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LOW-ENERGY NEGATIVE ION INJECTION BEAMLINE FOR EXPERIMENTS WITH ANTIPROTONIC ATOMS AT AEgIS

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Abstract

The interaction of low-energy antiprotons with nuclear targets provides fundamental knowledge about proton and neutron densities of many nuclei through the capture process, cascade on lower electron orbits, and annihilation with the nucleon. The expelled electrons produce X-rays and with the recoil particles after annihilation, thus, a sufficient amount of information can be obtained about this interaction. However, all previous experiments were done via formation of antiprotonic atoms in solid or gaseous targets. Therefore, annihilation occurs prior to reaching the S or P orbital levels and precise measurements are missing. Recently, the AEgIS collaboration [1] proposed a conceptually new experimental scheme. The creation of cold antiprotonic atoms in a vacuum guarantees the absence of the Stark effect. And with sub-ns timing and synchronization, previous experimental obstacles would be resolved. This will allow atomic properties, evolution, and fragmentation processes to be studied with improved precision and extended lifetimes. In this paper, an overview of the experimental scheme is given, along with details on the negative ion injection beamline in the AEgIS experiment.

INTRODUCTION

Novel approaches to study bound systems containing antiprotons such as light anti-nuclei, protonium, and other atoms or ions, where one of the orbital electrons is replaced by an antiproton will create new opportunities for studies into fundamental processes in nuclear and atomic physics.

Antiprotonic atoms may become a “swiss knife" that will uncover various properties of different nuclei, stable and radioactive isotopes, in a more precise way. Two of the well-known applications of such atoms, are the identification of neutron and proton densities on the surface of the nucleus, and the estimation of the neutron skin thicknesses for neutron-rich atoms [2]. The annihilation of antiprotons is most likely followed by meson emission, with the dominating process being pion production.

The reconstruction of annihilation inside antiprotonic atoms confined in a trap, paves the way for event-by-event detection of the emitted X-rays along with the determination of the charge multiplicity of the annihilation, We are able to resolve antiproton annihilations on protons (secondary pion charge = 0) from those on neutrons (secondary pion charge = −1) as long as all secondaries resulting from the annihilation are identified correctly.

In some cases, a final nucleus ${}^{A-1}_{Z-1}X$ or ${}^{A-1}_{Z}X$ may have a recoil energy that is low enough to remain trapped inside a particle trap. These fragments will help further understand the interaction between an antiparticle and an initial atomic nucleus.

Additionally, investigations into antiprotonic systems will allow a wide range of exotic physics topics covered in the recent reviews about existing and approachable in the near term experiments with an antimatter to be investigated [3–5].

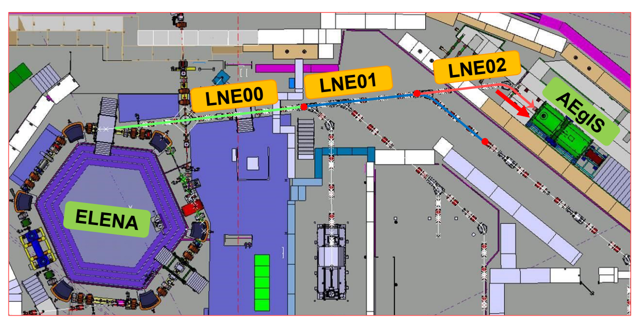

Figure 1: Top view CAD model of part of the AD hall with ELENA and the AEgIS experiment highlighted. Antiproton transfer is done via three electrostatic sections (LNE).

Low energy operation will improve atom formation and the trapping efficiency of antiprotons that is required for the proposed studies. Thus, the ELENA ring [6] in CERN’s Antimatter Factory remains the only facility capable of providing low energy (100) antiproton bunches, which are further slowed down to trappable energies (<5 keV) using drift tubes, an RFQ or moderating foils.

AEgIS is one of the experiments located in AD hall [1], performing studies into the formation of $\bar{H}$ and, primarily, gravity experiments with cold antimatter. The CAD model

