ELENA PROJECT STATUS

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Abstract

The Extra Low Energy Antiproton ring (ELENA) is a small ring at CERN which will be built to increase substantially the number of usable antiprotons delivered to the experiments for studies with antihydrogen and antiprotonic nuclei. The project is now at stage of finishing the technical design. This presentation reviews the major features of ELENA: the ring, transfer lines and experimental area layout, the choice of the basic machine parameters and the main challenges. Electron cooling plays a key role in ELENA both for efficient deceleration as well as for preparing extracted beam with parameters defined by the experiments. The choice of machine optics as a tool for achieving the required parameters and fitting the available space is discussed. The important systems like the magnets, vacuum, beam instrumentations and others are reviewed as well.

INTRODUCTION

The construction of ELENA ring will allow significantly increase intensity of antiproton beam which is now delivered to experiments. The AD beam extracted energy is 5.3 MeV, while most experiments need antiprotons at 3-5 keV which is defined by trap voltage. Further deceleration is done with degrading foils where particles lose energy and straggle (see Fig.1). As result only 0.3% of antiprotons are captured into trap.

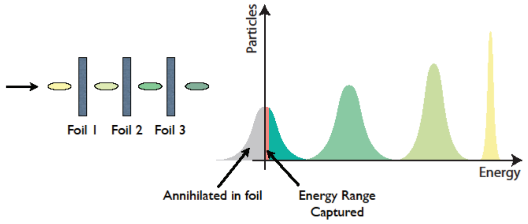

Figure 1: Antiproton deceleration after AD.

With much lower extracted beam energy in ELENA compared with that in AD, the degrading foil still needed, but very thin (Fig.2). The capture efficiency is very high (~30%) because straggling spread is of order of kV.

The particular choice of extraction energy E=100 keV is defined by space charge limit due to incoherent tune shift, strong IBS (intra-beam scattering), high vacuum about $3\cdot10^{-12}$ Torr is required for good lifetime [1]. Extra advantage is a possibility to equip ELENA extraction lines with electrostatic elements. Finally, the foil between extraction line and trap is mandatory to separate high vacuum in trap from lower in line, and its thickness of 1µm is a technology limit.

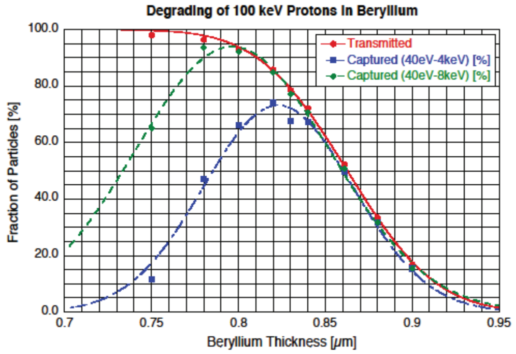

Figure 2: Antiproton deceleration in foil after ELENA.

RING LAYOUT

The ELENA machine will be installed in the AD hall which allows keeping existing experimental areas in place. Its position and orientation inside of AD ring is chosen to make the beam injection and two beam extractions in the most efficient way [2], with minimal strength of kickers and septum (Fig.3). The extraction towards the existing experiments (ASACUSA, ALPHA, ATRAP, ACE and AEGIS) and one coming soon (BASE) is made from the top right of the ring, and towards future experiments one of which (GBAR) is approved, is made from the bottom left part of the ring.

An 800 mm thick concrete shielding around the new machine and the new experimental areas is sufficient to ensure radiation levels in case of total beam loss of below 3 µSv/h at any point in the hall and below 0.5 µSv/h on the planned visitor platform.

