should still work. Moreover, ATRAP could run for 24 hours rather than 6 hours per day on average giving another factor of 4 advantage. Together this means that the ELENA upgrade to the AD would make is possible for ATRAP to use 500 million antiprotons per day on average. This is a factor of 100 more trapped and cooled antiprotons on average compared to what will be possible with four experiments and no ELENA upgrade.

Can ATRAP actually run for 24 hours per day? With current personnel levels we could not run more 12 hours per day, but personnel levels could be increased. Some time without antiprotons is required to maintain the cryogenic systems but this could be automated much more if there was the opportunity to run a bigger fraction of the day. The result is that if the antiprotons become available ATRAP will find a way to use them efficiently.

There are also advantages to other experiments that go beyond the estimates provided above. Right now when ATRAP is not accumulating antiprotons during its shift the unused antiprotons are wasted. Other experiments cannot use them because the exact time that they would be available cannot be predicted well and switching from one experiment to another sometimes can be accomplished in a few minutes but it can also take 15 minutes to a half hour. With the ELENA upgrade any antiprotons not being accepted by ATRAP can be directed to experiments that are accepting antiprotons on a AD pulse by AD pulse basis. Similarly, ATRAP could put antiprotons not being used by other experiments to good use.

How important is a 100-fold increase in the number of trapped antiprotons for ATRAP? The increased number is extremely important. When four experiments begin running at the AD ATRAP will make only 4 attempts to make and trap antihydrogen atoms per day on average. It is very difficult to make progress at this rate during a time when we must use such trials to develop the new methods that this low energy frontier requires. The ELENA upgrade and the shared mode will allow us to make up to four times more trials, each of which has much better statistics. Once we get to antihydrogen spectroscopy the statistical uncertainties will go inversely as the square root of the number of antihydrogen atoms. The ELENA upgrade will thus allow measurements to be made about ten times more precisely for the same amount of time.

There is no doubt that the ELENA upgrade to the AD is extremely important to ATRAP. It would greatly speed the scientific progress and the ultimate measurement accuracy.

4.2 Significant Advantage of the ELENA Upgrade for ASACUSA (AD-3)

Over the last decade of AD operation, the ASACUSA collaboration has measured the transition frequencies of antiprotonic Helium atoms to a relative precision of 9 parts in 10^9 by laser spectroscopy. By comparing the experimental values with three-body QED calculations, the antiproton-to-electron mass ratio was determined as 1836.152674(5). These experiments involved first the deceleration of the 5.3 MeV antiproton beam provided by AD to 80 keV using the RFQD. Antiprotonic Helium was then synthesized by allowing these antiprotons to stop in a low-density Helium target. The atoms were then irradiated by nanosecond laser pulses of typical diameter 30 - 40 mm. The experimental precision is currently limited by the relatively small number of antiprotons that can be stopped ($\sim 3 \times 10^6$ antiprotons per AD cycle). The emittance and energy spread in the RFQD-decelerated beam is so large (100 π mm mrad and >10 keV) that most of the antiprotons ($\sim\ 2 \times 10^7$) are not stopped in the Helium target but rather annihilate in the RFQD, the low-energy beamlines, or the metallic walls of the experimental apparatus. The charged pions emerging from all these annihilations cause a large background in the experimental data.

Monte-Carlo simulations indicate that the higher intensity and lower emittance of the electron-cooled antiproton beam available from ELENA would lead to a 10-fold increase in the number of synthesized antiprotonic Helium atoms, whereas the background annihilations described above would be suppressed by an order of magnitude. This would greatly improve both the statistical error and signal-to-noise ratio in the experimental data. Further studies on the systematic errors could then be carried out. The transition frequencies of antiprotonic Helium can in principle be measured with a precision $< \ 10^{-9}$. These experiments coupled with further progress in QED calculations may ultimately lead to an antiproton-to-electron mass ratio which is more precise than the known proton-to-electron one.

4.3 Implications of the ELENA Upgrade for ACE (AD-4)

The proposed lay-out of the ELENA upgrade will continue to allow extraction of higher energy beams directly to experiments, if so requested. This will allow ACE to continue running in the current standard mode. Additionally, the availability of ultra-low energy antiprotons will permit the performance of nano-dosimetry experiments and the study of DNA level damage in individual cells, providing a more detailed understanding of the biological effects of therapeutic particle beams as well as from high energy background radiation encountered in space.

4.4 Significant Advantage of the ELENA Upgrade for ALPHA (AD-5)

The ALPHA collaboration is working towards trapping of antihydrogen and eventually towards spectroscopy of trapped antihydrogen. The statistical considerations for rare-event spectroscopy have been described above with regards to other AD experiments. These of course apply to ALPHA as well, and it is obvious that the addition of ELENA will have a huge impact on the viability of many of the proposed spectroscopy experiments in the ALPHA device. ALPHA has already spent many months searching for trapped antihydrogen using various techniques of mixing antiprotons and positrons in a multipole magnetic trap for neutral anti-atoms. These efforts tend to alternate between "learning curve" dominated experiments and "statistically limited" experiments. In the former, progress is generally limited by the effort to develop the new experimental techniques necessary for improving the trapping experiment, rather than by the antiproton flux. In the latter, a trapping experiment is repeated many times to look for a significant signal of trapped antihydrogen being released from the trap. The expected increase in antiproton number with ELENA will have an immediate impact on the statistically limited experiments. In fact, experiments that look promising but aren't viable with the AD alone will immediately become possible. For example, some mixing techniques produce a lot of antihydrogen, but produce it in states and at energies that are unlikely to be trapped. Other techniques produce much less antihydrogen, but produce it in a more trappable state. These latter techniques are not currently promising in our apparatus, but would become very compelling with ELENA-type antiproton fluxes. In both cases, the probability of success scales directly with the number of antiprotons available. Given the current understanding of trapping dynamics in these experiments, it is likely that ELENA is in fact necessary to achieving enough trapped antihydrogen atoms to make spectroscopy viable in the future.

4.5 Significant Advantage of the ELENA Upgrade for AEGIS (AD-6)

The primary goal of the AEGIS experiment is to measure the gravitational interaction of antihydrogen, initially to 1%, by forming a pulsed horizontal beam of ultra-cold antihydrogen atoms, and measuring their vertical displacement under the effect of gravity by means of a Moiré deflectometer and high-resolution position sensitive detector. A number of secondary goals, most of which involve producing a beam of antihydrogen atoms as well, are also being pursued; for several of these, their feasibility hinges on the availability of a larger number of antiprotons than currently feasible.

Antihydrogen production will proceed via interaction of Rydberg positronium with antiprotons. With the parameters of the AEGIS apparatus, we expect of the order of 1% of all antiprotons to be incorporated into an antihydrogen atom in the beam; all other things being equal, a hundredfold increase in the number of antiprotons will increase the production rate of cold antihydrogen by up to a factor of 100. The precision reachable by the experiment is determined by statistical and systematic errors (which we aim to keep at a fraction of the statistical error). Reaching the aimed-at precision of 1% on the gravitational coupling of antihydrogen requires 10^4 antihydrogen atoms reaching the far end of the deflectometer, which corresponds to approximately one month of beam time. The apparatus must be monitored and kept stable to better than 1 μm over this time. A ten to hundred-fold increase in the number of antiprotons would reduce the necessary beam time accordingly to a few days, a far more manageable situation. This will also allow dividing the data into velocity bins, and allow a measurement of the shift of the falling distance as a function of the time spent in the deflectometer, in the course of a one-week to one-month measurement period. Experience gained with the first measurement will however be necessary to determine how far the systematic error can be reduced.

The techniques required in the AEGIS experiment go beyond the state of the art in several cases, and their combination is novel. The expected production rate of antihydrogen atoms is of the order of 1 Hz on average, once all procedures have been optimized (given the pulsed nature of the experiment, 100 atoms are expected to be produced every 100 s). The initial production rates will lie well below their optimal values, and in some cases even modest increases in the number of available antiprotons, and thus atoms, can greatly expedite the commissioning and optimization procedures. Reaching the target of 100 mK antiprotons is a very demanding endeavour, and this too will take much effort to reach. The main effect of a somewhat higher temperature antiproton cloud is to increase the divergence of the antihydrogen beam, but it does not affect the formation rate of antihydrogen atoms. Should only warmer ($\sim$ 1 K) antiprotons be available initially, an increase in their number would allow collimating more severely without reducing the absolute flux with respect to the values assumed in the proposal.

4.6 Implications of the ELENA Upgrade for New Experiments

As indicated in section 2.3 there are new research proposals which need low-energy antiprotons and an upgrade of ELENA would allow more experiments to be served. Here the implications for the different experiments are summarized:

4.6.1 "Measurement of the spin-dependence of the proton-antiproton interaction at the AD-ring"

Using an internal polarized hydrogen storage-cell gas-target in the AD-ring the total, spin-dependent $p\bar{p}$ cross sections, σ_1 and σ_2 should be measured at $\bar{p}$ beam energies in the range from 50 to 450 MeV. The benefit of ELENA for this PAX collaboration [4] is an indirect one. Once ELENA provides higher luminosity to the external experiments, it is of course much easier to accomodate additional AD users and their requests, such as PAX.

4.6.2 "A measurement of the acceleration of antihydrogen in the gravity field of the Earth"

The aim of the experiment [5] is to measure the acceleration of ultra slow antimatter atoms by using antihydrogen. The production involves creating $\bar{H}^+$ ions via a two-step charge exchange process $\bar{p} + Ps \longrightarrow \bar{H} + e^-$, followed by $\bar{H} + Ps \longrightarrow \bar{H}^+ + e^-$. The excess positron is then photo-detached in order to recover a neutral and slow $\bar{H}$ at μ K temperatures. As a large number of positronium atoms are needed for this experiment, an intense source of slow positrons based on a mini linac is being developed at Saclay. Such a source could also serve other experiments or be duplicated. An upgrade of the AD with ELENA would certainly make the possibility for additional experiments more viable.

4.6.3 “Double-strangeness production with antiprotons at the AD-ring”

A 4π detector is needed consisting of a magnetic spectrometer for the identification of charged particles and a calorimeter for the detection of neutral decay products. The central detector is a time projection chamber with GEM readout, which is currently being developed. It is planned to build and test the setup such that thereafter it could be installed at the AD. More detailed studies are planned at FLAIR after successful studies at the AD. This experiment will require a slow extraction of the low-energy antiproton beam, an issue which will be considered in section 4.7.

4.6.4 “Antiprotonic atom X-ray studies at AD from selected elements with low Z”

The study of selected light antiprotonic atoms with low Z gives access to various phenomena of the strong interaction and of cascade effects originating from the interplay of the electron shells with the $\bar{p}$ during the de-excitation cascade occurring after capture. Again, this experiment will require a slow extraction of the low-energy antiproton beam, an issue which will be considered in the following section 4.7.

4.7 Slow extraction of a low-energy antiproton beam

Some proposed experiments need slow extracted beam which has not been foreseen in the current feasibility study for reasons which could be summarized as follows:
a) the intention was to keep the costs as low as possible
and
b) the ELENA ring was designed to be as small as possible due to the limited space available in the AD-hall and due to reasons of space-charge and beam observation.

In principle slow extraction is possible but the impact on adding slow extraction equipment and the requirements of the new experiments needing this option has to be evaluated in a detailed new design study.

On the other hand, MUSASHI captures, cools and extracts antiprotons and has already succeeded in delivering an ultra slow DC antiproton beam of 1×10^6 antiprotons every 4 AD shots, which likely can be transported over a distance of several meters. Combining the MUSASHI setup with ELENA will in principle produce a factor of ten stronger DC beam which can be further improved if the ELENA beam is distributed to different experiments shot by shot. Still, a priori, the complex MUSASHI apparatus can not be regarded as an open facility for general users since its operation has to be discussed in the light of the individual experimental conditions, needs and interests.

5 The Design, Construction and Funding of ELENA

Clear consensus: A careful study of ELENA has resulted in a clear consensus in the low-energy antiproton 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 [16] that should be considered as part of this proposal, along with this discussion of the advantage and importance of the upgrade, and the attached discussion of the scientific case that was recently issued.

Time-scale and costs: Detailed estimates in section 17 of the feasibility study [16] indicate that three years after approval of the project the commissioning with beam could start and suggest that 10.219 MCHF plus 58.0 FTE person-years are required to realize the ELENA upgrade to the AD. The cost breakdown is summarized in the Conclusions of [16] (Table 38 of Section 18).

Funding: Funding for ELENA is a considerable challenge that will require the generous consideration and strong support of CERN. Most of the AD users are from low-energy physics communities with no tradition or mechanism for funding either substantial facilities or upgrades to facilities. Nevertheless, some substantial contributions have already been offered, others are currently being investigated, and some users have agreed to apply for funding once the SPSC and the CERN management have approved this proposal.

- The Cockcroft Accelerator Institute has communicated its desire to be involved with its participation to be negotiated with the CERN management.
- The CEA-IRFU at Saclay (France) envisages contributing to the multipole ring magnets, in collaboration with CERN design engineers, with dedicated funding to be sought.
- 400 kCHF and three man-years for diagnostics have been offered by the Junior Research Group at the MPQ-MPI Garching led by Dr. Masaki Hori funded by the EU, Germany, and Japan. Further contributions for ELENA are being sought.
- An application will be made in Denmark for funding to cover the ring and injection line magnets. Experience from the building of ASTRID is offered for the detailed design and construction of ELENA.
- Some US, German and other collaborators on the AD experiments are interested in participation in ELENA and will request additional funding to support their participation and the project. It is difficult to predict the outcome.

We need the approval of the SPSC, as a first step, and the guidance and strong support of the CERN management as a second, for ELENA to become a reality. The ELENA upgrade can only succeed if it is established as an important CERN priority.

6 Modifications Required to Approved Experiments

All of the larger approved experiments – ATRAP, ALPHA, ASACUSA and AEGIS – unambiguously and enthusiastically support the ELENA upgrade. The increased number of antiprotons justifies the modifications required to these experiments. The standard research program of the smaller ACE collaboration will neither profit nor suffer from this upgrade as long as they maintain their direct access to AD antiprotons, which is foreseen.

The modifications to the approved experiments are well understood in large part because ASACUSA has already demonstrated what is required to effectively use 100 keV antiprotons. The required modifications are as follows:

1. The current beam lines, the RFQD (including its large amplifiers), and the direct access to the AD via these lines will be removed.

2. Electrostatic beam lines, considered part of the ELENA upgrade, must be installed in their place with the magnetic shielding needed to preserve well-controlled particle trajectories in the presence of the fringing field of the solenoids that are part of the traps used by the experiments. Measurements have shown that these fringing fields are relatively weak (< 100 Gauss) over most of the AD beam lines. They can be effectively shielded by placing several layers of iron and μ-metal plates around the typically 200-mm-diameter stainless steel pipes containing the electrostatic beam lines.

3. ATRAP and ALPHA will replace their metal antiproton energy degrader windows with very thin degrader windows, just as ASACUSA has demonstrated to work for 100 keV antiprotons [20]. AEGIS will do the same. ASACUSA has carried out intensive R&D work during the years 2000-2006 to find the optimum degrader material which simultaneously satisfies the four requirements:

   Vacuum leak tightness: Windows of typically 30 mm diameter will be used to separate the $p < 10^{-9}$ mb vacuum of the ELENA beam lines from the higher vacuum of $p < 10^{-14}$ mb in the antiproton traps. Initial experiments – using a commercial carbon foil – showed that small pinholes allowed contaminant gases to leak from the accelerator to the trap, causing the antiprotons to prematurely annihilate. However, two layers of plastic foils [20] with a total thickness of 1.2 μm yielded antiproton trapping lifetimes compatible with antihydrogen experiments.

   Thickness uniformity: A uniform thickness (<10%) of the foil must be ensured for an equal deceleration of the antiprotons and an efficient capture by the trap. The foil used now achieves a trapping efficiency of 25%.

   Mechanical rigidity: The presently used plastic foil supports a pressure difference of 5 mb, and was observed to be quite robust after repeated cycles of the apparatus between atmospheric pressure and vacuum. In contrast, carbon foils easily shattered by mechanical vibrations or rough handling.

