THE ELENA PROJECT AT CERN

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(Received December 8, 2014)

CERN has a longstanding tradition of pursuing fundamental physics on extreme low and high energy scales. The present physics knowledge is successfully described by the Standard Model and the General Relativity. In the anti-matter regime, many predictions of this established theory still remain experimentally unverified and one of the most fundamental open problems in physics concerns the question of asymmetry between particles: why is the observable and visible universe apparently composed almost entirely of matter and not of anti-matter? There is a huge interest in the very compelling scientific case for anti-hydrogen and low energy anti-proton physics, here to name especially the Workshop on New Opportunities in the Physics Landscape at CERN which was convened in May 2009 by the CERN Directorate and culminated in the decision for the final approval of the construction of the Extra Low ENergy Anti-proton (ELENA) ring by the Research Board in June 2011. ELENA is a CERN project aiming to construct a small 30 m circumference synchrotron to further decelerate anti-protons from the Anti-proton Decelerator (AD) from 5.3 MeV down to 100 keV.

DOI:10.5506/APhysPolB.46.181
PACS numbers: 29.20.–c, 36.10.–k, 37.10.De, 41.20.–q

1. Introduction

The layout of the ELENA ring [1, 2] with its main components is sketched in Fig. 1. Controlled deceleration in a synchrotron equipped with an electron cooler to reduce the emittances in all three planes will allow the existing AD experiments to increase substantially their anti-proton capture efficiencies and render new experiments possible. The ELENA design is now well advanced and the project is moving to the implementation phase. Component design and construction are taking place at present for installation foreseen during the second half of 2015 and the beginning of 2016 followed by ring

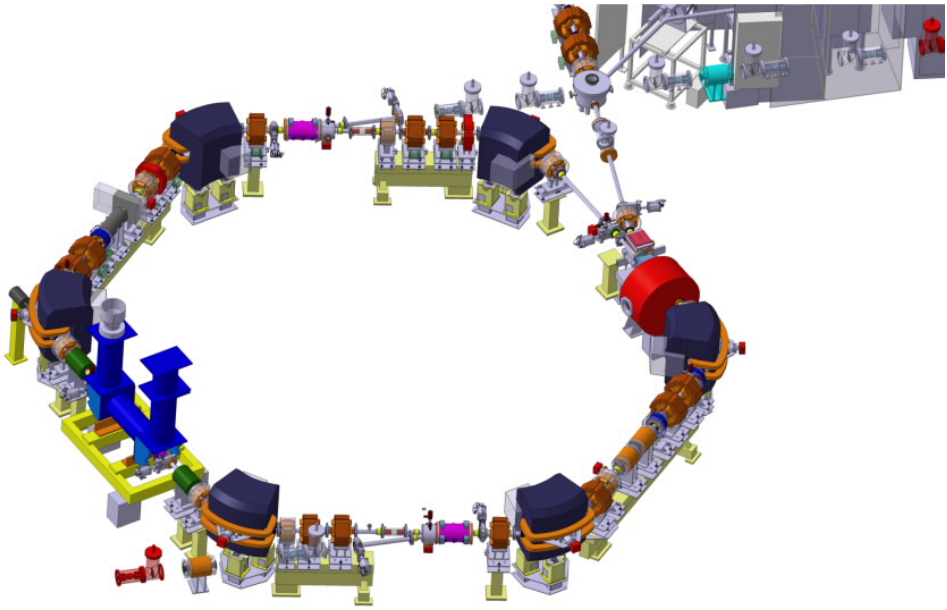


Fig. 1. Layout of the ELENA ring and its components.