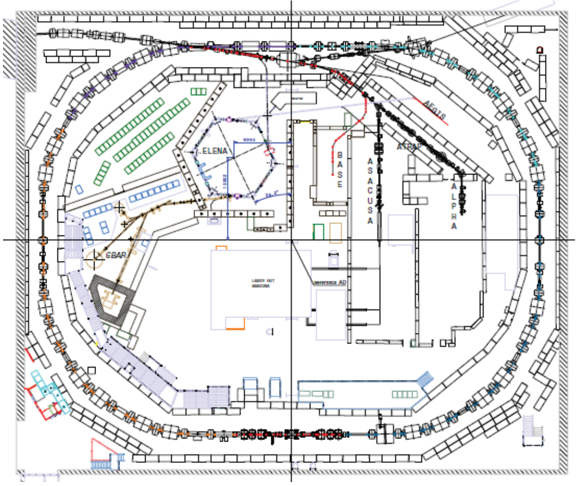

Figure 3: AD hall layout with ELENA and experimental areas.

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BEAM TRANSFER FROM AD TO ELENA

Initial part of AD extraction line will be used for beam transfer to ELENA. It will be modified significantly to start separation of ELENA beam as soon as possible. The separation is made by two bending magnets of 40° each (Fig.4). The rest of the line up to injection septum is equipped with extra quadrupoles, combined correctors, instrumentation and vacuum equipment.

While the Twiss functions matching at the kicker position is possible, the dispersion matching is impossible due to its zero value at the beginning of line and special line geometry. Yet mismatches of dispersion and its derivative are minimized to reduce emittance blow up during injection into ELENA. To reduce blow up further down, electron cooling in AD will be applied during bunch compression right before beam extraction, resulting in reduction of ejected beam momentum spread. Special care to reduce beam coherent oscillation after injection will be taken as well.

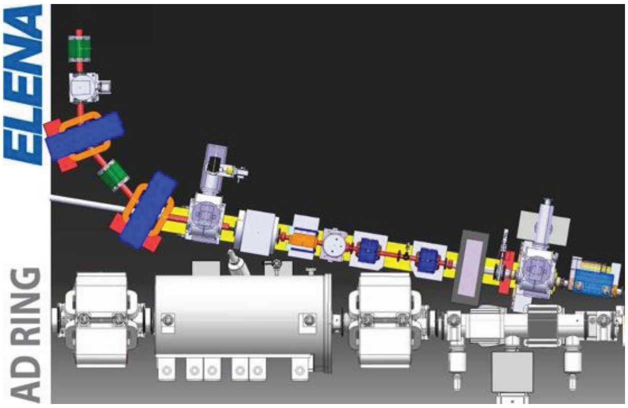

Figure 4: Initial part of ELENA injection line.

THE ELENA CYCLE

Right after injection into ELENA at 100 MeV/c the beam is decelerated to 35 MeV/c where electron cooling is applied first time to reduce emittances and momentum spread. Cooling is applied a second time after deceleration at extraction momentum of 13.7 MeV/c in order to achieve required values for beam emittances and momentum spread (Fig.5). The final goal is delivering to experiments beam with $1\sigma_{x,y}$~1 mm.

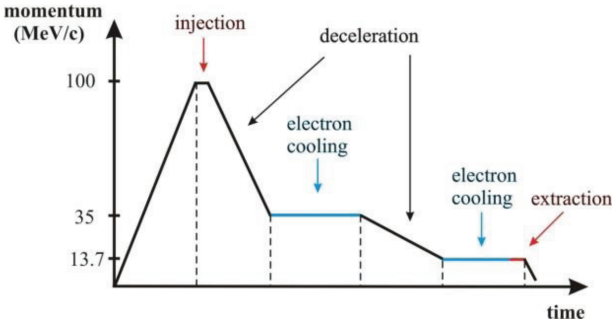

Figure 5: Schematic view of ELENA cycle.

After cooling, beam is bunched at harmonic *h*=4 and compressed to make each bunch 1.3 m long, and extracted to the experiments. Choice of extracted beam parameters is mainly limited by transverse space charge, resulting in control of emittances at the end of the cooling process. The main parameters of ELENA are given in Table 1.