   Spatial profile detection: The alignment of the 100 keV antiproton beam was crucial for optimizing the number of trapped antiprotons.
   Therefore, ASACUSA evaporated 15 nm-thick aluminum strips with a width

of 1 mm on the foil arranged in an XY configuration [21]. When antiprotons traversed these strips, secondary electrons were emitted from them, enabling a non-destructive measurement of the spatial profile of the antiproton beam.

4. As mentioned above, all experiments will require careful attention to vacuum pumping and isolating the trap and beam line vacua. The beam lines will be pumped by a series of titanium getter and sublimation pumps to a pressure of $p < 10^{-9}$ mb at room temperature, whereas the traps will be cryogenically pumped to $p < 10^{-14}$ mb at $T = 4$ K. The ASACUSA vacuum windows have been successfully used to separate this ≈ 5 orders of magnitude difference in pressure.

5. Possibly ATRAP and ALHPA will no longer benefit from the auxiliary solenoids that they now use to efficiently capture antiprotons which are slowed from 5 MeV within a "thick" degrader window. Eventually this has to be demonstrated.

6. ATRAP and ALPHA (and AEGIS) will need to provide detectors for steering the antiproton beam for 100 keV antiprotons rather than for MeV antiprotons. A wire detector like that used by ASACUSA is one choice. Here a grid of 10 - 30 μm thick wires arranged in an XY configuration is placed in the beam. This grid allows 98% of the antiprotons to pass through and enter the trap, whereas only 2% are intercepted which induce the emission of secondary electrons from each wire to be measured by charge-sensitive amplifiers. This detector has been operated successfully for ten years with minimal maintenance.
   Another option is just to steer the beam to maximize the number of trapped antiprotons. A segmented μ-strip Si detector with a hole in its center, as frequently used, offers a third possibility.

7. The sequence of electrode manipulations needed to trap and cool the antiprotons will remain essentially unchanged. Little or no modifications will be needed in the trap electrodes or control software.

All these alterations have to be regarded as minor actions in view of the significant gain in usable antiprotons with ELENA and fortunately, their feasibility has already been demonstrated. The ASACUSA beam development team offered to provide technical assistance if needed. In addition, the costs for the required modifications are well within the budgets of the experiments and will be covered by the collaborations.

7 Conclusions

Thanks to CERN's unique past (LEAR) and present (AD) low-energy antiproton facilities, there is an important and flourishing scientific program that requires more antiprotons than the AD can provide today. There are not enough antiprotons for the scientific program that is already approved at CERN. The recent workshop convened by the Director General and the Research Director showed clearly that there are many additional proposals that are worthy of careful consideration.

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

8 Acknowledgments

We are grateful to the CERN Directorate for initiating the Workshop on "New Opportunities in the Physics Landscape at CERN" to consider the prospects for future non-LHC physics at CERN. This workshop clearly revealed the strong need for the ELENA upgrade, and crystalized the consensus within the community that the continued scientific progress in low-energy antihydrogen physics requires moving rapidly in this direction.

We would like to thank P. Belochitskii, T. Eriksson, S. Maury, D. Möhl, F. Pedersen and G. Tranquille for their careful study of the ELENA option and for their enthusiasm for making this upgrade work. Their contribution to parts of this proposal was decisive and vital which is gratefully appreciated.

We would like to thank Andy Sessler for very helpful comments during the preparation of this proposal and we value very much the continuous interest and useful discussions with our SPS-Coordinator H. Breuker.

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10 Appendices

1. "The Case for the Antiproton Decelerator – Workshop Summary"
   H. Abramowicz
   The most recent case for the importance and richness of the scientific program at the AD is in the report on the May 2009 workshop: "**New Opportunities in the Physics Landscape at CERN**", convened by CERN's Director General and Research Director to consider the prospects for future non-LHC physics at CERN.

2. "**ELENA - a Preliminary Cost and Feasibility Study**,"
   M.-E. Angoletta, M. Barnes, A. Beuret, P. Belochitskii, J. Borburgh, P. Bourquin, M. Buzio, D. Cornuet, T. Eriksson, T. Fowler, M. Hori, E. Mahner, S. Maury, D. Möhl, J. Monteiro, S. Pasinelli, F. Pedersen, U. Raich, L. Soby, P. Strubin, G. Tranquille, and T. Zickler.

3. "Members and Affiliations of Approved AD–Experiments".

4. "Letter from Prof. Swapan Chattopadhyay of the Cockcroft Institute".

Appendix 1:

The Case for the Antiproton Decelerator – Workshop Summary

H. Abramowicz

The most recent case for the importance and richness of the scientific program
at the AD is this summary report on the May 2009 workshop:

“New Opportunities in the Physics Landscape at CERN”

The Case for the Antiproton Decelerator – Workshop Summary

H. Abramowicz –convener, with the help of
M. Doser, G. Gabrielse, R. Hayano, K. Jungmann,
R. Lehnert, E. Widmann, J. Zmeskal

1 Physics motivation

The established physics is successfully described by the Standard Model (SM) and General Relativity (GR). However, many predictions of this theoretical framework currently remain experimentally unverified in the antimatter regime providing general impetus for tests involving antimatter. Concrete motivations arise in a number of theoretical approaches extending the SM and GR to include a consistent unified description of three cornerstones of physics: Lorentz symmetry, quantum mechanics, and gravity. The Standard-Model Extension (SME) governs a large set of the emerging effects relevant for low-energy antimatter experiments (for a recent review see [1]).

Access to low energy antiprotons ($\overline{p}$) offers excellent and unique opportunities to study the properties of fundamental forces and of symmetries in nature. Experiments with $\overline{p}$ can substantially contribute to our knowledge of atomic, nuclear and particle physics, in a complementary way to that to be acquired at the highest energy accelerators such as LHC. In particular, searches for new interactions, i.e. SME, can be carried out by studying discrete symmetries such as CPT, and furthermore, known interactions can be precisely tested and fundamental constants can be extracted from accurate measurements on free $\overline{p}$ and on bound two- and three-body systems such as antihydrogen ($\overline{\mathrm{H}} = \overline{p}e^+$), the antiprotonic helium ion $(\mathrm{He}^{++}\overline{p})^+$ and the antiprotonic atomcule $(\mathrm{He}^{++}\overline{p}e^-)$.

The prospect of performing spectroscopic investigations of antihydrogen, $\overline{\mathrm{H}}$, opens the possibility for clean Planck-reach CPT tests [2]. Since CPT invariance is essentially a consequence of Lorentz symmetry and quantum mechanics, $\overline{\mathrm{H}}$ spectroscopy probes these two important foundations of physics at interesting sensitivity levels [3]. Second, $\overline{\mathrm{H}}$ is particularly well suited to determine the gravitational interaction of antimatter [4], which has never been adequately measured before. Since cold $\overline{\mathrm{H}}$ production is currently only practical at the AD, this facility is uniquely positioned for essential experimental research at the interface of the aforementioned three cornerstones of physics.

The trapping of a single $\overline{p}$ in a Penning trap, the formation and precise studies of antiprotonic helium ions and atoms [5] and recently the production of $\overline{\mathrm{H}}$ [6] have been among the pioneering experiments, which demonstrated the power of low energy $\overline{p}$ physics. They have led already to precise values for $\overline{p}$ parameters, accurate tests of bound two- and three-body Quantum Electrodynamics (QED), tests of the CPT theorem and a better understanding of atom formation from their constituents. They also contribute significantly already at this early stage to the NIST adjustment of fundamental constants [7].

The experimental program towards laser and microwave spectroscopy of $\overline{\mathrm{H}}$ is progressing remarkably well, if compared to exotic atom spectroscopy in other systems. Future experiments promise more precise tests of the Standard Theory and have a robust potential to discover New Physics, in areas which cannot be accessed with similar accuracy by other means. The central issue in precision physics is the control over systematic effects. That requires besides care and the necessary time to develop novel instruments and methods also adequate statistics in order to measure systematic effects with the appropriate care and accuracy. Precision experiments with low energy $\overline{p}$'s share therefore the need for intense particle sources and the need for time to develop novel instrumentation with all other experiments, which aim for high precision in exotic fundamental systems. There is no lack of ideas. The over-subscription of the AD program is the best indicator for the demand.

The experimental programs - carried out in the past mostly at the former LEAR facility and at present at the AD facility at CERN - will not only benefit from intense future sources of low energy $\overline{p}$'s. They are urgently needed for speedy progress. The highest possible $\overline{p}$ fluxes should not only be aimed for in the long run at new facilities such as the planned FLAIR facility at GSI [8]. In order to maximize the potential of delicate precision experiments to enhance our understanding of the basic forces in nature and to influence theoretical model building, the ELENA facility [9] is urgently needed. Examples of key $\overline{p}$ experiments have been discussed at this workshop and compared with other experiments in the field. Among the central issues is their potential to obtain important information on basic symmetries such as CPT. $\overline{\mathrm{H}}$ gravity experiments will be the only ones for the foreseeable future to gain crucial insights into antiparticle gravitation. Further a potential exists to learn about nuclear neutron distributions in $\overline{p}$ annihilation experiments. Other data needed for a number of experiments and upcoming facilities can be additionally gathered at a facility for $\overline{p}$'s at CERN with the highest possible $\overline{p}$ flux. Therefore ELENA is the way to go to maintain and boost a well motivated and challenging physics program with high visibility in science and in public.

2 Future of existing experiments

At present, four experiments take data at the CERN AD. The three experiments which are the heaviest users of beam time are alphabetically ALPHA, ASACUSA and ATRAP. The ACE experiment addresses the issue of $\overline{p}$ in cancer therapy.

The initial goal of ALPHA is to trap $\overline{\mathrm{H}}$ atoms in a neutral magnetic trap so that they can be studied in detail. The long term goal is the spectroscopic comparison of H and $\overline{\mathrm{H}}$. At present, ALPHA demonstrated the formation $\overline{\mathrm{H}}$ in a neutral trap [10] and will concentrate in the next two years on trapping $\overline{\mathrm{H}}$. In the next steps, the apparatus will have to be modified and expanded to perform a progression of increasingly precise microwave and laser spectroscopic measurements on $\overline{\mathrm{H}}$.

ASACUSA's precision spectroscopy of antiprotonic helium atoms tests CPT invariance (p vs $\overline{p}$ mass comparison) and contributes to the CODATA fundamental physical constants [7, 11]. In addition, ASACUSA has started to develop alternative methods to produce $\overline{\mathrm{H}}$ atoms in a "cusp trap" [12] or in a superconducting Paul trap [13]. With these, the $\overline{\mathrm{H}}$ ground-state hyperfine splitting will be measured. These precision experiments as well as other nuclear and atomic physics experiments which make use of ASACUSA's unique ultra low energy facility will benefit from ELENA's high-quality beam.

ATRAP continues to make good progress toward producing cold $\overline{\mathrm{H}}$ in a state that can be trapped [14]. Though the production of $\overline{\mathrm{H}}$ within the fields of a Penning-Ioffe trap has been demonstrated, no trapped atoms have yet been detected, presumably because the atoms formed are yet too energetic to be trapped. The latest substantial step towards atom trapping is in obtaining what seems to be 1.2 K plasmas of electrons and positrons from which it should be possible to obtain much colder $\overline{\mathrm{H}}$ atoms than has previously been possible. A new Ioffe trap, under construction, promises to allow much more detection sensitivity for trapped $\overline{\mathrm{H}}$ atoms. A solid-state Lyman alpha source is starting to produce some of the laser light that we will need to cool $\overline{\mathrm{H}}$ atoms and to perform sensitive laser spectroscopy.

The ACE experiment [15] has not been represented at this workshop, yet the importance of studies that may contribute to cancer therapy taking into account the higher efficiency of radiation with $\overline{p}$ at a CERN facility cannot be stressed enough.

Much has been accomplished but much remains before the goals for which the AD was built are realized – the precise comparison of the properties of $\overline{\mathrm{H}}$ and H atoms. Since for most experiments, the learning curve depends crucially on the number of delivered $\overline{p}$'s, they would all applaud an upgrade of the AD.

3 New experiments

The main goal of the proposed and recently approved AEGIS experiment [16] is the first ever measurement of the gravitational interaction of $\overline{\mathrm{H}}$ to 1%. This requires developing new techniques to form a cold beam of $\overline{\mathrm{H}}$, which will also allow in-flight spectroscopy of $\overline{\mathrm{H}}$. The R&D is part of the experiment; a number of techniques requiring most or all of the final apparatus will be validated: formation of positronium in $E \times B$-fields from a nano-structured target, laser excitation of positronium in $E \times B$-fields, formation of Rydberg $\overline{\mathrm{H}}$ and acceleration of Rydberg $\overline{\mathrm{H}}$. Parallel R&D is being carried out with the goal of improving the efficiency of the experiment (laser-cooling of negative Os ions to obtain colder $\overline{p}$'s, simulations of field-manipulating Rydberg positronium). Investment costs will be most significant during the years of construction of the apparatus (2010-2012).

The physics program extends well beyond the foreseen extension of the AD to 2016, and would greatly benefit from the greater availability of $\overline{p}$'s that ELENA would allow.

In addition, new ideas have been presented at this workshop.

- "A measurement of the acceleration of $\overline{\mathrm{H}}$ atoms in the gravity field of the Earth using $\overline{\mathrm{H}}^{+}$ ions".
  The aim of the experiment using $\overline{\mathrm{H}}^{+}$-ions [17] is to measure the acceleration of ultra slow neutral $\overline{\mathrm{H}}$ atoms in the Earth gravitational field. The production involves the charge exchange process $\overline{p} + \mathrm{Ps} \rightarrow \overline{\mathrm{H}} + e^{-}$, followed by $\overline{\mathrm{H}} + \mathrm{Ps} \rightarrow \overline{\mathrm{H}}^{+} + e^{-}$. The excess positron is then photo-detached in order to recover a neutral and slow $\overline{\mathrm{H}}$ (μK temperatures). The R&D is in progress on high density positronium formation and e^{+} production, as well as positronium excitation and e^{+} trapping (2011). Antiproton trapping, based on ASACUSA experience, should be improved. Ion sympathetic cooling and photo-detachment R&D should be launched as soon as possible with $\overline{p}$'s. Matter counterpart of some of the above reactions could be measured by 2012. An electron linac should be installed at the AD aroub this time to produce an intense slow e^{+} flux. The free fall measurement could be completed in 2014.

- "Measurement of the spin-dependence of the $p\overline{p}$ interactions at the AD-ring".
  The idea is to use an internal polarized H storage-cell gas-target in the AD-ring to determine for the first time the two total, spin-dependent, $p\overline{p}$ cross sections, σ_1 and σ_2 at $\overline{p}$ beam energies in the range from 50 to 450 MeV. A Technical Proposal will be submitted at the beginning of April to the SPS committee at CERN.

- "Double-strangeness production with $\overline{p}$'s at the AD-ring".
  The physics goal of the experiment is the study of double-strangeness production with stopped $\overline{p}$'s and to search for $\overline{K}$-mediated deeply bound nuclear clusters that contain two $\overline{K}$'s, like $K^{-}K^{-}pnn$. The possibility of their existence is a hot topic in the further understanding of kaon nucleon/nuclei reactions and for the study of chiral restoration in a nuclear medium [18]. A 4π detector is needed consisting of a magnetic spectrometer for the identification of charged particles and a calorimeter for the detection of neutral decay products. The central detector is a time projection chamber with GEM readout, which is currently being developed within a Joint Research Activity in the FP7 project "HadronPhysics2". A fully operational prototype

will be built within this project till middle of 2011. A collaboration will be formed, capable of building the detector and target system, within the next 6 months. In parallel funding has to be secured. It is planned to build and test the setup within the next three years, so that it could be installed at the AD, earliest in the 2012/2013 shutdown. An operation for 3 years with one month per year is foreseen for the initial program at the AD. More detailed studies are planned at FLAIR after successful studies at the AD.

- "Antiprotonic atom X-ray studies at AD from selected elements with low Z."
  The study of light antiprotonic atoms gives access to various phenomena both of strong interaction and cascade effects originating from the interplay of the electron shells with the $\overline{p}$ during the de-excitation cascade occurring after capture [19].