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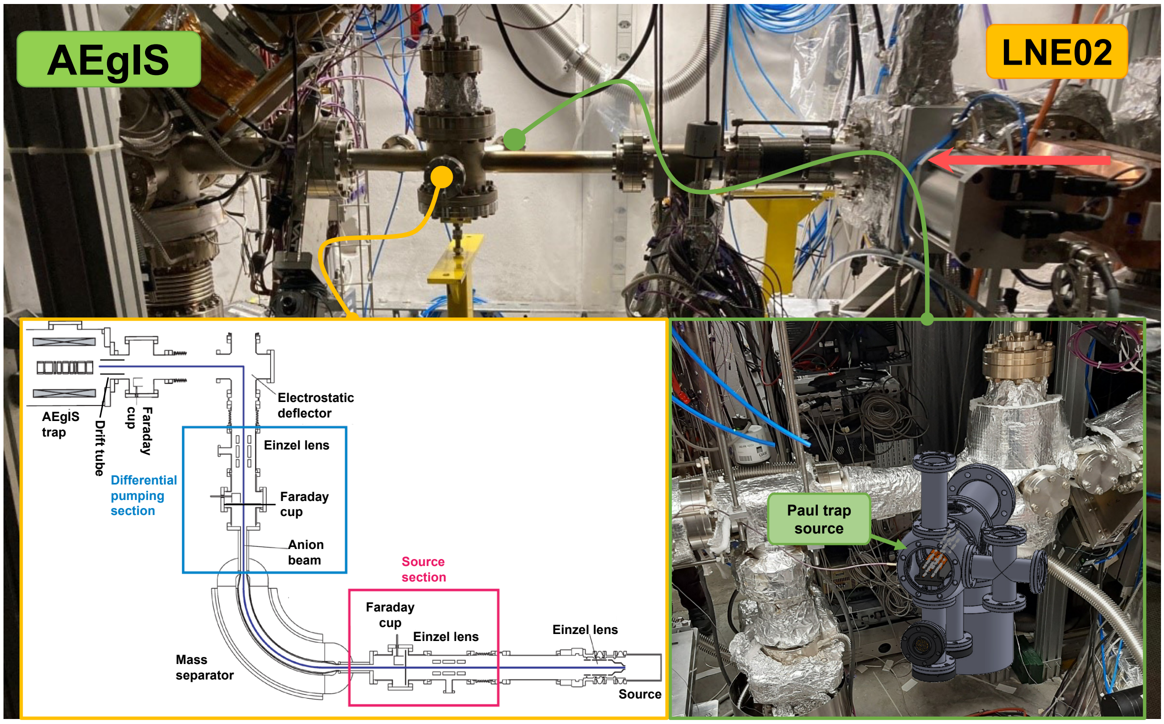

Figure 2: Suggested connection points for anion sources. Branch schematics for Cs sputter source (Bottom left). The first vision of the future connection for the Paul trap source (Bottom right).

of this experiment, together with the ELENA ring and electrostatic beam lines guiding antiprotons, are shown in Fig. 1.

Lately, the AEgIS collaboration proposed an experimental scheme to perform an experimental studies with antiprotonic bound systems. Unlike the PUMA experiment [2], the production of ion species will be done in situ via additional Paul trap and/or sputter sources.

To improve the current experimental beamline and allow simultaneous usage of three beams, we present a new beamline concept after the antiproton beam handover point and realistic simulations of the ion injection into the AEgIS experiment.

THE PROPOSED SCHEME

The future AEgIS experimental plans include the capability to operate two different anion production schemes, either using iodine in a Paul trap or caesium sputter sources.

Thus, any new beamline needs to allow the passage of an antiproton bunch and provide bending of both anion species. Another functionality that is highly desirable is backward extraction from the trap. The initial relative position and junction points for both ion sources are shown in Fig. 2. In order to provide more space for the ion beam optics it was decided to replace the junction chamber (∅ 100 mm) with a larger chamber (∅ 160 mm). Additionally, due to space limitations, the initial connection at 90° for the caesium source was decreased to 75°. An electrostatic focusing and deflection scheme was chosen as the preferable option due to the low energy of the anions and the mass independence of the electrostatic fields. The suggested beamline design will be able to handle low anion currents up to 10 µA in continuous or bunched mode operation, and provide deceleration via a drift tube before injection into the trap.

DEFLECTION CHAMBER DESIGN

Due to the standalone nature of the ion beamline and its small dimensions, the design was carried out in CST Studio [7] where anion beam tracking is possible. An intermediate design of the bending section is given in Fig. 3. Most of the

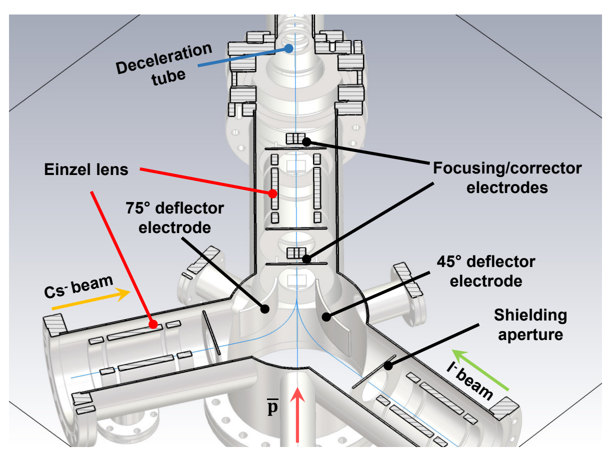

Figure 3: Parallel cut of the deflection chamber design created in CST. The main components are labeled. Thin blue lines correspond to the ideal trajectory of the particle from both branches. Two sets of corrector electrodes provide additional beam steering or focusing.