Table 1: ELENA Machine and Beam Parameters

Momentum range, MeV/c	100 – 13.7
Energy range, MeV	5.3 – 0.1
Circumference, m	30.4
Intensity of injected beam	$3 \cdot 10^{7}$
Total intensity of ejected beam	$1.8 \cdot 10^{7}$
Number of extracted bunches	4
Emittances (h/v),π·mm·mrad,[95%]	4 / 4
$\Delta p/p$ of extracted beam, [95%]	$2.5 \cdot 10^{-3}$
Bunch length at 100 keV, m /ns	1.3 / 300
Required (dynamic) vacuum, Torr	$3 \cdot 10^{-12}$
Machine tunes h/v	2.3/1.3

RING LATTICE AND MAIN LIMITATIONS

ELENA optics choices are strongly dictated by various constraints [3]. A circumference *C*=30.4 m (equal to 1/6 of the AD ring) was chosen to provide enough space for equipment. Hexagonal ring layout was found the best suitable for beam injection and two extractions within the designated AD Experimental Area.

The tune choice is dictated by main intensity limitation imposed at extraction energy by space charge (incoherent tune shift, see below). Two possible working points have been considered, both near the coupling difference resonance. One is Q_h=2.3, Qv=1.3 and another one is Q_h=1.3, Qv=2.3.

The choice of the length of bending magnet is a delicate issue for ELENA ring. The longer bending magnet makes smaller contribution to the beam focusing and easy optics adjustment. On the contrary side, the shorter bending magnet allows operating at extraction energy with magnetic field not too small. In addition, shorter magnets provide more space for other equipment placement, which is very critical for ELENA ring due to limited space inside of AD hall. These resulted in compromised value of bending length 0.97 m and a magnetic field in ELENA at extraction energy of 493 G.

With these parameters focusing done by bending magnet is significantly stronger than that by any of the quadrupoles. By varying the edge angle at the entrance and exit of bending magnet one can make this focusing stronger in one or another plane. Three quadrupole families are used to control tunes and to some extent beta function values in the electron cooler. The maximal beta

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function values throughout of the ring as well as the vertical beta function value in bending magnets have been under control as well.

It was found that optics is optimal with edge angle of 17° for tunes Q_h=2.3, Qv=1.3. The "inversed tunes" (Q_h=1.3, Qv=2.3) have been abandoned due to high dispersion in electron cooler.

The lattice functions are shown in Fig. 6. Neglecting small effect of electron cooler on optics, one can consider ELENA ring with periodicity of 2.

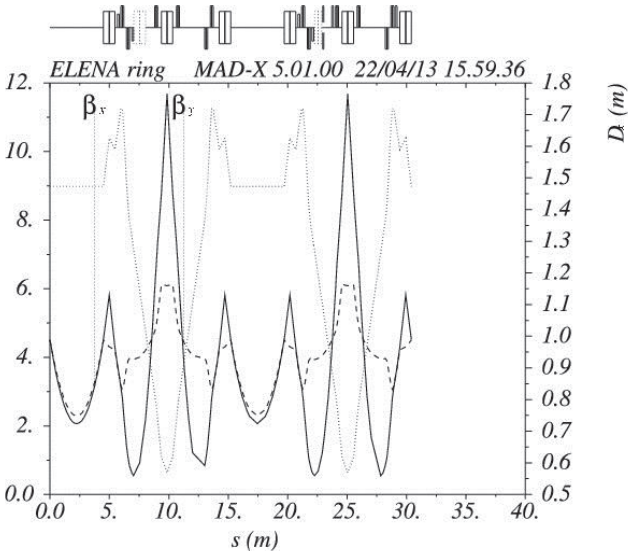

Figure 6: ELENA ring lattice functions.

The first order chromaticity correction is done with 2 families each consisting of 2 sextupoles. The members of the same family placed in identical positions of each period of the ring (Fig.6). Due to strong focussing in bending magnets it is not easy to find proper positions for sextupoles in ELENA. To facilitate that, one has to foresee a proper separation of the horizontal and the vertical beta functions.