4 Overview of low-energy $\overline{p}$ facilities

The AD facility at CERN is unique – at present, no low-energy $\overline{p}$ facilities other than the AD exist. The next facility to possibly come on line is FLAIR, at the earliest in 2016 and more realistically in 2018 (finances have not yet been approved and political support is still required). FLAIR will provide a 1000-fold increase of trapped $\overline{p}$'s over the AD and a 10-fold increase of trapped $\overline{p}$'s over the AD+ELENA, as well as significantly more floor space for experiments. Current progress in the experiments at the AD towards trapping of $\overline{\mathrm{H}}$ is limited by the availability of $\overline{p}$'s, and reaching the physics goals of the current round of experiments would be greatly facilitated by the ELENA low-energy decelerator.

The formation of $\overline{\mathrm{H}}$ typically requires a large number of $\overline{p}$'s at high densities which cannot be achieved at the present $\overline{\mathrm{H}}$ experiments with a single AD bunch. Stacking techniques are used to increase the number of trapped $\overline{p}$'s. The efficiency of the experiments would be hugely improved and the productivity and the availability of the unique user facility AD at CERN with its great scientific potential would be greatly enhanced if a further deceleration and cooling storage ring would be installed between the AD and the experiments. Such a ring could be the suggested ELENA ring [9]. It is envisaged that ELENA will increase the phase space density at 100 keV by one to two orders of magnitude, depending whether the experiments are already using the RFQD or not, respectively. This would raise the efficiency of the $\overline{p}/\overline{\mathrm{H}}$ program at CERN by a very large factor. The construction of a rather small machine for this purpose is feasible. The main challenges for such a project of deceleration to very low energies, such as ultra low vacuum and effective electron cooling, can be managed. The proposed ELENA ring can be located inside the AD hall without large modifications. All installation work for ELENA can be done without significant influence on the AD operation for physics, but for commissioning some extra time would have to be scheduled. The experience gained at existing low-energy storage rings such as AD (CERN), ASTRID (Aarhus), TSR (Heidelberg), and CRYRING (Stockholm) can be exploited in the design and construction of ELENA.

5 Summary

CERN not only leads the world in "high energy" physics. It has long also distinguished itself by pursuing fundamental particle physics at lower energy scales when the laboratory possesses the unique capability to do so. CERN introduced the world's lowest energy $\overline{p}$'s at 5 MeV. Experimenters at LEAR and then the AD introduced particle traps to lower the energy by up to an additional ten orders of magnitude in energy, making it possible to compare q/m for the $\overline{p}$ and p at the 9 parts in 10^{10} level. Now, $\overline{\mathrm{H}}$ is being formed by two different methods at the AD. The expectation is that $\overline{\mathrm{H}}$ spectroscopy will provide comparisons of $\overline{\mathrm{H}}$ and H at much higher precision. Formation of beams of $\overline{\mathrm{H}}$ in the ground state is an alternative approach to trapping and also allows to study the gravitational properties of $\overline{\mathrm{H}}$. The newly proposed experiments would further reduce the availability of $\overline{p}$'s. An upgraded AD, able to deliver many more $\overline{p}$'s at lower energies to experiments, would speed the progress.

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Appendix 2:

ELENA - a Preliminary Cost and Feasibility Study

M.-E. Angoletta, M. Barnes, A. Beuret, P. Belochitskii, J. Borburgh,
P. Bourquin, M. Buzio, D. Cornuet, T. Eriksson, T. Fowler, M. Hori,
E. Mahner, S. Maury, D. Möhl, J. Monteiro, S. Pasinelli, F. Pedersen,
U. Raich, L. Soby, P. Strubin, G. Tranquille, and T. Zickler.

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN — A&B DEPARTMENT

CERN-AB-2007-079 OP

ELENA – a preliminary cost and feasibility study

M.-E.Angoletta, M.Barnes, A.Beuret, P.Belochitskii, J.Borburgh, P.Bourquin, M.Buzio, D.Cornuet, *T.Eriksson*, T.Fowler, M.Hori, E.Mahner, S.Maury, D.Mohl, J.Monteiro, S.Pasinelli, F.Pedersen, U.Raich, L.Soby, P.Strubin, G.Tranquille, T.Zickler

CERN, Geneva, Switzerland

Abstract

To produce dense pbar beams at very low energies (100-200 keV), a small decelerator ring could be built and installed between the existing AD ring and the experimental area. Phase-space blowup during deceleration would be compensated by electron cooling in order to obtain final emittances comparable to the 5MeV beam presently delivered by the AD.

This report describes preliminary machine parameters and layout of ELENA and also gives an approximate estimate of cost and manpower needs.

Geneva, Switzerland
December, 2007

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1. Introduction

ELENA (Extra Low ENergy Antiprotons) is a compact ring for further deceleration and cooling of 5.3 MeV pbars delivered by the CERN Antiproton Decelerator. The AD physics program is focused on trapping pbars in Penning traps where antihydrogen is formed after recombination with positrons. The ultimate goal is to trap and perform spectroscopy on Hbars. In today's set-up, most (99.9%) of the pbars produced are lost by the use of degrader foils to decelerate from AD ejection energy down to around 5 keV, which is suitable for trapping.

By using a ring equipped with beam cooling, high deceleration efficiency and important increases in phase-space density can be obtained, resulting in an increased number of trapped antiprotons. For the ATRAP and ALPHA experiments, improvements of 2 orders of magnitude can be expected. ASACUSA on the other hand presently use first an RFQD for deceleration to 100 keV, and then additionally an ultra-thin degrader (1 micron thick) for deceleration to 5 keV. Here, a 10-fold increase can be expected thanks to reduced transverse and longitudinal emittances.

With a circumference of about 26m, ELENA can be located in the AD hall where assembly and commissioning would not disturb current AD operation too much.

Decelerating to these low energies is certainly new and challenging, not the least for the design of the electron cooler with electron beam energy of just 200 eV.

2. ELENA overview

ELENA is to be located inside of AD Hall with a circumference as small as possible to minimize space requirements and to reduce intensity limitations due to space-charge induced tune shift. The new ring is located so that current AD operation during assembly and commissioning will be disturbed as little as possible.

AD experimental areas could be kept as they are now. But much lower beam energies require new transfer line elements and diagnostics.

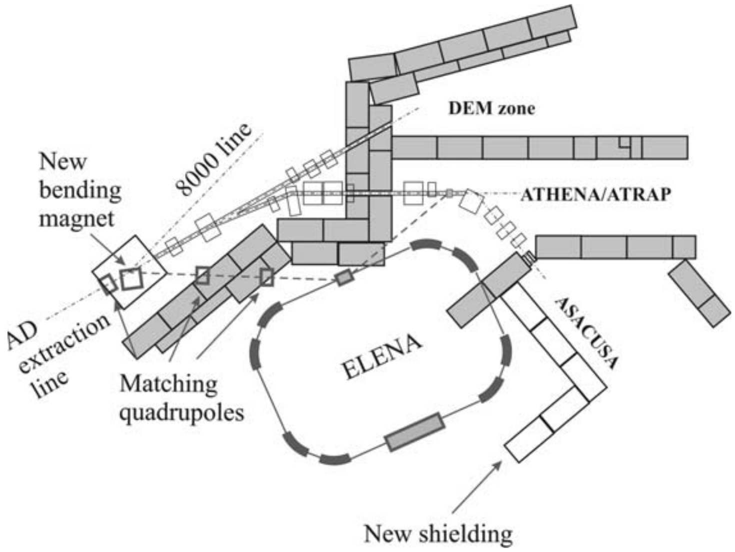


Fig.1. **ELENA placement versus existing AD beam lines.**

Ring configuration:

- Simple lattice with 8 dipoles and 8 multipoles
- One long straight section is used for beam injection and fast extraction, another is suitable for the electron cooler
- Two short straight sections are used for RF, diagnostics and other equipment

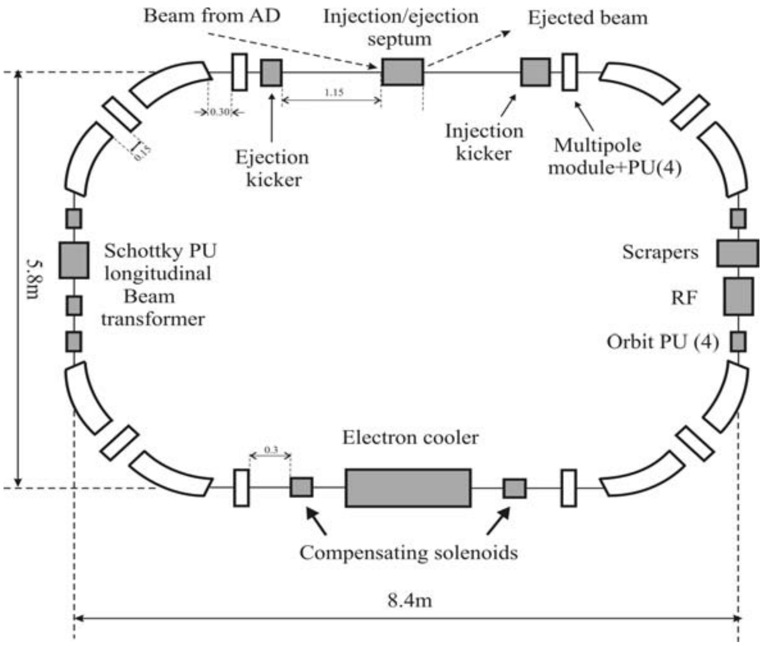


Fig.2. **ELENA layout**

Momentum, MeV/c	100 – 13.7
Energy, MeV	5.3 – 0.1
Circumference, m	26.062
Betatron tunes Qx/Qy	1.45/1.42
Emittances at 100 keV, π.mm.mrad, [4σ, 95%]	5 / 5
Δp/p after cooling, [4σ, 95%]	10^{-4}
Estimated Δp/p of ejected beam taking IBS into account,[4σ, 95%]	$2*10^{-3}$
Intensity limitation by space charge, bunched/coasting beam	$1.1*10^{7} / 2.2*10^{8}$
Maximal incoherent tune shift	0.10
Bunch length at 100 keV, m / ns	1.3 / 300
Expected cooling time at 100 keV, sec	1
Required vacuum* for Δε=0.5π mm mrad/s,Torr	$3*10^{-12}$
IBS blow up times for bunched beam* (εx,y=5π mm mrad, Δp/p=1 10-3), s	1.1 / -9.1 / 0.85
* No electron cooling is assumed	

Table 1. **ELENA basic parameters**

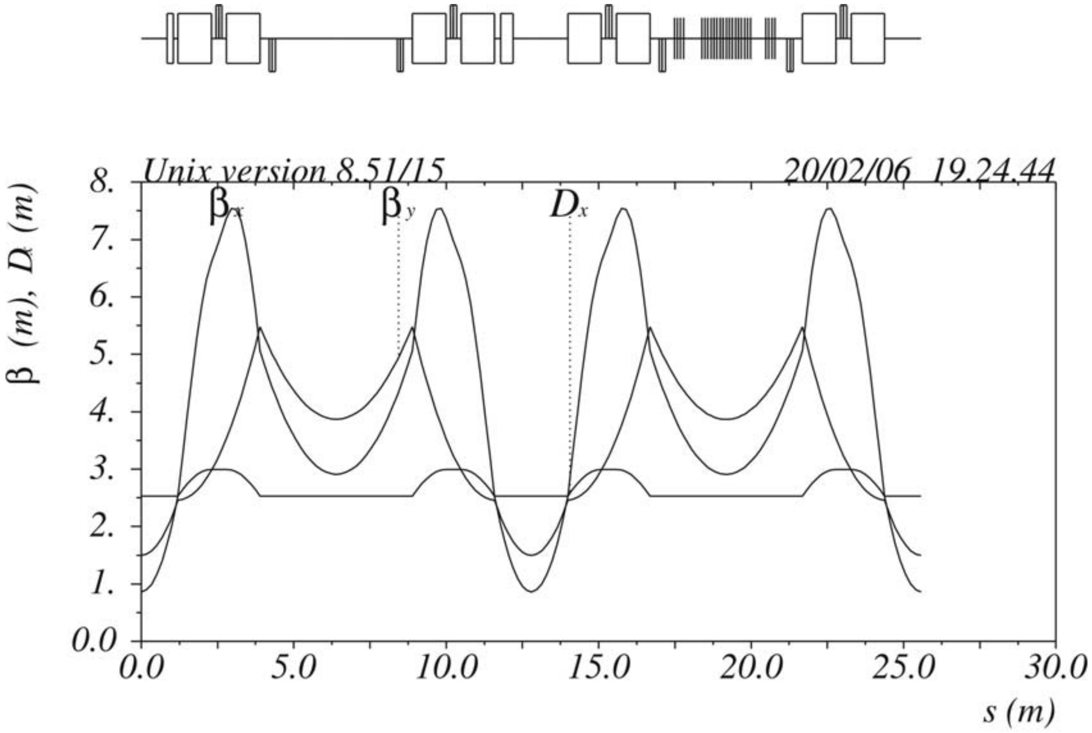


Fig.3. **Fig.3. ELENA lattice functions (electron cooler off)**

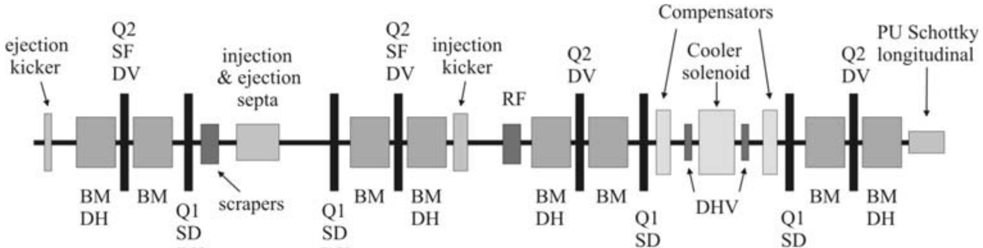


Fig.4. **Fig.4. Schematic layout of ELENA magnetic elements**

3. Ring and injection line magnets

The ring magnet system of ELENA consists of C-shaped bending magnets, quadrupoles and correcting elements. The parameters for bending magnets (totally 8 identical units) are given below in [Table 2]. A schematic representation of the edge-angle focussing is seen in [Fig. 5] Normal quadrupoles, skew quadrupoles for coupling correction, sextupoles for chromaticity correction and horizontal and vertical orbit correctors are integrated in one module [Fig. 6]. Basic parameters are given in [Table 3]. 8 of these modules will be used in the ELENA ring.

The transfer line from the existing AD will start at the BHZ8000 location with a new smaller bending magnet replacing the large BHZ8000. Furthermore, 3 quadrupoles for matching and 2 combined H/V correctors are required. See [Table 4] for parameters.