commissioning until the end of 2016. New electrostatic transfer lines to the experiments will be installed and commissioned during the first half of 2017, followed by the first physics operation with ELENA. Basic limitations like intra beam scattering limiting the emittances obtained under electron cooling and direct space charge effects is reviewed, and the status of the project is reported. In that sense, ELENA is an upgrade of the Anti-proton Decelerator (AD) [3] at CERN and is devoted to experiments for physics using low energy anti-protons. The AD is a unique facility constructed after the completion of the exploitation of the Low Energy Anti-proton Ring LEAR and providing low 5.3 MeV energy anti-protons to experiments. Most experiments further decelerate the beam using degrader foils or a decelerating Radio Frequency Quadrupole RFQD, and then capture the beam in traps. Both processes to decelerate are not optimal and lead to significant anti-proton losses. Deceleration with a degrader foil is limited by energy straggling such that, even with optimized thickness, many anti-protons are stopped in the foil and annihilate there and many still have a too high energy to be trapped; this results in a trapping efficiency well below 1%. Matching to the RFQD is difficult, in particular in the longitudinal plane, and physical emittances increase during the deceleration resulting in losses.

The ELENA project aims at constructing a small 30.4 m circumference synchrotron to improve the trapping efficiencies of existing experiments by one to two orders of magnitude by controlled deceleration in a small synchrotron and reduction of the emittances with an electron cooler. New types of experiments will become feasible. The anti-protons will be injected at 5.3 MeV, an energy reachable safely in the AD and then decelerated down to 100 keV possible with such a small ring. Electron cooling will be applied at an intermediate plateau and at the final energy. Moreover, ELENA will not send the full available intensity in one bunch to one experiment, but send several (baseline four) bunches with lower intensity to several experiments. The resulting longer runs for the experiments are considered an advantage despite the lower intensity. A sketch of the ELENA machine in the AD hall is shown in Fig. 2. The main physics topics at ELENA are the anti-hydrogen production with consecutive studies of the features of this anti-matter atom, the anti-proton–nucleon interaction by testing the QED to extremely high precision as well as the demanding question of the gravitation force between matter and anti-matter.

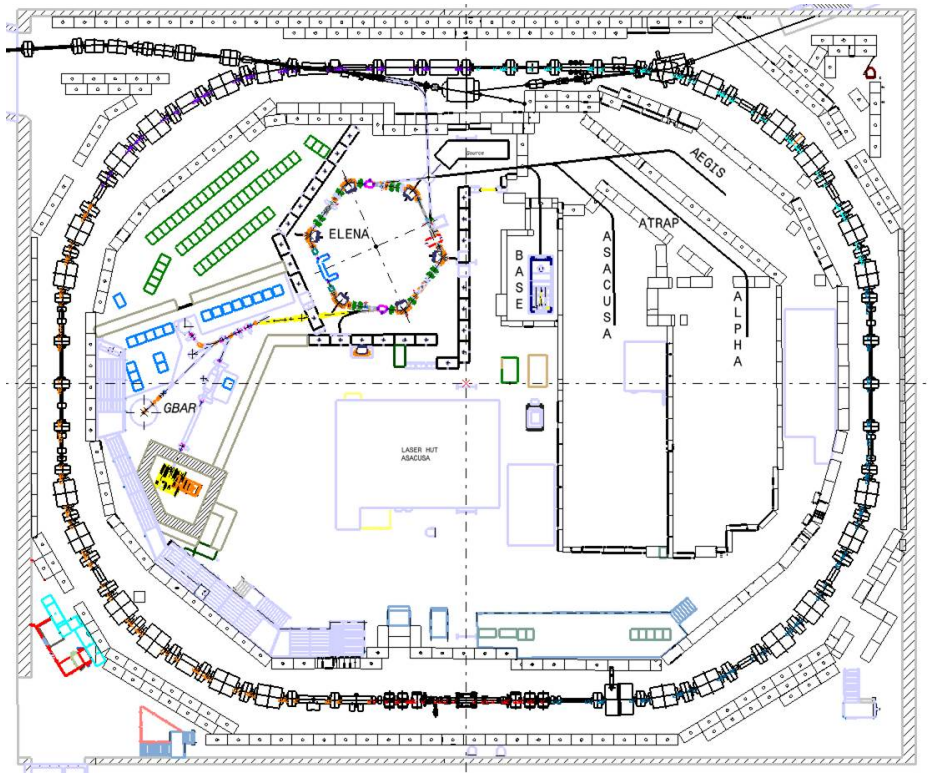


Fig. 2. ELENA in the AD Hall, where in the inner part of the AD ring the experiments are hosted as well.