The main intensity limitations in ELENA are imposed at the extraction energy by incoherent tune shift due to space charge and by IBS. Both are most critical during a short time at the end of bunch compression before beam extraction. The incoherent tune shift is given by

$$\Delta Q = -\frac{G_T r_p N_b}{2\pi\varepsilon_x \beta^2\gamma^3}\frac{G_L C}{l_b}.$$

Here r_p =1.54·10^{-18} m, factors G_T=1÷2 and G_L=1÷2 depend on transverse and longitudinal beam distributions. With 60% of deceleration efficiency in ELENA (see Table 1) for the basic scenario with 4 extracted bunches the number of particles in one bunch is N_b=0.45·10^7. At extraction energy β =1.46·10^{-2}, the bunch length l_b=1.3m (300ns), beam emittances $\varepsilon_{x,y}$=4π mm mrad, G_T=G_L=2 the tune shift is ΔQ=-0.12, which is on the safe side for ELENA due to proper choice of the working point and weak nonlinearities in machine. Yet it can be reduced by factor ~2 with flattened longitudinal beam distribution by superimposing RF voltage harmonics 4 and 8. The use of double harmonics makes possible to put in future extraction of 3 and 2 bunches as well.

First studies of residual gas effects showed that with a pressure of 3·10^{-12} Torr many antiprotons do not interact at all during a typical 100 keV plateau with a rest gas molecule [4]. Thus, both beam losses due to large angle scattering and blow-up due to small angle scattering are dominated by single scattering events. Both loss rates and blow-up (neglecting particles undergoing large angle scattering) are significant, but not yet a serious limitation.

ELECTRON COOLING

The cooler will be based on the device that was built for the S-LSR ring [5] in Japan and will incorporate adiabatic expansion to reduce the electron beam temperature as well as electrostatic bending plates for efficient collection of the electron beam. Work is on-going to optimize the gun design and cooling simulations using BETACOOL [6] will help to fine-tune the final parameters of the cooler. The electron cooling section consists of the cooler itself, two compensating solenoids to compensate the coupling produced by main solenoid, and two combined orbit correctors to align antiproton beam w.r.t. electron beam of the cooler. The beam position monitors are placed inside of orbit correctors (Fig.7). The main parameters of the cooler are specified in Table 2.

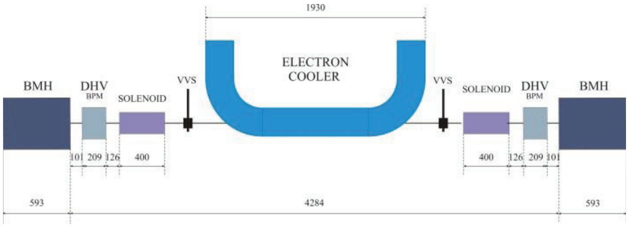

Figure 7: Schematic layout of electron cooling section.

Table 2: Electron Cooling Parameters

Momentum	35 MeV/c	13.7 MeV/c
β	0.037	0.015
E beam energy	355 eV	55 eV
E current	5 mA	2 mA
Drift section length, m	1.0	
Expansion factor	10	
Cathode radius	7.9 mm	
E beam radius	25 mm	

At the extraction energy the IBS is strong and it is the limiting factor for equilibrium beam emittances and momentum spread at the end of cooling, which value is $\Delta p/p$ (95%) $=1\cdot10^{-3}$ [7]. Then the coasting beam is captured into RF bucket and compressed to make it as short as 1.3 m. The momentum spread value at the end of bunch compression is value $\Delta p/p$ (95%) $\sim7.5\cdot10^{-3}$ which is too high for efficient beam transport in electrostatic lines. The initial studies of bunched beam cooling with the BETACOOL program showed that this value can be significantly reduced by extension of the cooling to the beam capture and compression processes [8]. To use electron cooling effectively, beam bunching must be done slower in about 1 sec. As result a final momentum spread of $\Delta p/p$ (95%) $\sim2.5\cdot10^{-3}$ is achieved.