ELENA main bending magnet specifications	
Magnet field	0.23 T
Gap height	75.0 mm
Iron length	1017 mm
Effective length	1100 mm
SBdl	0.25 Tm
Momentum	100 MeV/c
B r	0.33 Tm
Deflection angle	45.0 degrees
Good field region	± 31 mm
Field homogeneity in GFR	< 0.08 %
Nominal current	192 A
Max. dI/dT	200 A/s
Magnet resistance (hot)	67.5 mOhm
Max. dissipated power	2.5 kW
Inductance	21.9 mH
Max. total voltage	17.3 V
Edge angle, degrees	0/24.1

Table 2. Ring bending magnet parameters

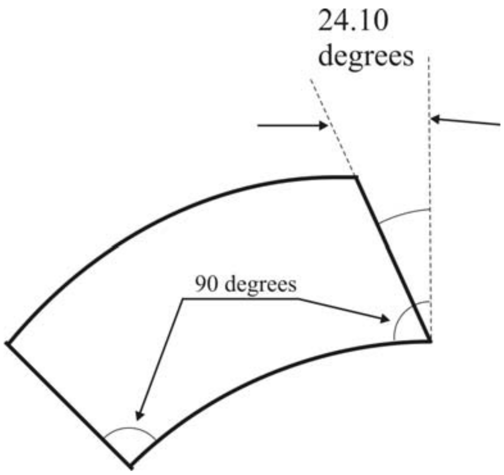
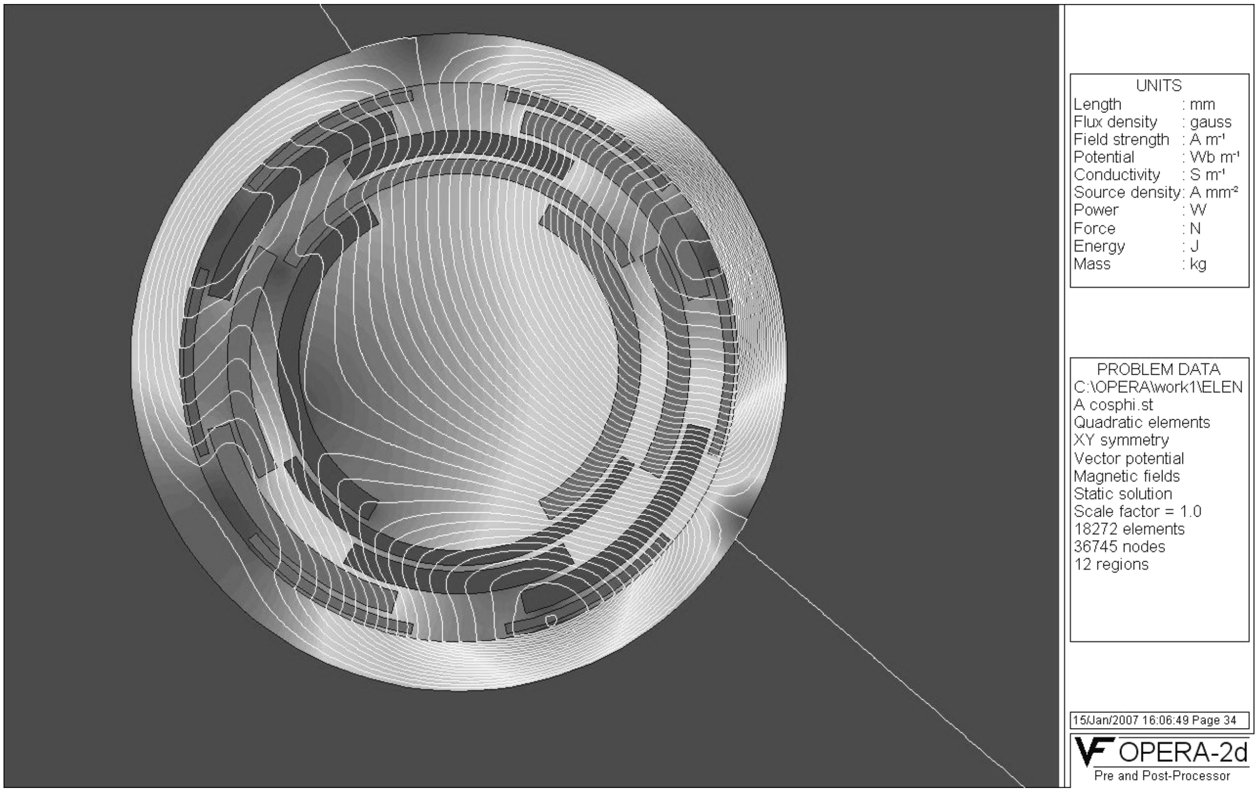


Fig.5. ELENA main bending magnet basic layout.

Number of magnets (+ spares)	8 + 1	
Magnet characteristics		
Horizontal dipole module		
Magnetic field	16.44	mT
Integrated field	4.54	mT m
Magnetic length	276.0	mm
Nominal current	37.0	A
Resistance	51.7	mOhm
Inductance	1.4	mH
Nominal voltage	1.9	V
Dissipated power	70.8	W
Vertical dipole module		
Magnetic field	12.37	mT
Integrated field	3.12	mT m
Magnetic length	252.0	mm
Nominal current	25.0	A
Resistance	90.2	mOhm
Inductance	2.2	mH
Nominal voltage	2.3	V
Dissipated power	56.4	W
Normal quadrupole module		
Gradient	191.38	mT / m
Integrated gradient	62.01	mT m / m
Magnetic length	324.0	mm
Nominal current	38.0	A
Resistance	68.3	mOhm
Inductance	1.2	mH
Nominal voltage	2.6	V
Dissipated power	98.7	W
Skew quadrupole module		
Gradient	200.91	mT / m
Integrated gradient	62.68	mT m / m
Magnetic length	312.0	mm
Nominal current	38.0	A
Resistance	77.2	mOhm
Inductance	1.2	mH
Nominal voltage	2.9	V
Dissipated power	111.4	W
Sextupole module		
Sextupole gradient	1.50	T / m^2
Integrated sextupole gradient	0.51	T m / m^2
Magnetic length	339.0	mm
Nominal current	11.0	A
Resistance	359.6	mOhm
Inductance	3.1	mH
Nominal voltage	4.0	V
Dissipated power	43.5	W
Dimensions		
Aperture diameter	128	mm
Total magnet weight	96	kg
Total magnet length	420	mm
Iron core outer diamater	267	mm

Table 3. Ring multipole magnet parameters



UNITS
Length : mm
Flux density : gauss
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg

PROBLEM DATA
C:\OPERA\work1\ELEN
A cosphi.st
Quadratic elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Scale factor = 1.0
18272 elements
36745 nodes
12 regions

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Fig.6. **Ring multipole schematic layout**

Injection line bending magnet	
Magnet field	0.28 T
Gap height	100.0 mm
Iron length	800.0 mm
Effective length	910.0 mm
SBdl	0.25 Tm
Momentum	100 MeV/c
B r	0.33 Tm
Deflection angle	45.0 degrees
Good field region	± 75 mm
Field homogeneity in GFR	< 0.3 %
Nominal current	175 A
Max. dI/dT	100 A/s
Magnet resistance	99.6 mOhm
Max. dissipated power	3.1 kW
Inductance	63.4 mH
Max. total voltage	23.8 V
Injection line Quadrupoles	laminated, air cooled
Gradient	0.8 T/m
Aperture radius	60.0 mm
Iron length	300.0 mm
Effective length	348.0 mm
SGdl	0.29 Tm/m
Momentum	100 MeV/c
Quadrupole strength k	2.49 m-2
Focal length	1.21 m
Good field region radius	48 mm
Field quality in GFR	< 0.01 %
Nominal current	20 A
Max. dI/dT	10.0 A/s
Magnet resistance (warm)	191.7 mOhm
Max. dissipated power (dc)	76.7 W
Inductance	45.7 mH
Max. total voltage	4.3 V
Injection line H/V corrector	
Magnet field	15.0 mT
Free aperture	150.0 mm
Iron length	200.0 mm
Effective length	353.6 mm
SBdl	5.3 mTm
Momentum	100 MeV/c
B r	0.33 Tm
Deflection angle	16 mrad
Good field region (% of free aperture)	80 %
Field homogeneity in GFR	< 8 %
Electrical parameters	per plane = 2 coils in series
Nominal current	10 A
dI/dT	10 A/s
Magnet resistance	471.5 mOhm
Max. dissipated power	47.2 W
Inductance	46.0 mH
Max. total voltage	5.2 V

Table 4. Injection line magnet parameters

Resource Estimate Summary

Ring + injection line magnets	Material (kCHF)	Manpower FSU(kCHF)	Manpower FTE (MY)
Main Ring Bending Magnets (8 + 2 spares)	350		
Main Ring Combined Correctors (8 + 1)	200		
Electron Cooler Compensation Solenoids (2 + 1)	33		
Injection Line Bending Magnets (1 + 1)	80		
Injection Line Quadrupoles (3 + 1)	60		
Injection Line Correctors (2 + 1)	27		
Supports	50		
Electric and hydraulic connections	50		
Specification drawings		(64)*	
Contract follow-up		48	
Test and preparation		18	
Installation (incl. transport)		9	
Commissioning		9	
Survey	35		0.2
Engineer			0.8
Tech. engineer			1.3
Technician			0.9
Magnetic measurements		75	
Total	885	160	3.2

(*) Accounted for in design and drawings chapter

Table 5. Magnet resources

4. Power converters/cabling

The magnet data's and requirements are recapitulated in table 6. Considering the relatively low power needed, all converters are rated for DC performance. The current overall precision considered is $\pm 10^{-4}$ of the maximum current of the converter.

Circuit name	**Magnet**					**Load**	**Proposed converter ratings**			
	Nb of	R (mΩ)	L (mH)	In (A)	di/dt (A/s)	Voltage (V)	Current (A)	Voltage (V)	Power (kW)	Qty
Ring										
Main bending	8	71.7	26.8	182	200	154	200	200	40	1
Trim bend *	1	71.7	26.8	3	3	7	10	20	0.2	4
Multipole corr.*	1	*50*	*25*	100	100	16	100	20	2	22
Injection line										
Bending	1	99.6	63.4	175	100	33	200	50	10	1
H/V corr.*	1	472	46	10	10	9	10	20	0.2	4
Quad	1	192	45.7	20	20	13	20	20	0.4	3
e-cooler										
Solenoid	1			200	200	47	200	50	10	2
Compensator	1			200	200	47	200	50	10	2
HV	1			0.1		1000	0.1	1000	0.1	1
Corr. Coil*	1			10	10	24	10	50	0.5	10
H/V Corr.*	1			10	10	24	10	50	0.5	2
Septum										
Injection	1	6.7	0.4	991	1000	13	1000	20	20	1
Extraction	1	6.7	0.4	248	250	11	250	20	5	1

Table 6. Power converter requirements

The proposed power converter ratings and quantities are deduced from magnet parameters and DC cable voltage drop. Standardisation on existing CERN or commercial product is also taken into account. All corrector and trim (marked by*) require the 4 quadrants behaviour. The various types of converters are recapitulated in table 7 with their estimated prices. One spare converter is taken into account for type 2, 4 and 5.

Converter type	Current (A)	Voltage (V)	Power (kW)	Qty	Price (kCHF)	
					unit	total
1	200	200	40	1	70	70
2	250	50	12.5	7	20	140
3	1000	20	20	1	60	60
4	20	50	1	24	5	120
5	100	20	2	23	9	207
6	0.1	1000	0.1	1	5	5
					Total	**602**

Table 7. Power converters summary and cost

Remote control

The converter shall be controlled either by existing Mil 1553 , RS 422 or the foreseen new control system. The system shall provide the control command and status, the function generator (analogue and digital) and the acquisition over the full machine cycle.

The remote control costs are not taken into account in our estimate.

Installation

The power converter installation is foreseen in building 193; in place of the AD return loop power converters which have been dismantled in 2005. The converter type 1 and 3 shall occupy each a space of 2 racks. The rest of the converter shall be installed in 12 individual racks. This results in a cost of 15 kCHF.

AC cabling

The ac supply of the converter system shall be feed from the existing distribution panel whose feeders have been free from the AD return Loop. The need is 2 line of 16 A per racks, over a distance of ~ 20 m.

The estimated price per ac cable is 200 CHF, on which 50 CHF is to be added for the connections. The estimated ac cabling cost is then 250 CHF per 16 A ac feed. Making a total cost for the ac cabling of 6 kCHF for the 12 racks. Two line of 125 A have to be added for converter type 1 and 3 which will bring the total for the ac cabling to 8 kCHF.

TS/EL is responsible for this item, and shall be submitted for approval.

DC cabling

The estimated cable length between the equipment building 193 and the ELENA ring is estimated at 120 m. The cost of dc cabling is recapitulated in table 8. It should be noted that the cabling cost for the converters of type 5 (100 A) is almost a factor four higher then for type 3 (20A). Considering the cable cost saving, we would strongly recommend designing corrector magnets with lower current and higher voltage then the contrary.

Converter type	Current (A)	Qty	Cable			total cost (kCHF)
			type	cost/m	ends	
1	200	1	2 x 150	40	40	4.84
2	250	6	2 x 150	40	40	29.04
3	1000	1	6 x 240	180	360	21.96
4	20	23	2 x 10	7	30	20.01
5	100	22	2 x 70	30	30	79.86
6	0.1	1	2 x 10	7	30	0.87
Total DC cabling						156.58

Table 8. dc cabling cost

Interlocks

TS/EL responsible for this item, propose 60 kCHF for this item, which represent ~1 kCHF per magnet. A complement of 5 kCHF for cable trays extension shall be taken into account. Alternative solution using PLC will be considered at a later stage.

Resource Estimate Summary

The estimated costs and resources for the project are:

Power converters, ring + inj.line	Material (kCHF)	Manpower FTE (MY)
Power converter including installation	617	1
Cabling ac dc and magnet interlocks	240	0.5
Total	857	1.5

Table 9. Power converter resources

The power converter group is in charge of the power converter and their installation in the building.

All cabling ac, dc, interlocks is the responsibility of TS/EL. The proposed solutions and estimates including 10 kCHF for unforeseen have been approved by TS/EL

Connections to the remote control system are not included.

5. Injection/ejection septa

Layout

This resource estimate is based on the layout sketched in Fig. 7. Space shall be reserved for Ø50 mm incoming and extracted beam chambers. Space shall also be reserved for a Ø100 mm orbiting beam chamber. The physical injected beam size assumed was Ø28 mm, while for the extracted beam Ø26 mm was used. The incoming beam shall be at 21º with respect to the straight section, while the extracted beam shall be at 30º with respect to the straight section.

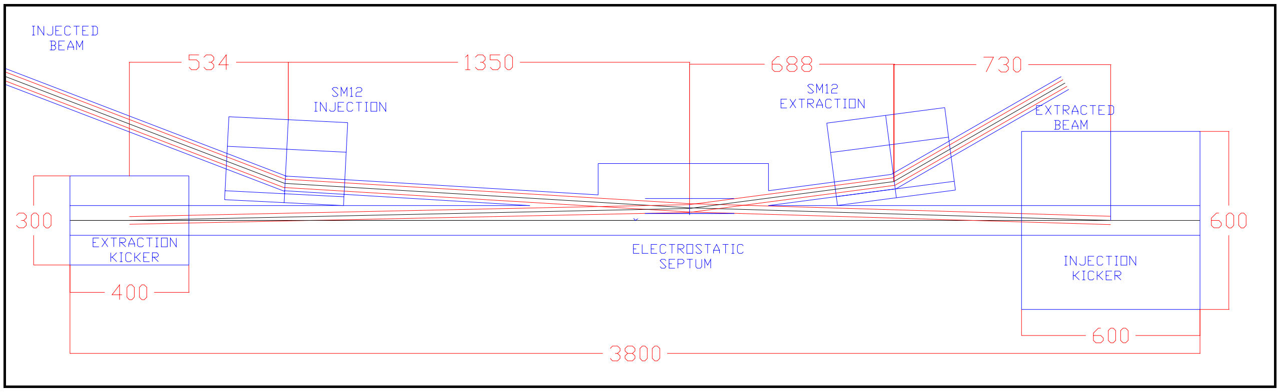


Fig.7. **Layout of the injection and extraction area (all dimensions indicated are physical lengths)**

The beam is first deflected by a magnetic DC septum recovered from LEAR, previously called SM12. Subsequently the beam is further deflected by an electrostatic septum before entering the injection kicker. The electrostatic septum shall be purpose designed and built for this specific application. The extracted beam is first deflected by the extraction kicker to enter the gap of the electrostatic septum. The voltage applied to this septum shall be adjustable and dependant on the extraction energy of the beam. Subsequently the beam passes through a second magnetic DC septum identical to the magnetic injection septum (previously, the SM12 spare septum for LEAR). Table 10 summarises the principal parameters for the magnetic septa, while Table 11 summarises the parameters for the electrostatic septa, both for injection and extraction.

SEPTA

Magnetic Septa

The magnets and coils already exist at CERN and can be installed in the injection and extraction lines to and from ELENA. No spare coil is foreseen to be built, taking into consideration the fact that the magnets will operate at less than half of their design current. New mechanical supports need to be designed and constructed for the magnets and the vacuum chambers. Removal of the magnets is foreseen to allow the vacuum chambers to be baked out. Purpose built electrical bus bars and new demineralised water manifolds need to be designed, manufactured and installed. A dedicated interlock system (PLC based) will also be required. To note that the supply of the power converters and the design and supply of the vacuum chambers is not considered to be under the responsibility of the BT group.

