ELENA: FROM THE FIRST IDEAS TO THE PROJECT

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Abstract

Successful commissioning of the CERN Antiproton Decelerator (AD) in 2000 was followed by significant progress in the creation of anti-hydrogen atoms. The extraction energy of the decelerated antiprotons is nevertheless very high compared to that required by the experiments and results in a trapping efficiency of only 0.1% to 3%. To improve this value by an order of magnitude the study of an Extra Low ENergy Antiproton ring (ELENA) started in 2003 and was approved as a CERN construction project in 2011. During these years the choice of the main machine parameters such as the beam extraction energy, emittance and bunch length were defined, taking into account requests from the physics community. The main challenges were also identified, such as dealing with the large space charge tune, the ultra-high vacuum required and the tight requirements for the electron cooler. Housing the ELENA ring within the AD hall significantly reduced the project cost as well as simplifying the beam transfer from AD to ELENA and from ELENA to the existing experimental areas. This contribution will follow ELENA from its beginnings to the final, approved project proposal.

INTRODUCTION

CERN has provided experiments with antiprotons since 1980 and is the world's unique source of low energy antiprotons. In the shadow of the discovery of the W and Z bosons in the SPS, the Low Energy Antiproton Ring (LEAR) contributed to a number widely recognised scientific successes that include:

- The most precise comparison of the charge-to-mass ratio for the proton and antiproton resulting in the most stringent test to date of CPT invariance with baryons.
- Some of the most precise studies of CP violation.
- First observation of fast anti-hydrogen atoms.

LEAR was stopped in 1996 for its conversion to an ion accumulator ring (LEIR) but since 2000 the Antiproton Decelerator (AD) has continued to deliver low energy antiproton beams to experiments mainly concerned with the production, trapping and spectroscopy of anti-hydrogen atoms. Large numbers of anti-hydrogen atoms are now routinely produced and more recently the collaborations have managed to trap these antiatoms for sufficiently long periods such that ALPHA has been able to perform the first microwave spectroscopy studies.

FIRST IDEAS ON ELENA

Already in the LEAR era many experiments requested a facility which would provide antiprotons at energies much lower that the extraction energy of the LEAR ring [1,2]. They all required a resonant extraction system to make more efficient use of the available beam. The first proposal for such a ring was made in 1982 [3] and was baptised "ELENA" for Extra Low ENergy Antiproton ring. Fig. 1 shows the proposed layout consisting of four 90° bending D-magnets and four straight sections of 1.4 length each. The ring circumference of 7.85 m corresponded to 1/10 the LEAR circumference and all magnets were to be equipped with pole face windings to allow the fine tuning of the ring parameters. One of the straight sections would also be equipped with an electron cooler to ensure a small beam emittance at the low energy plateau of 200 keV. The length of the deceleration cycle was to be about 7 seconds, in which the beam would be cooled, decelerated to 200 keV and then resonantly extracted during 100 ms.

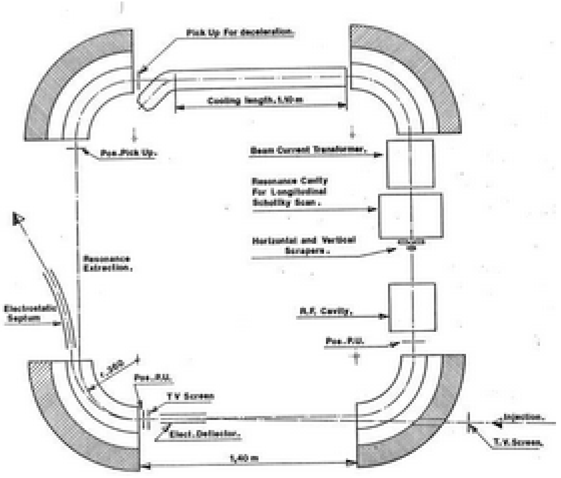

Figure 1: The first ELENA proposal (1982).

Table 1: Main Parameters

Kin. Energy range	5 Mev	200 keV
Momentum range	100 MeV/c	20 MeV/c
Circumference	7.85 m	
Bending radius	0.37 m	
Magnetic field	0.9 T	0.18 T
Tune	$Q_h = 1.63$	$Q_v = 1.43$
e gun voltage	2870 V	113 V
e current	20 mA	0.16 mA
Magnetic guiding field	380 G	76 G
Cooling length	1.1 m	

ELENA AS AN EXTENSION TO THE AD

The AD is an "All-In-One" machine which is in operation since 2000. It collects antiprotons, decelerates them in four 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 about 100 seconds, delivers about 3×10^7 in a pulse of 150 ns length.