VACUUM

Beam physics considerations call for an average pressure of around $3\cdot10^{-12}$ Torr and a gas composition mainly given by hydrogen and low-Z gas species, meaning extreme high-vacuum regime (XHV).

All vacuum chambers are made of austenitic stainless steel with low permeability, e.g. 316LN. Vacuum firing all materials in-house is considered. Massive NEG-coating is applied everywhere possible, in order to reduce the gas load and obtain a distributed pumping profile for getterable gases. Additional pumping is installed on each dipole magnet and on each straight section, by using integrated NEG and ion-pump combinations. Additional pumping is foreseen on the injection and on the two extraction elements and on the electron-cooler, possibly using NEG-strips on the latter as done on the AD machine, but the details of this have not been defined yet. The vacuum system is designed for a 300° C bakeout and NEG-coating activation and all-metal gate valves and ConFlat-type joints are envisaged everywhere. Similar solutions are implemented for the experimental beam lines: a low net outgassing rate is particularly important in the area near the ELENA ring, as backstreaming of gas species from the experimental beamlines to the ring should be minimized, given the average pressure requirements.

BEAM INSTRUMENTATION

To measure the closed orbit during the deceleration cycle 10 electrostatic H&V beam position monitors will be installed inside 6 ring quadrupoles and 4 orbit correctors. Their expected resolution is 0.1 mm with an accuracy of 0.3 to 0.5 mm. A prototype should be ready in 2013 and the manufacturing of the units will follow a year later. Design of PU, analogue electronics as well as digital acquisition is optimized in view of using the 20 BPM's as one big Shottky PU.

The tune measurement system based on the BBQ systems used on other rings [9] will use one pick-up to provide the tune evolution throughout the cycle.

As in the AD, it is planned to use a high sensitivity longitudinal Schottky pick-up to measure the beam intensity.

Scrapers will be used to destructively measure the transverse profile (and hence emittance) of the circulating beam. Ionisation profile monitors could also be used but they have the detrimental effect of inducing a strong transverse kick on the beam and the gas injection system required to increase the ionisation rate will cause a large bump in pressure around a significant proportion of the circumference.

ELECTROSTATIC TRANSFER LINES

At 100 keV, a single fast electrostatic separator can be used to extract all bunches at once with subsequent switching into the different transfer lines. One extraction will serve the four existing and one new experimental lines while the other can serve two new experiments (Fig.8). The total length of lines are about 100 m. A preliminary geometric design of the beam lines aims at maximising the distance from superconducting magnets of the experiments which can disturb the beam trajectory in the transfer lines during the field ramp. Seven fast separators are used to distribute extracted bunches to the different experiments.

In addition H^-/p beams can be injected into ring for commissioning from the dedicated source via 4m beam line. The installation of the source imposes extra constraints on the optics design and some hardware elements.

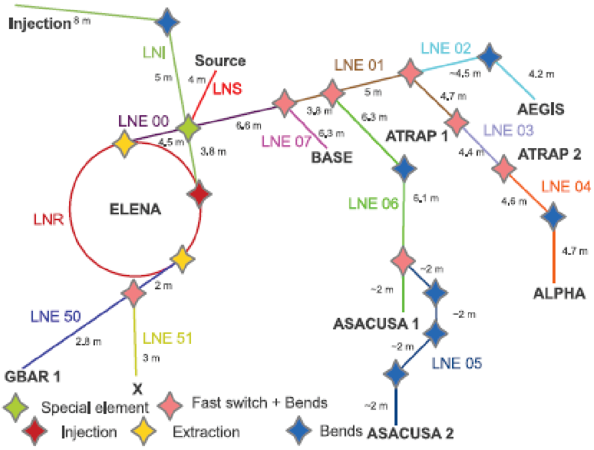

Figure 8: Schematic layout of ELENA transfer lines. The upper extraction delivers beams to existing experimental area, the lower extraction to the new experimental area.