Magnetic septa	Injection septum	Extraction septum	
Deflection angle	303	392	mrad
Beam momentum	100	13.7 (19.4)	MeV/c
Beam energy	5.3	0.100 (0.200)	MeV
Integrated magnetic field (∫B.dl)	0.101	0.018 (0.025)	T.m
Gap field	0.337	0.060 (0.084)	T
Gap height	74		mm
Gap width between conductors	135		mm
Magnet length (physical)	400		mm
Magnetic equivalent length	300		mm
Septum conductor thickness	22.8		mm
Number of conductor turns	20		
Current (DC.)	991	176 (248)	A
Magnet inductance	400		μH
Magnet resistance	6.7		mΩ
Demineralised cooling water requirement			l/min.

Table 10. **Technical specifications of the magnetic septa (between brackets the alternative extraction energy values)**

Electrostatic Septum

The electrostatic septum shall form an integral part of the ELENA ring itself. The purpose built electrostatic septum will have to be designed from scratch. It will use a titanium plate (1 mm thickness) as septum, since the device will be operated with a positive voltage on the electrode because of the antiprotons. No remote displacement system will be foreseen for the septum or for the electrode, thus minimising cost and complexity. The septum shall be designed and constructed to cope with the extremely severe vacuum requirements of ELENA. The vacuum vessel will be equipped with ion pumps, titanium sublimators and NEG coated surfaces. It will be bakeable at 300ºC to obtain a vacuum of 10^{-12} mbar. The device shall incorporate a dedicated mechanical support. No spare septum is foreseen to be built, since the time needed for a repair is of little influence on the down time of the machine, which will be dominated by the bake-out time in the case of an intervention. Only spare parts for long-lead items such as certain HV components will be manufactured. The power supply shall be procured from industry, and an interface shall be provided (PLC based) to take into account the septa interlocks. The device shall be capable of changing its operational mode from injection to extraction settings within 3 seconds.

Electrostatic septa	Injection settings	Extraction settings	
Beam momentum	100	13.7 (19.4)	MeV/c
Beam energy	5.3	0.100 (0.200)	MeV
Deflection provided by septum	30		mrad
Required electric field	1.272	0.088 (0.176)	MV/m
Gap between electrodes	50		mm
Nominal voltage	63.6	4.4 (8.8)	kV
Septum thickness (titanium)	1		mm
Septum length	0.300		m
Anode length (stainless steel)	0.250		m
Septum position w.r.t. orbiting beam axis	24		mm
Tank length	0.500		m

Table 11. **Technical specifications of the electrostatic septum (between brackets the alternative extraction energy values)**

Resource Estimate

The budget estimate is given in 2006 prices. For both magnetic septa the installation cost amounts to 50 kCHF (excluding the magnets which are already available at CERN) and 1.0 m.y. of manpower (see table 12). For the electrostatic septum the cost estimate is approximately 170 kCHF and 1.9 m.y. of manpower, including the control electronics. Items like design office and industrial support are included under the material cost.

Magnetic septa		
Mechanical supports	12	kCHF
Water battery	12	kCHF
Interlock system, PLC's	15	kCHF
Bus bar	5	kCHF
Cabling, installation	6	kCHF
Total for both magnetic septa	**50**	**kCHF**
Cat 2	0.1	m.y.
Cat 3	0.3 + 0.3	m.y.
Cat 4	0.3	m.y.
Total manpower	**1.0**	**m.y.**

Table 12. **Resource estimate for the Magnetic Septa (magnets not included)**

Electrostatic septum		
Mechanical support	5	kCHF
Vacuum vessel	25	kCHF
Vacuum components (VPI, Ti sublimator, NEG, heating jackets, gauges)	22	kCHF
HV components (feedthrough, HV deflectors, septum, anode, incl. Spares)	35	kCHF
Power supply	12	kCHF
Interlock system, PLC's	15	kCHF
Cabling	10	kCHF
Design office	46	kCHF
Total for electrostatic septum	**170**	kCHF
Cat 2	0.7	m.y.
Cat 3	0.4+0.4	m.y.
Cat 4	0.4	m.y.
Total manpower	**1.9**	**m.y.**

Table 13. **Resource estimate for the Electrostatic Septum**

Resource Estimate Summary

Injection/ejection septa	Material (kCHF)	Manpower FSU(kCHF)	Manpower FTE (MY)
2 magnetic septa	50*		1.0
Electrostatic septum	170		1.9
Total	220		2.9

(*) Foresees the use of existing magnets

Table 14. **Injection/ejection septa resources**

6. Injection/ejection Kickers

Proposed displacement of AD Kicker modules for ELENA implementation.

A part of the kicker platform which contains equipment for 4 kicker modules has to be relocated in order to make place for the ELENA ring. The smaller of the two blocks represent the PFN cable drums, whilst the larger represents the steel platform holding the HV switches and associated equipment. Rack space for the control electronics can be found by reconfiguring and re-cabling of adjacent kicker module racks.

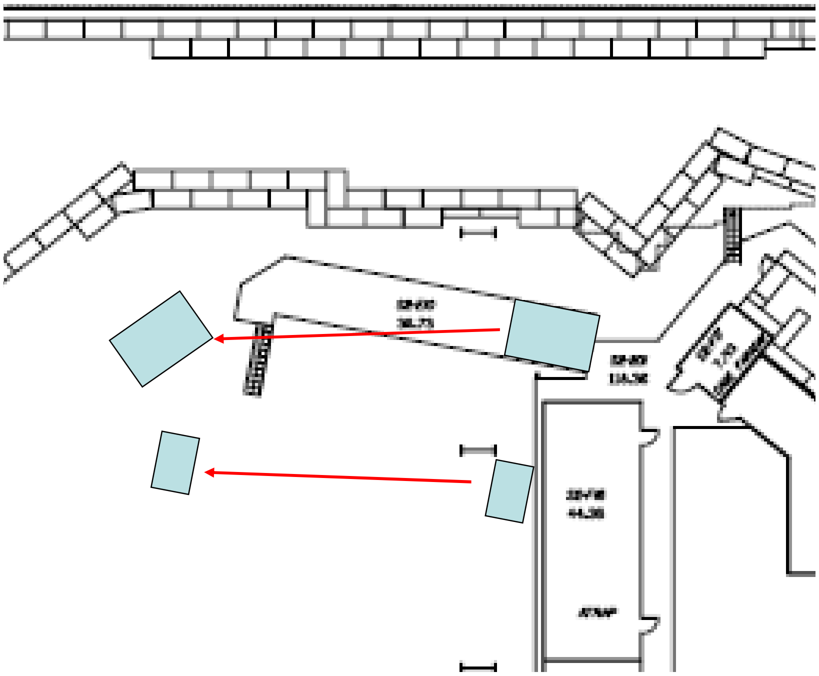


Fig.8. **Kicker PFN platform relocation**

Both kicker modules have to be fully bakeable. Basic parameters can be found in table 15.

Injection kicker	
Required angle @5.3 MeV, mrad	30
Magnetic length, mm	505
Magnetic strength, G•m	100
Max. rise/Fall time, ns	300
Flat top, ns	400
Good field region, h/v mm (=gap height/width)	50/50
Vacuum tube connectors	Flange for ¢ =100mm
Ejection kicker	
Required angle @200 keV, mrad	30
Magnetic length, mm	275
Magnetic strength, G•m	20
Max. rise/Fall time, ns	1000
Flat top, ns	400
Good field region, h/v mm (=gap height/width)	50/50
Vacuum tube connectors	Flange for ¢ =100mm

Table 15. **Kicker specifications**

Kicker system costs					
	Magnet & vacuum tanks	HV power supplies	Electronics	Fluids systems	Cost (kCHF)
Injection kicker	150	20*	150	30	330
Ejection kicker	85	150	100	15	350
Displacement of AD equipment	150				

(*) Foresees the re-use of spare AD equipment

Table 16. **Kicker costs**

Resource Estimate Summary

Injection/ejection kickers	Material (kCHF)	Manpower FSU(kCHF)	Manpower FTE (MY)
Total	830		4.8

Table 17. **Injection/ejection kicker resources**

7. Electron cooler

Electron Cooling for ELENA

Electron cooling will be essential in ELENA in order to obtain the small emittance antiproton beams needed for extraction to the trap experiments. Given the space available in the ring, the cooling section will occupy one of the 5m long straight sections of the machine. The cooler itself will take up almost half the available space and the rest of the section will accommodate the machine quadrupoles and the compensation solenoids of the cooler.

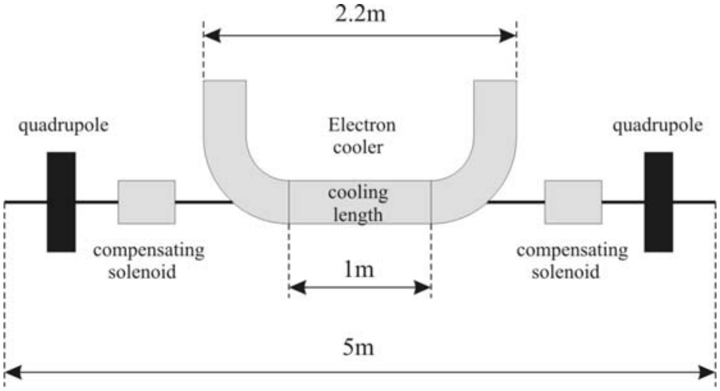


Fig.9. Electron cooler section

Cooling will be needed at two momenta during the ELENA deceleration cycle. At the intermediate momentum of 35 MeV/c the antiproton beam will need to be cooled in order to guarantee that it can be decelerated further to 14 MeV/c without any excessive blowup of the beam dimensions which could lead to beam loss. At 14 MeV/c the cooling will ensure that the phase-space characteristics of the extracted antiproton beam fit the requirements of the experiments. For fast and efficient cooling special attention must be paid to the design of the electron gun and the quality of the longitudinal magnetic field guiding the electrons form the gun to the collector. The main characteristics of the proposed device are summarized in table 17.

The electron gun must produce a cold ($T_\perp < 0.1$ eV, $T_\parallel < 1$meV) and relatively intense electron beam ($n_e \approx 3\mathrm{x}10^{12}$ cm^{-3}). The use of a photocathode cannot be considered as it is complicated to operate and has a short lifetime. Instead a conventional thermionic cathode will be used and the electrodes will be designed in such a way to minimise the transverse temperature after acceleration to the desired energy. The gun is immersed in a longitudinal field of 700 G which is adiabatically reduced to maximum field of 200 G in the transition between the gun solenoid and the toroid. In this manner the transverse temperature can be reduced further through adiabatic beam expansion. The lower field in the toroids and cooling section is also necessary to facilitate the compensation of the perturbations (closed orbit distortion and coupling) induced by the electron cooler. After the gun, the electrons are bent in a 90º toroid where they merge with the circulating antiprotons over a distance of 1m. At the exit of this cooling section, the electrons are bent away from the antiprotons by a second 90º toroid. The complete magnetic guiding system will consist of a series of small solenoid “pancakes” which can be individually adjusted. In this manner the transverse components of the longitudinal field are kept small ($B_\perp/B_\parallel < 10^{-4}$) ensuring a minimal perturbation to the electron beam transverse temperature. To improve the electron beam collection efficiency, the use of electrostatic bending plates in the toroids can also be envisaged. Their usefulness has been demonstrated on recent coolers and in a machine like ELENA, where the vacuum must be kept as low a possible, they will help to ensure that electron losses are kept to a minimum. The vacuum system will be the same as was used for the LEIR cooler, namely; NEG cartridges at the gun and collector where the gas load is the highest, NEG strips in the toroid chambers, and NEG coating of the vacuum chamber as well as ion pumps in the cooling section.

Momentum (MeV/c)	35	14
□	0.037	0.015
Electron beam energy (eV)	355	57
Electron current (mA)	15	2
Electron beam density (cm^{-3})	4.3×10^{12}	1.4×10^{12}
Bgun (G)	600	
Bcooling section (G)	150	
Expansion factor	4	
Cathode radius (mm)	12.7	
Electron beam radius (mm)	25.4	

Table 18. **Main characteristics of the ELENA cooler.**

The estimated cost of such a cooler is about 1.35MCHF (not including power supplies) over a 3 year period. The breakdown of the required resources over this period is summarised in the table below. 50 kCHF is estimated for controls equipment: VME crate + modules

	Year 1	Year 2	Year 3
Budget	200 kCHF	800 kCHF	350 kCHF
Manpower	0.5 Eng., 0.5 Tech.	1 Eng., 1 Tech.	1 Eng., 1 Tech., 1 Mech.

Table 19. **Breakdown of resources required for the ELENA cooler design, construction and commissioning.**

The cost for software development for cooler controls is not included in this estimate.

Resource Estimate Summary

Electron cooler	Material (kCHF)	Manpower FTE (MY)
Total	1350	6.5

Table 20. **Electron cooler resources**

8. Vacuum system

The ELENA ring will be fully bakeable (300 C) with NEG coated chambers. Ring average pressure should be around 1*E-12. Permanent bake-out equipment is installed in the magnets. Mobile mechanical pumping groups and mobile diagnostics (RGA) will be used.

Etude, prototypes, suivi	**Nombre**	**Prix unité (CHF)**	**Prix (kCHF)**
Bureau de dessin (heures) *	1’000	51	(51*)
Prototypes			80
Déplacements, visites usines	10	5’000	50
		Total étude, prototypes, suivi:	**130**

Arc (4 cellules de 2 dipoles + 1 multipole)	**Nombre**	**Prix unité (CHF)**	**Prix (kCHF)**
Chambres dipole (“vacuum fired & NEG coated”)	8	5000	40
Chambres quad (“vacuum fired & NEG coated”)	8	3’500	28
Compensateurs (avec contacts RF)	16	4’500	72
Chambres de pompage	4	5’000	20
Pompes ioniques avec alimentation	4	8’000	32
Jauges Pirani avec alimentation	4	1’000	4
Jauges Penning avec alimentation	4	1’500	6
Vannes de secteur	8	20’000	160
Vannes de prévidage	4	2’500	10
Câblage (m)	500	10	5
		Total arc:	**377**

Sections droites	**Nombre**	**Prix unité (CHF)**	**Prix (kCHF)**
Chambres (“vacuum fired & NEG coated”)	8	3’000	24
Compensateurs (avec contacts RF)	16	4’500	72
Chambres de pompage	6	5’000	30
Transitions	8	2’500	20
Pompes ioniques avec alimentation	8	8’000	64
Jauges Pirani avec alimentation	4	1’000	4
Jauges Penning avec alimentation	4	1’500	6
Vannes de secteur	0	2’000	0
Vannes de prévidage	4	2’500	10
Câblage (m)	300	10	3
Supports	30	500	15
		Total sections droites:	**248**

Etuvage	**Nombre**	**Prix unité (CHF)**	**Prix (kCHF)**
Equipement de chauffage et thermocouple	50	1'500	75
Racks de réglage	4	15'000	60
Consomables			5
		Total étuvage:	**140**

Pompage et diagnostic mobile	**Nombre**	**Prix unité (CHF)**	**Prix (kCHF)**
Groupes de pompage	2	20'000	40
Boîtes magiques	2	50'000	100
Détecteurs de fuites	1	20'000	20
		Total pompage et diagnostic mobile:	**160**

Système de contrôle et interlocks	**Nombre**	**Prix unité (CHF)**	**Prix (kCHF)**
PLC (secteur)	2	6'000	12
PLC (groupes, boîtes magiques)	4	4'000	16
Chassis interlocks	1	5'000	5
Chassis vannes	8	4'000	32
Entrée / sorties déportées	4	3'000	12
Câblage (m)	100	30	3
Racks	4	2'500	10
Software de supervision (collaboration)	1	30'000	30
		Total système de contrôle et interlocks:	**120**

Installation	**Nombre**	**Prix unité (CHF)**	**Prix (kCHF)**
Mécanique (h)	200	60	12
Détection, réparation (h)	40	80	3
Contrôles	40	60	2
Suivi qualité	80	120	10
		Total installation:	**27**
		Total général:	***1'202***

(*) Accounted for in the design and drawings chapter

Table 21. Vacuum equipment

Resource Estimate Summary

Vacuum	Material (kCHF)	Manpower FSU (kCHF)	Manpower FTE (MY)
Total	1175	27	5.0

Table 22. Vacuum resources

9. RF system + Schottky diagnostics

RF System

RF Operations and Components

The ELENA RF system serves to capture the injected antiproton beam from the AD through bucket to bucket transfer, decelerate the beam from the injection momentum of 100 MeV/c (T = 5.3 MeV) to an intermediate momentum of typically 35 MeV/c (T= 653 keV) and adiabatically de-bunch the beam for electron cooling.