Most of the AD experiments (ALPHA and ATRAP) need antiprotons with 3 to 5 keV kinetic energy, significantly lower than 5.3MeV which is the lower limit of AD. Today antiprotons from the AD are decelerated further down by sets of degraders. This results in poor efficiency due to adiabatic blow up of beam emittances and due to scattering and annihilation. Less than 0.5 % of AD beam can be trapped.

At ASACUSA an RFQD is used for antiproton deceleration to around 100 keV kinetic energy. However, deceleration in the RFQD is accompanied by adiabatic blow up (a factor 7 in each plane) which causes significant reduction in trapping efficiency. RFQD operation is also very sensitive to trajectory and optics mismatch errors often resulting in difficult and time consuming tuning of the AD to RFQD transfer line. About 70% of the beam is lost after passing through the RFQD after which beam transport is difficult due to large transverse beam sizes (about 160mm).Typically, about 3-5% of the AD antiprotons can be captured at ASACUSA.

The idea of using a smaller ring to further decelerate the antiproton beam to an energy where the trapping efficiency could be greatly enhanced was revived in 2003 with an initial study of a new ELENA ring.

In this initial design a number of constraints had to be taken into account given the AD environment and the need to reduce costs, the most important of these being:

- Must be compact to fit in the available space inside the AD Hall.
- One long straight section for electron cooler is required.
- Must be placed in AD Hall in an optimal way for the transfer of antiprotons from AD and deliver them to existing and additional experimental areas.
- Must be placed in the AD Hall in a way to minimize the reshuffling of existing equipment.
- The initial part of existing AD ejection line should be used (constraints on position and orientation of ELENA ring).
- The Laser Hut of the ASACUSA experiment should stay in place.

Fig. 2 shows the first version of the new ELENA ring. It consisted of 4 90º C-shaped combined-function bending magnets, two long straight sections for injection/ejection and electron cooling, and two shorter straight sections for diagnostics and the RF cavity needed for the deceleration. The total circumference was 21.9 m with an extraction energy of 100 keV (13.7 MeV/c) defined by the requirements of the physics experiments and accelerator beam issues that one can encounter in a compact low energy ring, namely:

- Space charge limit for antiproton beam.
- Beam lifetime: residual gas, IBS at extraction energy.
- Vacuum pressure in the machine ($3 \cdot 10^{-12}$ Torr average)
- Good quality of electron beam for cooling (limited by space charge of electron beam).
- Foil thickness for separation of transfer line and trap vacuum.

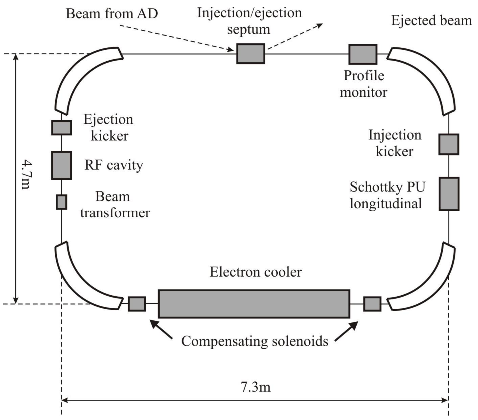

Figure 2: ELENA in 2003.

The above layout evolved somewhat in the feasibility and cost study that was conducted in 2007 [4]. The ring circumference was increased to 26.06 m (1/7 of the AD circumference) and the bending blocks were split into two. This increase in circumference was necessary in order to accommodate for the extra multipole magnets that had been inserted at the exit of each new 45º bending magnet. The multipoles would enable a better control and fine tuning of the ring optics (Fig. 3).