2. ELENA main features

The main features and possible issues of the new facility ELENA are:

— ELENA is operated at an unusually low energy for a synchrotron with a magnetic focusing structure. Thus, any possible performance limitation has to be evaluated with particular attention to the low beam energy. Many of the features listed below are the consequence of this unusual energy range.

— The machine will be located inside the existing AD hall. This is an economic solution as no large additional building is needed to house the new ring and experiments, and further more allows for keeping existing experiments at their present location. A smaller new building has been completed recently in order to free space in the AD hall for the ELENA ring and a second experimental area.

— The lattice design has to cope with typical difficulties for small machines as few quadrupole families to adjust optics parameters, constraints on lattice parameters to be fulfilled and to deal with strong focusing due to the bending magnets. An important condition was to find a layout suitable for installation in the AD hall and compatible with the position of the injection, and the two extractions towards the foreseen experimental areas. The ELENA ring has hexagonal shape and two-fold periodicity (neglecting the perturbation of the lattice due to the cooler). Two slightly longer straight sections without quadrupoles house the electron cooler with associated equipment and the injection line. Three quadrupole families (one magnet of each family in each of the remaining four sections) allow adjusting the lattice.

— A good magnetic field quality has to be guaranteed despite the very low magnetic fields required and remanence and hysteresis effect. From the beginning of the project, it had been foreseen to apply thinning, *i.e.* mixing of non-magnetic stainless steel laminations with magnetic laminations, for the main bending magnets; this increases the magnetic flux density in the magnetic laminations and reduces hysteresis effects. Quadrupole prototypes are constructed to test whether thinning is appropriate for quadrupoles and, possibly, sextupoles as well. Orbit correctors will be constructed without magnetic cores to avoid any effects related to hysteresis.

— Electron cooling will be applied at an intermediate energy of around 650 keV to reduce emittances before further deceleration and avoid losses, and at the final energy of 100 keV. The design of the ELENA cooler is based on the one constructed for the L-LSR ring in Kyoto,

but with parameters optimised for our case. First simulations of electron cooling at 100 keV predicted final energy spreads of the coasting beam by about one order of magnitude larger than expected initially. With adiabatic bunching without electron cooling, this would have led to energy spreads at the limit of the acceptance of the transfer lines and unacceptable for some experiments. In order to reduce the energy spread of bunches sent to the experiment, bunched beam electron cooling will be applied by keeping the cooler switched on during the capture process.

— Emittance blow-up due to intra beam scattering is expected to be the main performance limitation and to determine, together with the performance of electron cooling, the characteristics of the beams extracted and sent to the experiment.

— Beam diagnostics is challenging due to the low intensity and velocity. For example, the lowest beam currents are well below 1 A, which is well below the capabilities of standard slow beam current transformers. Thus, the intensity of coasting beams during electron cooling will be determined by Schottky diagnostics using optimised pick-ups. Further diagnostics in the ring are low noise position pick-ups (precision better than 0.1 mm), a tune measurement BBQ system, a scraper to determine destructively emittances and possibly an ionization profile monitor (feasibility under study). Diagnostics in the lines comprises TV stations, GEM monitors and micro-wire profile monitors.

— Cross sections for interactions with rest gas molecules as scattering out of the acceptance or emittance blow-up become large at low energies. These effects have to be evaluated with care paying attention to the very low energy in order not to overestimate emittance blow-up. The machine will be fully bakeable and equipped with NEG coatings wherever possible in order to reach the challenging nominal pressure of 3×10^{-12} Torr and to guarantee that interactions with rest gas is not the main performance limitation.