This if followed by adiabatic rebunching of the beam for further deceleration to the extraction momentum of 13.7 MeV/c (T = 100 keV), another de-bunching, cooling and re-bunching for extraction to the experiments.

The RF system consists of an RF cavity, an ultra low noise longitudinal pick-up system, and a low level RF system.

As in the AD, the ultra low noise longitudinal pick-up is in also used for intensity measurements by RF current measurements when the beam is bunched as well as longitudinal Schottky scans (momentum spread and intensity) when the beam is debunched. The signal processing for these measurements are an integral part of the low level RF system.

Typical Beam and Machine Parameters and RF Voltage Requirements

The circumference of Elena is C_{ELENA} = 26.06 m = C_{AD} / 7 such that straightforward synchronized bucket to bucket transfer can take place at every turn from AD to ELENA.

The required RF frequency range for h = 1 operation is therefore a ratio of about 7 from **1.22 MHz to 168 kHz**.

The ELENA lattice is assumed to have a momentum compaction factor $\alpha = 1/\gamma_{tr}^2 = 0.65$ or $\gamma_{tr} = 1.24$.

With a well adjusted electron cooling in the AD and using electron cooling during the iso-adiabatic capture at 100 MeV/c, the AD is capable of delivering a longitudinal emittance of **1.3 meVs** [95%].

Assuming that the electron cooling is capable to cool the de-bunched beam to a relative momentum spread of $\Delta p/p = 10^{-4}$ both at 35 and 13.7 MeV/c, the longitudinal emittance gets further reduced to **0.3 meVs** at 35 MeV/c and **0.1 meVs** at the extraction momentum of 13.7 MeV/c.

At injection the required voltage to match the ELENA bucket to the AD bucket using 500 V_p in the AD is 4 V_p. This corresponds to a bunch length of 230 ns for E_{lon} = 1.3 meVs. Much larger longitudinal emittances can easily be transferred if needed by using a higher RF voltage in ELENA and bunch rotation in the AD.

To obtain an extracted bunch length of about 300 ns with E_{lon} = 0.1 meVs an RF voltage of 11 V_p is required. The corresponding $\Delta p/p = 1.4\ 10^{-3}$ [4σ, 95%].

The bucket area with V_{RF} = 11 V_p produces a stationary bucket area of about 15 meVs without much variation with energy. Assuming a deceleration or ramp time of 5 seconds, an energy loss of 1.5 Volts per turn is required, and the moving bucket area will be reduced to about 11.5 meVs, which seems adequate.

The minimum RF voltage required is the initial RF voltage required for iso-adiabatic capture of the cooled (0.1 meVs) beam prior to extraction. A full bucket is obtained with only V_{RF} = 0.7 mV, and even with such an initial capture voltage significant longitudinal blow-up will take place. With and adiabaticity coefficient of 0.3, the required duration of the capture is 1.4 seconds. Like in the AD, better extracted longitudinal emittances may be obtained by keeping the electron cooling on during a part of the capture.

A **controlled voltage range of 0.7 mV to 11 V** is therefore suggested. This corresponds to a dynamic range of 16000 or 84 dB which is larger than the 70 dB currently achieved in the AD with analog logarithmic detectors and. However, by using digital receivers and digital modulators with switch-able DAC range as used in the LEIR RF system this can hopefully be achieved.

The challenge in the ELENA RF system therefore the large dynamic voltage range required.

Longitudinal Pick-up

A low noise phase pick-up is required for the low level RF system phase loop, and additionally with adequate bandwidth to measure the bunch length at the lowest revolution frequency (low frequency cut-off ~20 kHz, base line droop) and at the shortest bunch length encountered (high frequency cut-off ~20 MHz).

Additionally, if the noise level is low enough, the same pick-up can be used to measure longitudinal Schottky scans.

A pick-up composed of two doubly shielded ferrite cavities with integral ultra low noise JFET head amplifiers with low noise feedback like those built for the AD is proposed [2]. It consist of a high frequency unit like DR.USY4104 (high frequency 4L2 ferrites, $\mu = 200$, bandwidth 0.3 – 20 MHz, noise current) and a low frequency unit like DR.USY4105 (low frequency 4A15 ferrites, $\mu = 1200$, bandwidth 0.02 – 3 MHz). The two signals are summed in an amplifier with appropriate equalizers to ensure a combined bandwidth of 0.02 – 20 MHz. The crossover frequency is 1 MHz as the low frequency unit has the lowest noise below that frequency (typically 2.5 pA/sqrt(Hz)) while the high frequency unit has the lowest noise above that frequency (typically 1.5 pA/sqrt(Hz)).

If space is a problem (each unit is 54 cm flange to flange), shorter units (with higher noise levels) or a combined unit with both cavities within the same outer shielding could be developed.

Surplus 4L2 rings are available from the Booster, and do not need to be purchased.

The Schottky currents per particle and the number of particles are comparable to the AD numbers as the range of revolution frequencies are about the same. The worst case longitudinal Schottky signal to noise ratios are however slightly better than the AD as there is nowhere in the ELENA cycle where the width of the Schottky bands are as wide as the initial distribution in the AD after de-bunching at 100 MeV/c.

RF Cavity and Power Amplifier

The RF cavity could be built with either finemet or ferrite cores. Due to the low voltage requirements, there is no need to tune the cavity, and adequate broad band response is obtained by loading the cavity. With ten 4A15 ferrite rings (ferrite length 30 cm, μ = 1200) as used in the low frequency pick-up cavity, sufficient inductance (40 μH) is obtained to drive the resistively loaded cavity to the required voltage with a modest power amplifier of only 20W. A 4:1 step down transformer (like DR.USY4105) transform the 50 ohm load impedance to 3.125 ohms at the gap. To obtain 11 Volts peak at the gap, 44 Volts peak must be applied to the input of the 4:1 transformer integrated in the cavity.

A cheaper and shorter RF cavity may possibly be built using finemet cores.

Low Level RF System, Intensity measurements

The low level RF system is based on the software and digital building blocks developed for LEIR.

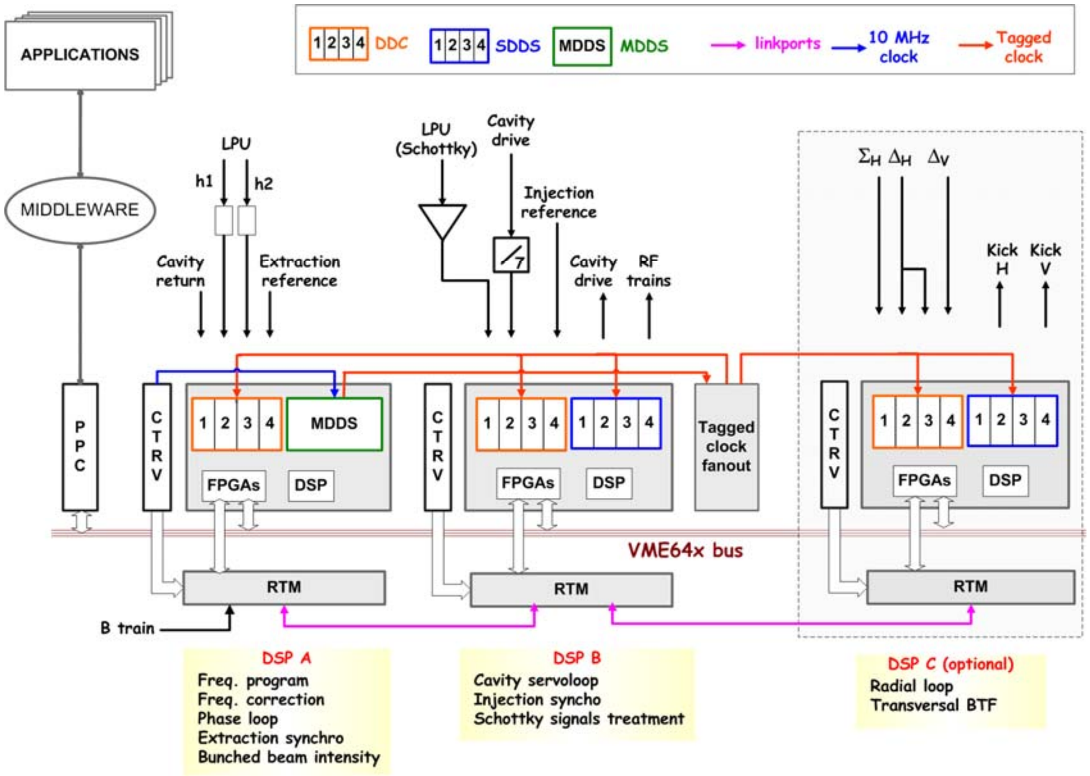


Fig.10. **Block diagram of the Elena RF and intensity diagnostics system.**

As in the AD, the beam currents are much too low to enable intensity measurements by a DC beam current transformer. RF current measurements at two harmonics (h = 1 and 2) are used for intensity measurement when the beam is bunched, and longitudinal Schottky power is used when the beam is de-bunched. The implementation of these functions (similar to AD [3]) in the digital low level RF system architecture is straightforward as the beam phase signal is already received in a DDC (Digital Down Converter) for use in the beam phase loop.

The basic low level RF system including the intensity and momentum distribution diagnostics can be implemented on two VME DSP mother boards, see fig. 1.

The Master DDS (located on DSP A mother board) operates on a suitable high harmonic of the revolution frequency, and drives all NCO's (Numerically Controlled Oscillators) in the Slave DDS's and DDC's with controlled relative phases.

DSP A receives a B-train derived from a coil in one of the bending magnets, and generates the basic frequency program. A software function generator generates a frequency correction function to correct for errors in the measured B-train. The DSP A also looks after the beam phase loop, the extraction synchro loop and the bunched beam intensity measurement based on the amplitude of first and second harmonic of the beam RF current.

The RF system requires a B-train system (preferably measured and synthetic as in the AD) to generate the frequency program, but this sub-system is not included in the RF system cost estimates below.

The second board DSP B looks after the digital cavity voltage servo loop, the injection synchro loop where the 7th sub-harmonic of the Elena RF signal is locked to the AD RF (= injection reference) prior to bucket to bucket transfer. The longitudinal Schottky treatment when the beam is debunched is also treated in DSP B: a high gain version of the longitudinal pick-up is connected to a DDC clocked at a fixed 40 MHz rate and tuned to an appropriate revolution harmonic (optimized for signal to noise ratio and best Schottky statistics).

If the tune measurement system using transverse BTF (Beam Transfer Function) as in the AD is required [4], a third DSP C board is needed. The generation of the digital M-shaped coloured noise excitation signal is straightforward with the SDDS daughter card using an appropriately filtered baseband noise excitation file. Besides transverse BTF, this board could also implement a radial loop (using a single pick-up) as has been developed for the LEIR.

Estimate of Elena RF and Longit. Schottky diagnostics system

		Material	Personell
Item	Description	[kCHF]	[FTE]
Low noise pick-ups for bunch lenghts, RF intensity, beam phase loop and long. Schottky			
PU LF (4A15 ferr.)	Low frequency pick-up (0.02 - 5 MHz	60	0.2
PU HF (4L2 ferr.) *)	High frequency pick-up (0.3 - 25MHz)	30	0.2
PU electr.	Electronics PU's (head+sum)	10	0.2
Low voltage broadband cavity and amplifier (1 mVp - 10Vp, 0.17 - 1.22 MHz)			
Cavity LF	Loaded ferrite/finemet cavity	60	0.2
Power Amplifier	~20 W if 4A15 ferrites used	5	
Digital low level RF, incl. bunch beam intensity and Schottky diagnostics			
VME crate	VME 64x with CPU	9.0	
CPU	Power PC	7.0	
2 DSP mother boards	2 x (RTM+DSP)	4.8	
Timing	2 x CTRV VME modules	1.4	
Master DDS	1 x MDDS	1.2	
Clock Fan-Out	1 x VME Clock Fan-out	1.0	
4 ch. Receiver	2 x 4 ch DDC daughter cards	4.0	
4 ch. Modulator	1 x 4 ch. SDDS daughter card	2.0	
HW tests and commissioning			0.2
Transverse BTF and Radial loop			
2 DSP mother boards	1 x (RTM+DSP)	2.4	
4 ch. Receiver	1 x 4 ch DDC daughter cards	2.0	
4 ch. Modulator	1 x 4 ch. SDDS daughter card	2.0	
Timing	2 x CTRV VME modules	1.4	
HW tests and commissioning			0.1
Lab equipment and spares			
Lab equipment	VME crate, Power PC, scope etc.	30	
Spare modules	Approx. 50% of system	20	
Digital LLRF and Longitudinal Diagnostic Software			
Global system design	All 3 layers for the 3 main items below		0.2
DSP, RTT, Appl.	Digital LLRF Software integration (DSP, RTT,App)		0.4
DSP, RTT, Appl.	Longit. Bunched beam intensity and Schottky		0.6
DSP, RTT, Appl.	Transverse BTF and Radial loop		0.5
Global system integration, commissioning with beam and setup			0.2
Diagnostic specific application (as for AD), provided by OP?			0.3
Cables, installation (FSU)		50.0	0.1 (FSU)
Total		303.2	3.3

*) ferrites for HF PU cavity recuperated from PSB stock

Table 23. **RF and Schottky system components**

Resource Estimate Summary

RF+Schottky	Material (kCHF)	Manpower FSU (kCHF)	Manpower FTE (MY)
Total	303	10	3.3

Table 24. **RF and Schottky diagnostics resources**

10. B-train systems

Both synthetic and measured B-trains will be used, with systems based on what is presently used in the AD and other machines in the PS-complex. Modernized electronics for the measured B-train is under study and will replace existing systems CERN-wide.

Synthetic B-train:

- VME-crate: 7 kCHF
- CPU: 6 kCHF
- CTRV+BTG cards: 2 kCHF
- Development (modeling/sw): 4 man-months

Measured B-train:

- Electronics: 15 kCHF
  (VME rack, data conditioning and acquisition, interface to machine control)
- NMR: 30 kCHF
  (estimated for the upcoming Metrolab PT2026, which should be fast enough for ELENA purposes, with one probe)
- Flux coil: 20 kCHF
  (1.5 m long coil, 45° bend, 1 unit + 1 spare)
- Installation and testing: 4 man-months

Resource Estimate Summary

B-trains	Material (kCHF)	Manpower FSU (kCHF)	Manpower FTE (MY)
Total	80		0.7

Table 25. **B-train resources**

11. Diagnostics

ELENA ring BPM Pickups

The proposed design is based on a stainless steel body containing 2 diagonal cut electrodes. Two such elements can be inserted in to a vacuum tank 140mm diameter and 400mm long or shorter if needed, in order to have a position measurement in both planes. In contrary to the ring PU no sigma electrode will be installed, but the sigma signal will be generated in the head amplifier. An existing head amplifier design made for Aarhus University 5 years ago can be used.

The Delta and Sigma signals will be acquired by a network analyzer as in the AD in order to obtain a good signal to noise ratio (BW~ 100Hz). Measurement time per PU ~30ms.

The theoretical resolution at 1*107 charges in a 3.4S bunch (15m) with beta = 0.0146 and a bunching factor of ~2 is 0.1mm (S/N=20). This resolution is calculated using theoretical white noise only, but as we know from the AD interference can be much higher. A similar performance as for the AD orbit should be possible.