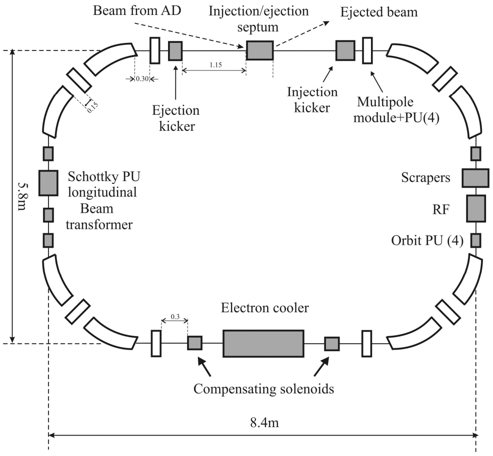

Figure 3: ELENA proposal in 2007.

A radical change in the ELENA design was made in the period 2007 – 2010 when a number of new proposals for experiments at the AD were presented to the SPSC [5,6]. It became clear that without a significant increase in the intensity of antiprotons effectively available to the experiments and the possibility to install new experiments in the hall, the AD physics program could not evolve [7].

For the updated feasibility study presented in 2010 [8], the ELENA design adopted a hexagonal shape with six straight sections roughly equal in length. Three sections are used for the injection and ejection elements, one for electron cooling and the two remaining for the RF, instrumentation and eventually a small internal target experiment (Fig. 4). To overcome the intensity limitations due to space-charge at low energy it was also decided to opt for an extraction scheme where the intensity is divided into four equal bunches and delivered to four different experiments quasi-simultaneously.

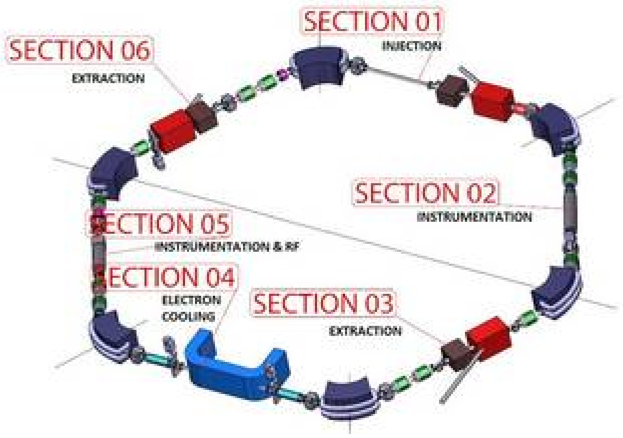

Figure 4: The new ELENA layout.

The use of combined-function magnets was dropped in favour of three quadrupole families, skew quadrupoles for the correction of the residual coupling due to the electron cooler solenoid and sextupoles for the chromaticity correction. The main benefits of the new design can be summarised as follows:

- More flexibility for injection and extraction.
- The total length of bending magnets is shorter, leaving more space for other equipment.
- The minimum magnetic field in the bending magnets (at 100 keV) is increased from 399 G to 493 G.
- The new 6 fold ring with its circumference increased to 30.4 m has a wider choice of tunes compared to the former design.
- Smaller beta function values resulting in a much reduced aperture required by the beam.

The location of the ring was also moved further away from the existing experimental zones, unfortunately increasing the distance from the existing experimental area, but opening up the possibility of having a new zone to install up to two new experiments.

ELENA assembly and commissioning will have a negligible impact on the current AD operation. In fact, the commissioning of the ring could take place in parallel with the present physics program with short periods dedicated to commissioning during the physics run.

The AD experimental area layout will not be significantly modified, but the much lower beam energies require the design and construction of completely new electrostatic transfer lines.

Table 2: Present ELENA Parameters

Kin. Energy range	5.3 Mev	648 keV	100 keV
Momentum range	100 MeV/c	35 MeV/c	13.7 MeV/c
Circumference	30.4 m		
Tune	$Q_h = 2.3 \quad Q_v = 1.3$		
Ring vacuum	3×10^{-12} Torr		
$N_{particles}$ injection	3×10^7		
$N_{particles}$ ejection	1.8×10^7		
$N_{bunches}$ ejection	1 to 4		
ε_h & ε_v at ejection	4 / 4 µm (95%)		
ΔP/P after cooling	2×10^{-4} (95%)		
e gun voltage		354 V	55 V
e current		10 mA	0.5 mA
B_{ecool}	100 G		
Cooling length	0.8 m		

ELENA was approved as a CERN project in June 2011 and work is continuing in fine-tuning the machine parameters in order to meet all the physics requirements [9]. Ring commissioning is scheduled for 2015 with the installation and setting-up of the electrostatic beam lines a year later.

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