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optical and bending elements are separated via grounded shields. The design of the vacuum chamber and beam pipe was limited by practical aspects (vacuum level of the LNE02 beamline, accessibility, voltage limits of 10 kV) and the required functionality.

Properties of Einzel Lenses

The scheme in Fig. 3 includes three Einzel lenses. These are made of three cylindrical electrodes for round beam operation. These lenses are always focusing and do not change the energy of the transmitted particle. The focusing properties of this type of lens are symmetrical. The first and third electrodes are at the same beamline potential V_0, and the middle electrode has a different potential V_M. The Einzel lens focusing properties depend on the geometry of the lens and voltage ratio V_0/V_M.

An Einzel lens has two operating modes depending on the V_M/V_0 ratio. When we consider negatively charged particles and $(V_M/V_0) < 0$, the lens works in acceleration-deceleration (A-D) mode, else, the lens works in deceleration-acceleration (D-A) mode. Figure 4 shows the geometry of the lens in the proposed design and the focal strength dependency on the central electrode voltage.

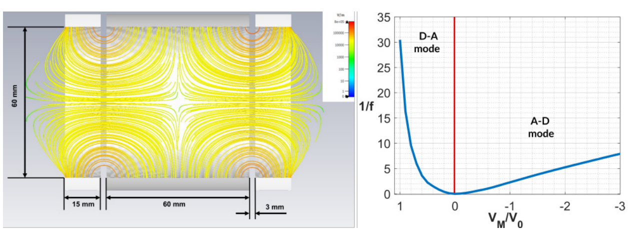

Figure 4: Cut of the Einzel lens designed in CST (left). The highest field is created near the gaps between the electrodes. The focusing strength depends on the potential ratio (right).

ION BEAM TRACKING

Tracking through the beamline for both angles has been performed, and results are shown in Fig. 5. The 2 keV iodine beam with a radius of 10 mm was utilized. The potentials were applied to one of the sides at a time (Einzel lens and bending electrode). In practice, the deflection chamber will be able to operate in DC and bunched beam modes. The Einzel lens after the bending is kept at 5.5 kV. For more energetic anion beams all voltages can be simply scaled up by a known linear factor.

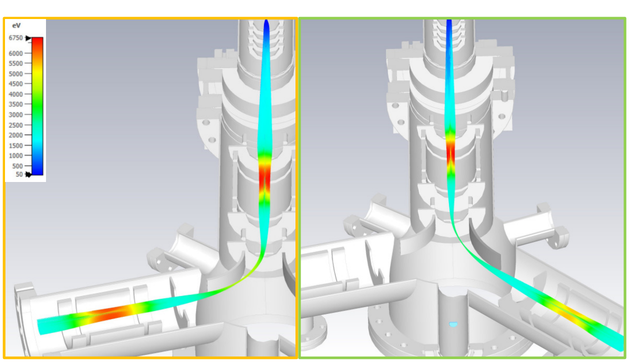

Figure 5: Tracking of 2 keV iodine beam in CST. Focusing in both deflection cases, 75° (left) and 45° (right), occurs close to the middle of the bending electrode.

Three sets of correctors, the first after the deflector, the second after the last Einzel lens, and the last one further downstream, will help keep the orbit close to the design orbit in the presence of magnetic stray fields. In order to test the performance of the correctors, the magnetic field from previous studies [8] was included into tracking simulation, taking into account only the closest 5 T solenoid, as shown in Fig. 6. The amplitude of the field close to the deflection chamber is ≈ 0.01 T.

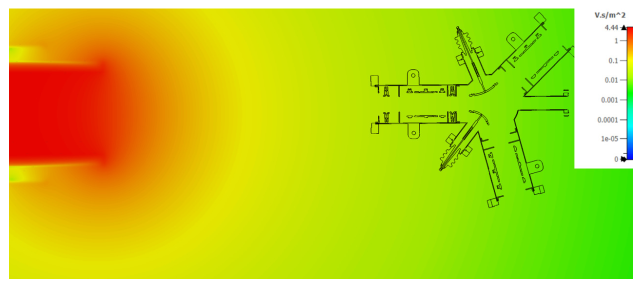

Figure 6: Magnetic field distribution, coming from the 5 T AEgIS solenoid, overlapping with the position of the deflection chamber.

CONCLUSIONS AND OUTLOOK

The proposed design of a new anion injection system for the AEgIS experiment was presented. This system will enable various experiments with antipotonic bound systems. Optimization targeted maximum transmission for antiproton bunches and the beams coming from two short branches with ion sources. The proposed scheme utilizes Einzel lenses and asymmetrical cylinder sectors for bending.

Currently, most of the injection system components are being fabricated. The aim is to tune the system and perform injection and trapping of ions from the Paul trap source by the end of 2022. The layout satisfies the requests from the AEgIS collaboration for future studies.

The proposed simulation framework has proven to provide reliable results for parameter tuning with both, DC and bunched beams.

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