	Units	**CHF/Unit**	**CHF**
Prototype	1	10k	10k
Manufacturing of Pus (H+V)	7	10k	70k
Cables	7	5k	35k
Head amplifier design	0	0	0
Manufacturing of HA	10	1k	10k
Other electronics design	1	6k	6k
Manufacturing other electronics	7	1k	7k
VME crate + VME module	1	17k	17k
Network analyzer	1	50k	50k
Other	1	20k	20k
TOTAL			**225 kCHF**

Table 26. **Estimated costs**

	Man months	**Comments**
PU design	6 (Eng)	In coll. with mech. designer
Prototype test	1 (Eng)	On test bench
Manufacturing of Pus (H+V)	1 (Tech)	Follow up of AP work
Tests of PUs	2 (Tech)	On test bench
Head amplifier design	0	Existing Aarhus amp.
Manufacturing and tests of HA	1 (Tech)	
Other electronics design	1 (Eng)	Control mod, signal distr.
Manufacturing other electronics	1 (Tech)	
Software	3 (Eng)	Copy from AD but on FESA
Installation	1 (Tech)	
Tests and commisioning	1 (Eng)	
Other	1 (Eng)	
TOTAL	**6 Tech.;14 Eng.**	

Table 27. **Estimated manpower**

ELENA emittance measurement using scrapers

This is a very rough cost estimate made on the assumption that the existing system for the AD can be copied, and that the drawings can be found. The system consist of 4 motorized scrapers, 2 scintillators with photo multipliers and high voltage supplies. Outside the ring a discriminator and summing modules (NIM) and a counter module (VME scaler) are needed.

	Units	**CHF/Unit**	**CHF**
Scraper mechanics incl. motors	4	10k	40k
Vacuum Tank	1	6k	6k
Motor controller	4	3k	12k
Cables	6	1k	6k
Scintillators	2	2k	4k
Photo multipliers	2	3k	6k
Nim modules	3	4k	12k
NIM crate	1	5k	5k
VME module (scaler)	1	4k	4k
VME crate	1	15k	15k
TOTAL			**110 kCHF**

Table 28. **Estimated cost**

	Man months
Design scintillators and support	1 (Tech)
Software	3 (Eng)
Manufacturing and installation	1 (Tech)
TOTAL	**2 Tech.;3 Eng.**

Table 29. **Estimated manpower**

Electron Cooling Related Diagnostics

In order to observe and optimise the cooling of low energy antiprotons in ELENA non-destructive diagnostics need to be developed. The measurement of the longitudinal cooling can only be done using Schottky diagnostics. A longitudinal Schottky pick-up will not only give the measurement of the momentum spread of the beam but also the beam intensity. In the transverse planes ionisation profile monitors (IPM) are the ideal instruments for measuring the evolution of the beam size throughout the deceleration cycle. However in a machine like ELENA where the vacuum will be in the 10^{-12} torr range and the intensity of the circulating is low, a gas injection system, similar to what is used on the AD, must also be installed. It is clear that the use of an IPM in ELENA would be limited to the machine commissioning/startup and for machine development. A horizontal monitor could be installed in one of the horizontal bending magnets and the vertical monitor would have its tank in one of the machine straight sections. The resolution of these detectors would be around 1mm.

If H^- injection is to be used on ELENA, a most useful detector would be a recombination detector placed at the exit of the bending magnet downstream from the electron cooler. This detector measures the radiative recombination rate of the electrons with the circulating proton beam. Coupled to a luminescent screen one observes directly on a monitor the transverse cooling of the proton beam.

Cost estimate:

2 IMPs (H & V), including HT power supplies, front-end electronics and DAQ system: 150 kCHF.

Recombination detector, including HT power supplies, CCD camera and DAQ system: 70 kCHF.

VME crate + modules: 30 kCHF

Tune measurement

See RF/Schottky for transverse BTF DSP-system. A dedicated kicker of a similar design to the one used in LEIR will be required. Cost including stripline structure, vacuum feedthroughs, electronics and amplifiers is estimated at 35 kCHF and 0.3 MY.

Intensity measurement

See RF/Schottky

Resource Estimate Summary

Diagnostics	Material (kCHF)	Manpower FSU (kCHF)	Manpower FTE (MY)
Total	620	85	2.4

Table 30. **Diagnostics resources**

12. Controls

Controls	Material(kCHF)	Manpower CERN FTE (MY)
OASIS (150MHz chassi + 500MHz chassi)	192	
Communication network	80	
Timing system	40	
General cabling	80	
Controls infrastructure in local control room	0	
Timing DSCs (2DSCs + 30 CO modules)	60	
Power suplies interface (2 DSCs + CO modules, does not include power controls budget prevision)	60	
Power controls FGC3 (35 supplies)	70	
Power controls PLC (100 HVsupplies)	100	
HW installation + SW development/adaptation		0.35
Cycle generation SW (LSA)		0.35
Total	682	0.70

Table 31. **Controls resources**

13. H- source

Discussions are underway to determine whether part of the ELENA setting-up can be done using a local H- source. The objective is to be able to do part of the commissioning independent of the CERN accelerator complex and it's run schedule. A 100 keV H- source can temporarily be installed in the new section of the AD to ELENA transfer line for commissioning and initial setting up of the electron cooler at 100keV and of the ejection lines.

Resource Estimate Summary

H- source	Material (kCHF)	Manpower (MY)
H- source	100	
Power supply	250	
Div.	50	
Total	400	0.5

Table 32. **H- resources**

14. Experimental area beam lines + instrumentation

Beam transport

Transport of 100 keV beams will not be an easy task, especially considering the operational difficulties experienced in keeping beam trajectories stable with today's AD setup where ejection beam energy is 5.3MeV (a factor 7 higher momentum). To gain better understanding of the problem, a study of the environmental magnetic fields in the area will have to be done.

Many solutions exist, including re-arrangement of the experimental areas in order to avoid passing through areas where fringe fields from experimental equipment are present. The final solution will also depend on the different experiments possible needs for both 5.3MeV and 100keV beams.

In this report, a preliminary solution permitting beam transport only of 100keV beams is used. The existing experimental area layout will here be retained which is an advantage for the AD experiments. The beamlines will be modified using electrostatic deflectors and quadrupole triplets and can be shielded with dual concentric layers of mu-metal wherever necessary. As much as possible of existing vacuum equipment etc. will be re-used. A rough estimate is given in Table 33.

Ejection lines	Qty	Price/unit (kCHF)	Cost (kCHF)	Manpower FTE (MY)
Quadrupole triplets	13	35	455	1.0
Dipolar deflectors	4	50	200	
Power supplies/cabling	104	2.3	240	
Controls				
Vacuum chamber modifications			500	2.0
Total			1395	3.0

Table 33. Ejection lines resources

Instrumentation

Non-destructive photocathode microwire beam profile monitors have been developed and are used by the ASCUSA collaboration, these would suit the new beamlines well.

Beam profile monitor specifications:

Number of detectors:	15 devices
Energy range:	10 keV to 20 MeV
Aperture:	60 x 60 mm
Active area:	48 x 48 mm
Spatial resolution:	1 mm or 1.5 mm
Dynamic range:	10000
Channels:	64 channels parallel readout
Sensitivity:	1e6 antiprotons in a 300-ns-long bunch
Transmission:	1-2% losses per detector.
Vacuum:	<1e-10 mb

Remotely controllable and readout is possible through the net.

Beam profile monitors	Cost/unit (kCHF)	Total cost/15 units (kCHF)
Vacuum chamber, UHV with 128 readout pins on ceramic bakeable to 200 degrees C, compatible to 1e-10 mb.	22,000	330,000
Electronics, CMOS parallel 64 channels, serial readout bonded on the above detector	25,600	384,000
Microwire electrodes, 32 x 32 mm 1 micron diameter on thick-film printed ceramic UHV board.	4,000 *2 (H+V)	120,000
Power supply +/- 15 V and +/- 5 V	400	6,000
Power supply - 100V, remote cabling and biasing	500	7,500
Cabling etc.	included	
Total	56,500	847,500

Table 34. **BPM resources**

Delivery time: 2 years from the date of order, including tests. Discussions are underway whether manpower could be supplied by the ASACUSA collaboration

Resource Estimate Summary

Ejection lines	Material (kCHF)	Manpower FTE (MY)
Electrostatic elements + beamline modifications	1395	3.0
Profile monitors	850	*
Total	2245	3.0

(*) Manpower could be provided by the ASACUSA collaboration

Table 35. **Exp. Area beamline resources**

15. Drawings and mechanical design

A global estimate for all work related to mechanical design and drawings has been made. Included are all ELENA items including injection and ejection lines.

Resource Estimate Summary

Design/drawings	Material (kCHF)	Manpower FSU or CERN (MY)
Total	NA	17

Table 36. **Design and drawings resources**

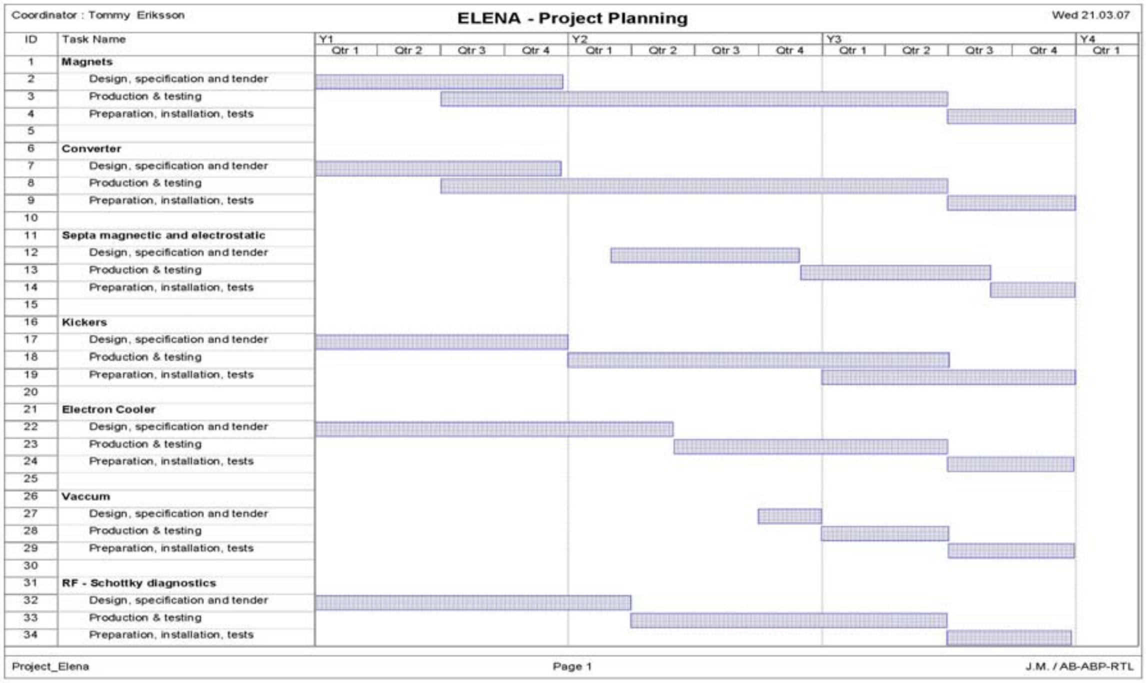
16. General items, Infrastructure, cooling water, electricity

Resource Estimate Summary

Design study + general	Material (kCHF)	Manpower FTE (MY)
Design study		5
Coordination		1.5
Electricity distribution	100	
Cooling water distribution	100	
Concrete shielding + access door	40	
Div.	50	
Total	290	6.5

Table 37. General items resources

17. Planning



Coordinator : Tommy Eriksson

ELENA - Project Planning

Wed 21.03.07

ID	Task Name
1	**Magnets**
2	Design, specification and tender
3	Production & testing
4	Preparation, installation, tests
5	
6	**Converter**
7	Design, specification and tender
8	Production & testing
9	Preparation, installation, tests
10	
11	**Septa magnectic and electrostatic**
12	Design, specification and tender
13	Production & testing
14	Preparation, installation, tests
15	
16	**Kickers**
17	Design, specification and tender
18	Production & testing
19	Preparation, installation, tests
20	
21	**Electron Cooler**
22	Design, specification and tender
23	Production & testing
24	Preparation, installation, tests
25	
26	**Vaccum**
27	Design, specification and tender
28	Production & testing
29	Preparation, installation, tests
30	
31	**RF - Schottky diagnostics**
32	Design, specification and tender
33	Production & testing
34	Preparation, installation, tests

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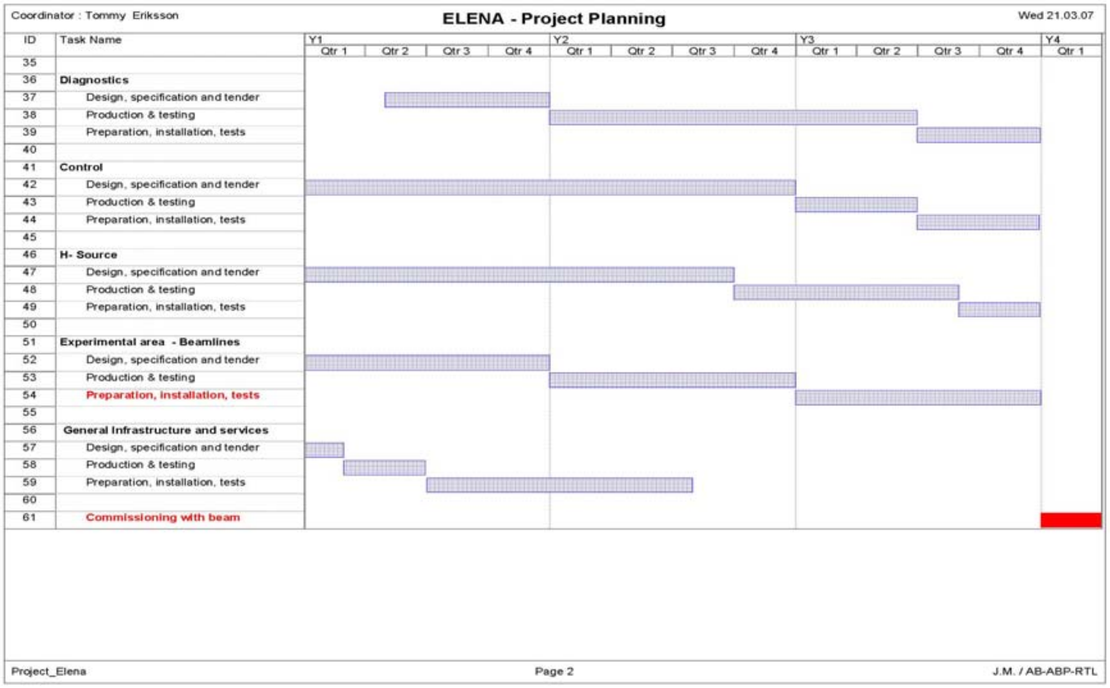

Coordinator : Tommy Eriksson

ELENA - Project Planning

Wed 21.03.07

ID	Task Name
35	
36	**Diagnostics**
37	Design, specification and tender
38	Production & testing
39	Preparation, installation, tests
40	
41	**Control**
42	Design, specification and tender
43	Production & testing
44	Preparation, installation, tests
45	
46	**H- Source**
47	Design, specification and tender
48	Production & testing
49	Preparation, installation, tests
50	
51	**Experimental area - Beamlines**
52	Design, specification and tender
53	Production & testing
54	**Preparation, installation, tests**
55	
56	**General Infrastructure and services**
57	Design, specification and tender
58	Production & testing
59	Preparation, installation, tests
60	
61	**Commissioning with beam**

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18. Conclusion

Despite the fact that much information is missing at this stage, this report tries to give an estimate of the cost and manpower needs for design and construction of ELENA [Table 38]. This estimate is likely to change as the design study progresses. It is worth noting that ELENA is a new machine with most items (ring, experimental area, electron cooler, use of H- source etc.) designed from scratch and thereby causing considerate construction costs.