During the geometry optimization studies the number of different bending angles was minimized [10]. This resulted in average bending angle of about 48°. Small deviations from this angle will be adjusted by redistributing the voltage on the plate. The fast extraction devices will be both used for extraction from ELENA as well for fast switching in the transfer lines.

An electrostatic switchyard will be installed at the crossing of injection and upper extraction transfer lines. The protons and H^- ions will be deflected there by ±53.75°. Protons can be injected either via ejection channel with normal polarity of ELENA ring, or via the injection line with inverted polarity of the ring (see Fig.9), which is useful for the lattice studies and for tests of electron cooling (if lifetime of H^- ions will be poor). At the same time free passage of injected and extracted antiproton beams must be possible.

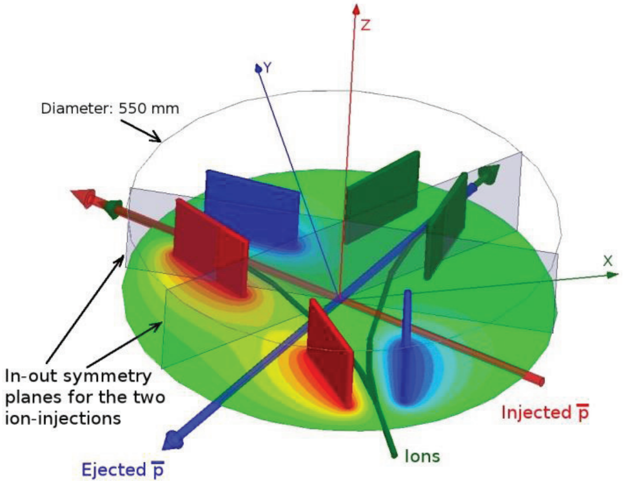

Figure 9: 3D model and simulated field (upper part only) of the switchyard.

The steering and focussing elements in the lines are considered to be electrostatic. Preliminary optics studies suggest a maximum operation voltage for quadrupoles of 5 kV considering a full aperture of 60 mm. The vacuum chamber will be equipped with up to three shielding layers to avoid influence from magnetic stray fields. Low-energy beam profile monitors [11] are foreseen to measure beam position and profile. Cherenkov counters for the timing profile and aluminium activation foils for absolute intensity measurement are envisaged [11].

PLANNING

For ELENA design, construction, installation and commissioning the main milestones and planned activities are:

- Summer 2013: Publish Technical Design Report.
- 01/2013 – 02/2014: AD Hall modifications.
- 04/2014: AD Hall extension (new building) completed.
- 12/2014 – 04/2015: Move kicker generators to new location.
- 01/2015 – 03/2016: ELENA installation.
- 12/2015 – 03/2016 connection ELENA to AD.
- 04/2016 – 11/2016: ELENA ring commissioning in parallel with the physics program.
- 12/2016 – 05/2017: Installation of new electrostatic beam lines to the experiments.
- 05/2017 – 08/2017: Commissioning of the new beam lines.
- 08/2017: Start of physics with 100 keV antiprotons.

CONCLUSION

The Technical Design Report of ELENA is at its final stage now. With beam extraction energy of 100 keV the number of trapped antiprotons at the experiments expected to be one to two orders of magnitude bigger compared to now. The layout of the ring, its injection line and transfer lines to experiments are fixed. The proposed lattice makes beam transfer convenient. In addition it provides safe operation with essential space charge at extraction energy. The bunched beam cooling is proposed to improve momentum spread of extracted beam which makes easy its transfer through electrostatic beam lines to experiments. The design of the main systems is close to completion. The base line for ELENA is operation with 4 extracted bunches, which will be sent to different experiments by use of fast electrostatic deflecting elements. Nevertheless options to operate with a smaller number of extracted bunches and higher intensities are foreseen as next steps.

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