— An RF system with a rather modest RF voltage of less than 500 V is sufficient for deceleration and to create short bunches at extraction. However, the system has to cover a large dynamic range.

— Direct space charge detuning is a significant effect despite the low intensity due the low energy and short bunches required for the experiment and would result in tune shift of almost -0.4 with only one extracted bunch. As mitigation measure, the available intensity will be split into several bunches to serve several experiments almost simultaneously.

— Extraction and transfer to the experiments is based on electrostatic elements as this is an efficient low-cost solution at these low energies.

— Commissioning of the ELENA ring will be done mainly with an external source providing H-ions or protons in parallel to AD operation for experiments. This allows injecting beam with a higher repetition rate than would be possible with anti-protons and a bunch every 100 s from the AD, and is expected to speed up commissioning despite the fact this implies starting at the lowest energy.

3. AD-ELENA performance

In operation since the end of 1999, the AD is an all-in-one machine which collects anti-protons, decelerates them in three steps via first stochastic and then electron cooling down to a momentum of 100 MeV/c or 5.3 MeV kinetic energy. A typical cycle lasts $\approx$ 110 seconds, delivers about 3×10^{7} $\bar{p}$ per pulse of $\sim$ 150 ns length. The foreseen cycle of ELENA has a length of about 25 seconds and fits well into the AD cycle. Thus, the overall timing sequence of available anti-proton bursts will still be determined by the AD cycle. The basic parameters for AD and for ELENA are presented in Table I and Table II, respectively.

TABLE I

AD — Basic Parameters.

Item	Value	Dimension
Circumference	182	m
Production beam	1.5×10^{13}	protons/cycle
Injected and cooled beam	4×10^{7}	anti-protons/cycle
Beam momenta max/min	3.6/0.1	GeV/c
Momenta for beam cooling:		
— stochastic cooling	3.6 and 2.0	GeV/c
— electron cooling	0.3 and 0.1	GeV/c
Transverse emittances	200–1	π mm mrad
Momentum spread	6×10^{-2}–1×10^{-4}	$\Delta p/p$
Average vacuum pressure	4×10^{-10}	Torr
Cycle length	100	s
Deceleration efficiency	85	%

TABLE II

ELENA — Basic Parameters.

Item	Value	Dimension
Circumference	30.4	m
Beam momenta max/min	100/13.7	MeV/c
Energy range max/min	5.3/0.1	MeV
Working point	2.3/1.3	Q_x/Q_y
Ring acceptance	75	π mm mrad
Intensity of injected/ejected beam	$3.0 \times 10^7/1.8 \times 10^7$	
Number of extracted bunches	≤ 4	
Emittances (h/v) of extracted bunches	4/4	π mm mrad [95%]
$\Delta p/p$ of extracted beam	2.5×10^{-3}	[95%]
Bunch length at 100 keV	1.3/300	m/ns
Required (dynamic) vacuum	3×10^{-12}	Torr

4. Physics at ELENA

ELENA will increase the number of useful anti-protons by one to two orders of magnitude and will allow serving up to four experiments simultaneously. Beam lines from ELENA to various experiments are shown in Fig. 3. The motivation for ELENA was driven by the perspective to increase the efficiency of the anti-proton facility with its compact and time consuming experiments, and by the steadily growing interest of additional research groups to share the available beam time. In particular, concrete motivations from the physics side arise in a number of theoretical approaches extending the es-