Item	**Material (kCHF)**	**Manpower FSU (kCHF)**	**Manpower FTE (MY)**
Magnets (ring+inj. line)	**885**	**160**	**3.2**
Power converters	**857**		**1.5**
Injection/ejection septa	**220**		**2.9**
Injection/ejection kickers	**830**		**4.8**
Electron cooler	**1350**		**6.5**
Vacuum	**1175**	**27**	**5.0**
RF + Schottky diagnostics	**303**	**10**	**3.3**
B-trains	**80**		**0.7**
Diagnostics	**620**	**85**	**2.4**
Controls	**682**		**0.7**
H- source	**400**		**0.5**
Experimental area	**2245**		**3.0**
Mech. Design/Drawings			**17.0**
Div.	**290**		**6.5**
Total (MCHF/MY)	**9.937**	**.282**	**58.0**
Grand Total (MCHF/MY)	**10.219**		**58.0**

Table 38. **ELENA cost estimate**

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Appendix 3:

Members and Affiliations of Approved AD–Experiments

AD-2 The ATRAP–COLLABORATION

J.S. Borbely[1], S. Böttner[2], G. Gabrielse[3,*], M.C. George[1], D. Grzonka[4], E.A. Hessels[1], D. Kolbe[2], A. Koglbauer[2], W.S. Kolthammer[3], P. Larochelle[3], R. McConnell[3], A. Müller[2], W. Oelert[4], P. Richerme[3], M. Scheid[2], T. Sefzick[4], A. Speck[5], R. Steinborn[2], C.H. Storry[1], J. Walz[2], M. Weel[1], J. Wrubel[3], and M. Zielinski[4]

[1] *York University, Department of Physics and Astronomy, Toronto, Ontario M3J 1P3, Canada*
[2] *Institut fur Physik, Johannes Gutenberg-Universitat, D-55099 Mainz, Germany*
[3] *Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[4] *IKP, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany*
[5] *Rowland Institute at Harvard, Harvard University, Cambridge, Massachusetts 02142, USA*

[*] *Spokesperson of the Collaboration*

AD-3 The ASACUSA–COLLABORATION

D. Barna[1,2], M. Charlton[3], M. Corradini[4], A. Dax[1], H. Dølrath[5], Y. Enomoto[6], S. Federmann[7], S. Friedreich[7], R.S. Hayano[1,*], H. Higaki[8], M. Hori[1,9], D. Horváth[2], C.A. Hunniford[10], H. Imao[6], B. Juhasz[7], Y. Kanai[8], K. Kira[8], H. Knudsen[5], T. Kobayashi[1], H-P E. Kristiansen[5], N. Kuroda[6], M. Leali[4], E. Lodi Rizzini[4], M. Lund[5], V. Mascagna[4], O. Massiczek[7], Y. Matsuda[6], R.W. McCullough[10], K. Michishio[8], S.P. Møller[5], A. Mohri[8], Y. Nagata[6], T. Pask[7], W. Pirkl[1], H. Saitoh[11], P. Somkuti[7], A. Sótér[9], K. Todoroki[1], K. Tökési[12], H.A. Torii[6], U. Uggerhøj[5], K. Umlaub[7], V.L. Varentsov[8], L. Venturelli[4], E. Widmann[7], Y. Yamazaki[6], Z. Yoshida[11], P. Zalán[2], and N. Zurlo[4]

[1] *Department of Physics, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033 Japan*
[2] *Research Institute for Particle and Nuclear Physics (KFKI), H-1525 Budapest, Hungary*
[3] *Department of Physics, Swansea University, Swansea SA2 8PP, Wales United Kingdom*
[4] *Dipartimento di Chimica e Fisica per l'Ingegneria e per i Materiali,*
Universita di Brescia, 25123 Brescia, Italy
[5] *Department of Physics and Astronomy, University of Aarhus, DK-8000 Aarhus C, Denmark*
[6] *Institute of Physics, University of Tokyo, Komaba, Meguro-ku, Tokyo 153-8902, Japan*
[7] *Stefan Meyer Institut fr subatomare Physik, Boltzmanngasse 3,1090 Vienna,Austria*
[8] *Atomic Physics Laboratory, RIKEN, Wako 351-01, Japan*
[9] *Max-Planck Institut für Quantenoptik, Hans-Kopfermann Strasse 1, D-85748 Garching, Germany*
[10] *The Queen's University of Belfast Belfast N. Ireland, BT7 1NN UK*
[11] *University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8568, Japan*
[12] *Institute of Nuclear Research (ATOMKI), H-4001 Debrecen, Hungary*

* *Spokesperson of the Collaboration*

AD-4 The ACE–COLLABORATION

J. Alsner[1], A. Angelopoulos[2], N. Bassler[2,3], G.-J. Beyer[4], F. Curreli[5], J. DeMarco[6], M. Doser[7], B. Fahimian[6], D. Hajdukovic[8], O. Hartley[4], R. Herrmann[3], M. Holzscheiter[9,10,*], K. Iwamoto[6], O. Jäkle[3], F.J. Kaiser[3], I. Kantemiris[2], J. Kavanagh[5], R. Keyes[9], H. Knudsen[11], S. Kovacevic[8], W. McBride[6], R. Miralbell[4], S.P. Møller[11], J. Overgaard[1], J. Petersen[1], O. Ratib[4], G. Schettino[5], S. Sellner[10], S. Tegami[10], D. Timson[5], S. Vranjes[12], C. Welsch[10], and B. Wouters[13]

[1] *Aarhus University Hospital*
[2] *University of Athens, Physics Department, Nuclear and Particle Physics Section*
[3] *DKFZ German Cancer Research Center, Heidelberg, Germany*
[4] *University de Genève, Faculté de Mèdicine Switzerland, Geneva*
[5] *Queens University Belfast, Department of Physics and Astronomy Northern Ireland, Belfast*
[6] *University of California, Los Angeles (UCLA) Department of Radiation Oncology United States of America, Los Angeles*
[7] *Conseil Europén pour la Recherche Nucléaire (CERN), Geneva, Switzerland*
[8] *University of Montenegro, Podgorica, Montenegro*
[9] *University of New Mexico, Department of Physics and Astronomy, United States of America, Albuquerque*
[10] *Max Planck Institute for Nuclear Physics, Heidelberg, Germany*
[11] *Aarhus University Department of Physics and Astronomy, Aarhus, Denmark*
[12] *Vinca Institute of Nuclear Sciences (VINCA), Serbia, Belgrade*
[13] *University of Toronto, Toronto, Canada*

* *Spokesperson of the Collaboration*

AD-5 The ALPHA–COLLABORATION

G.B. Andresen[1], W. Bertsche[2], P.D. Bowe[1], E. Butler[2], C.L. Cesar[3], S. Chapman[4]
M. Charlton[2], J. Fajans[4], M.C. Fujiwara[5], D.R. Gill[5], J.S. Hangst[1,*] W.N. Hardy[6]
R.S. Hayano[7], M.E. Hayden[8], A.J. Humphries[2], R. Hydomako[9], L. Kurchaninov[5]
R. Lambo[3], N. Madsen[2], P. Nolan[10], K. Olchanski[5], A. Olin[5], A. Povilus[4], P. Pusa[10]
F. Robicheaux[11], E. Sarid[12], D.M. Silveira[7,13], J.W. Storey[5], R.I. Thompson[9],
D.P. van der Werf[2], J.S. Wurtele[4], and Y. Yamazaki[13]

[1] *Department of Physics and Astronomy, Aarhus University, DK-8000 Aarhus C, Denmark*
[2] *Department of Physics, Swansea University, Swansea SA2 8PP, United Kingdom*
[3] *Instituto de Física, Universidade Federal do Rio de Janeiro, Rio de Janeiro 21941-972, Brazil*
[4] *Department of Physics, University of California at Berkeley, Berkeley, CA 94720-7300, USA*
[5] *TRIUMF, 4004 Wesbrook Mall Vancouver, BC V6T 2A3, Canada*
[6] *Department of Physics and Astronomy, University of British Columbia, Vancouver, BC V6T 1Z1, Canada*
[7] *Department of Physics, University of Tokyo, Tokyo 113-0033, Japan*
[8] *Department of Physics, Simon Fraser University, Burnaby, BC V5A 1S6, Canada*
[9] *Department of Physics and Astronomy, University of Calgary, Calgary T2N 1N4, Canada*
[10] *Department of Physics, University of Liverpool, Liverpool L69 7ZE, United Kingdom*
[11] *Department of Physics, Auburn University, Auburn, AL 36849-5311, USA*
[12] *Department of Physics, NRCN-Nuclear Research Center Negev, Beer Sheva, IL-84190, Israel*
[13] *Atomic Physics Laboratory, RIKEN, Saitama 351-0198, Japan*

* *Spokesperson of the Collaboration*

AD-6 The AEGIS–COLLABORATION

A.S. Belov[1], G.Bonomi[2], I. Boscolo[3], N. Brambilla[3], J. Bremer[11], R.S. Brusa[4], V. M. Byakov[5], L. Cabaret[6], C. Canali[8], C. Carraro[8], F. Castelli[3], S. Cialdi[3], D. Comparat[6], G. Consolati[9], L. Dassa[2], N. Djurelov[10], M. Doser[11,**], A. Dudarev[11], A. Dupasquier[9], T. Eisel[11], R. Ferragut[9], G. Ferrari[21], A. Fontana[2], M. Giammarchi[3], S. N. Gninenko[1], F. Haug[11], S.D. Hogan[15], A. Kellerbauer[7], D. Krasnicky[16], V. Lagomarsino[8], G. Manuzio[8], S. Mariazzi[4], V. A. Matveev[1], F. gt[15], G. Nebbia[4], P. Nedelec[17], T. Ninikowski[11], M. Oberthaler[18], D. Perini[11,+], V. Petracek[16], M. Prevedelli[13], F. Quasso[9], I.Y. Al-Qaradawi[19], C. Riccardi[2], O. Rohne[20], A. Rotondi[2], H. Sandaker[2]0, S. V. Stepanov[5], D. Sillou[12], H.H. Stroke[13], G. Testera[8,*], D. Trezzi[3], A. V. Turbabin[1], R. Vaccarone[8], A. Vairo[3], H.R.J.Walters[14], U. Warring[7], S. Zavatarelli[8], A. Zenoni[2], F. Villa[3], and D.S. Zvezhinskij[5]

[1] *INR Moscow, 60th Oct. Anniversary Prospekt 7A, RU-117 312 Moskva, Russia*
[2] *INFN Pavia-Brescia, Via Bassi 6, IT-Pavia, Italy and via Branze, IT-25133 Brescia, Italy*
[3] *INFN Milano, via Celoria 16, IT-20133 Milano, Italy*
[4] *INFN Padova-Trento, Via Marzolo 8, 35131 Padova, Italy and*
Via Sommarive, 14, I - 38123 Povo, Italy
[5] *ITEP Moscow, B. Cheremushkinskaya ulitsa 25, RU-117 259 Moskva, Russia*
[6] *Lab. Aime' Cotton, Campus d'Orsay, Bat.505, FR-91405 Orsay, France*
[7] *MPI-K Postfach 10 39 80, Saupfercheckweg 1, DE-69117 Heidelberg, Germany*
[8] *INFN Genova, via Dodecaneso 33, IT-16146 Genoa, Italy*
[9] *Politecnico Milano, Piazza Leonardo da Vinci, 32, IT-20133 Milano, Italy*
[10] *IRNE Sofia, Acad. G. Bonchev Str. 25-A, BG-1113 Sofia, Bulgary*
[11] *CERN, 1211 Geneva 23, Switzerland*
[12] *LAPP, Annecy, BP 110, 9 Chemin de Bellevue, FR-74941 Annecy-le-Vieux Cedex, France*
[13] *New York Univ., 4 Washington Place, New York NY 10003, USA*
[14] *Queen's U Belfast, University Road, Belfast BT7 1NN, UK*
[15] *ETH Zürich, Wolfgang-Pauli-Str. 10, 8093 Zrich, Switzerland*
[16] *Czech Tech. Univ, Prague, Brehova 7 , CZ-11519 Praha 1, Czech Republic*
[17] *UCBL Lyon, Batiment Paul Dirac, 43 Boulevard DU 11 NOVEMBRE 1918,*
69622 Villeurbanne cedex, France
[18] *Kirchhoff Inst. Of Phys., Im Neuenheimer Feld 227, DE-69120 Heidelberg, Germany*
[19] *Qatar University, P.O. Box 2713, Doha, Qatar*
[20] *Univ. Oslo, PO Box 1048, Blindern, NO-0316 Oslo 3, Norway*
[21] *INFN Firenze, Largo Enrico Fermi 2, IT-50125 Firenze, Italy*

* *Spokesperson of the Collaboration*
** *Deputy-Spokesperson of the Collaboration*
\+ *Techinical Coordinator of the Collaboration*

Appendix 4:

A letter from Prof. Swapan Chattopadhyay of the Cockcroft Institute expressing his strong interest in participating in the construction of ELENA.

an updated latter as the one copied here dated 10. October 2007 will follow soon.

The Cockcroft Institute
of Accelerator Science and Technology

**Daresbury Science and Innovation Campus,
Keckwick Lane, Daresbury, Warrington, WA4
4AD, Cheshire UK**

Office of the
Director
Prof. Dr. Swapan Chattopadhyay, *PhD. (Berkley)*
F InstP, FAPS, FAAAS
SIR JOHN COCKCROFT CHAIR OF PHYSICS
UNIVERSITIES OF LIVERPOOL, MANCHESTER AND LANCASTER

September1, 2009

TO:
Prof. Sergio Bertolucci
Director of Research and Computing
CERN

REFERENCE: ELENA

Dear Prof. Bertolucci,

This letter is to reiterate what I wrote almost two years ago and re-state our interest at the Cockcroft Institute (UK) in collaborating with CERN in the ELENA upgrade to the AD storage ring. Over the past two years our interactions with the Antiproton User community have grown simultaneously as the Cockcroft Institute has continued to mature by acquiring special expertise and skills base relevant to accelerator science and technology, but particularly in the areas of ring design, magnets, diagnostics, radio-frequency techniques and high current cold electron beams. Amongst the many areas and topics where our institute feels competent to contribute, I bring out a few boldly where there could be clear and substantial technical contributions, should there be a program established:

1. Ring design and magnets;
2. Electron cooler;
3. All purpose diagnostics;
4. RF and Schottky diagnostics;
5. Controls;
6. Experimental beam lines (including the electrostatic beam lines to distribute the low-energy antiprotons to experiments);
7. Overall design and coordination of the project.

The Cockcroft Institute has near-complete skills base in the design of all aspects of circular and linear accelerators, storage rings and charged particle beam lines. What particularly interests us is the challenging aspect of manipulation and control of very slow antiprotons and the necessary cooling and electrostatics techniques. We also have recently gained substantial capacity in all aspects of charged particle diagnostics.

We base our interest in ELENA upon the following:

(a) there is a strong and increasing interest in low energy antiproton science which can only be met today by CERN’s world-wide unique AD facility;

(b) the Elena upgrade would serve as a prototype of possible future facilities such as the FLAIR in the proposed FAIR complex near GSI, Germany in distant future;

(c) the CERN SPSC committee is clearly on record as supporting ELENA based upon the improved science that it would make possible;

(d) the CERN administration has mentioned this upgrade as one that it would like to carry out if staff and resources were available, though a successful LHC is clearly the first priority now;

(e) the AD program is now fully subscribed, and the rate at which scientific results can be obtained is already being limited by the number of antiprotons that are available;

(f) the ELENA upgrade would greatly increase the number of antiprotons available to low energy experiments, significantly increasing the quality of the science being carried out at the AD;

(g) with stable and fast switching of the antiprotons between experiments, it would also make it possible to accommodate more experiments at the AD;

(h) a preliminary study by the AD staff and some members of the antiproton user community has already established the feasibility of ELENA and identified how it could be positioned in the AD hall.;

(i) the good acceptance and the cooling within ELENA will make this upgrade a much more robust enhancement to the CERN AD facility than would an RFQ or any other decelerator method.

The ELENA upgrade fits into the developing plans of the Cockcroft Institute for a variety of reasons, one of the prime ones being the driving mission of the institute of being an enabling agent for world-class accelerator-driven precision science of the highest calibre globally. While we explore the actual scope of our involvement and access to real funding needed to bring this about, we are already exploring the in-kind contribution of certain magnets from our de-commissioned SRS ring at Daresbury for their suitability in the magnetic optics and lattice for the proposed ELENA ring.

Preliminary discussions have already taken place with many experts and interested scientists in the field such as Prof. Walter Oelert of Julich, Prof. Gerald Gabrielse of Harvard University, Prof. Dieter Mohl of CERN and Prof. Jonathan Wurtele of Berkeley. We anticipate further real developments in the opportunity for us to contribute – both in scope and in funding – as the evolving accelerator strategy of UK in the context of its partnership with CERN as one of its major member states, matures.

With my best regards,

Swapan Chattopadhyay

Swapan Chattopadhyay
Director, Cockcroft Institute

Copy:

Prof. Walter Oelert
Institut fur Kernphysik
Forschungszentrum Julich
52425 Julich
Germany