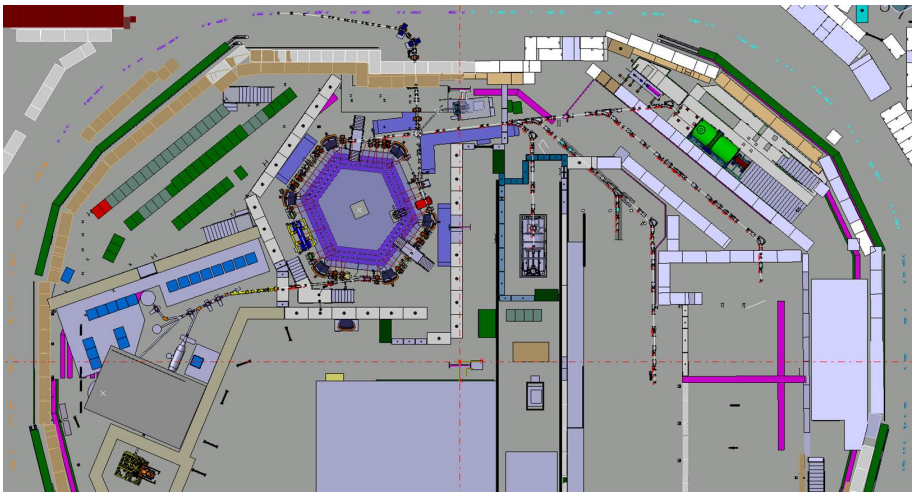


Fig. 3. ELENA and the beam lines to the different experiments in the AD Hall.

tablished model frame work including a consistent unified description of the corner stones of physics: Lorentz symmetry, quantum mechanics and gravity. Experiments with anti-protons will substantially increase the knowledge of atomic, nuclear and particle physics by testing precisely familiar interactions and fundamental constants, by studying discrete symmetries and by searching for new interactions. These days anti-hydrogen atoms are produced frequently by three collaborations at the AD: ATRAP [4], ALPHA [5], and ASACUSA [6] employing essentially similar methods. Whereas ATRAP and ALPHA produce anti-hydrogen at rest, ASACUSA produces a beam of these atoms for hyperfine transition studies in low magnetic fields. In 2002, both first the ATHENA Collaboration and shortly thereafter the ATRAP Group announced the creation of the first cold anti-hydrogen. Still, since the neutral anti-hydrogen atom is unaffected by the electric fields used to trap its charged components the anti-hydrogen hits the trap walls and annihilates very soon after its creation.

High-precision tests of the properties of anti-hydrogen in magnetic minimum traps can only be performed if the anti-hydrogen atoms are cold enough to be hold in place for a relatively long time. The anti-hydrogen atoms have a magnetic moment which interacts with an inhomogeneous magnetic field; low field seeking anti-hydrogen atoms can be trapped in a magnetic minimum. In fall 2010, the ALPHA Collaboration reported first the success of 38 trapped anti-hydrogen atoms. A year later, life times of more than 15 minutes of the anti-hydrogen atoms were observed by both collaborations ALPHA and ATRAP. Finally, ALPHA reported on the very first spectroscopy of an anti-matter atom, demonstrating the observation of resonant quantum transitions in anti-hydrogen by manipulating the internal spin state.

In addition, new supplementary experiments at the AD, as AEGIS [7] and GBAR [8] are presently preparing for precise measurements of the gravitational interaction between matter and anti-matter. Further, the BASE [9] Collaboration suggested a measurement of the magnetic moment of the anti-proton increasing the precision by a factor of 1000 as compared to the successful recent result of the ATRAP Group at the AD.

The basic concept of the ELENA ring and transfer lines to the experiment is completed, the TDR [2] is published, and the design and the integration of components are ongoing. The place inside the AD hall, where ELENA will be installed, will only be made available during the first part of 2015, when the kicker equipment can be moved to the new building, which is finished in its body shell. After installation in 2015 and 2016, the commissioning of the ELENA ring is planned for the second half of 2016 in parallel to AD operation mainly with the help of a dedicated source delivering 100 keV protons and H-ions. During the first part of 2017, the existing magnetic transfer lines from the AD to the experiments will be dismantled

and the new electrostatic lines from ELENA installed. After commissioning of the new electrostatic lines, first beams for physics are expected in the second half of 2017.

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