A Low Energy H^- Beamline for the ALPHA Antihydrogen Experiment

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Abstract. The CERN ALPHA experiment makes precision measurements of antihydrogen atoms, confined in a superconducting magnetic minimum trap. Recent measurements of the antihydrogen spectrum have already provided high-resolution tests of fundamental symmetries, and ALPHA has now embarked on an ambitious upgrade programme aimed at directly comparing hydrogen and antihydrogen within their existing atom trap. One aspect of this upgrade will be the development of a low-energy (50 eV) hydrogen ion source that is compatible with ALPHA's existing magnetic charged particle beamlines. PELLIS, previously developed at JYFL, is a 5 keV filament-driven source that generates H^- beams with low emittances and currents of up to 50 μA. Here, we explore the feasibility of a proposed electrostatic beamline design to transport H^- ions from a PELLIS-type ion source into ALPHA's various particle traps. We present SIMION simulations that were used to develop the beamline, focusing on components such as a quadrupole switchyard and drift tube deceleration stage.

1. Introduction

The ALPHA experiment at the CERN Antiproton Decelerator makes precision measurements of antihydrogen ($\overline{\mathrm{H}}$) atoms confined in a superconducting magnetic minimum trap. Comparing the spectrum of the familiar hydrogen atom to that of its antimatter counterpart provides unique, high-resolution tests of fundamental symmetries, and may help to explain the dominance of matter over antimatter in our universe. In recent years, the ALPHA collaboration has made landmark measurements of several features in the antihydrogen spectrum, including its narrow 1S-2S transition [1] and 1S-2P Lyman-alpha transitions [2]. To improve on these measurements, ALPHA is pursuing an ambitious upgrade programme to carry out high-precision measurements of both hydrogen and antihydrogen atoms in the environment of its existing atom trap.

In a typical ALPHA experimental cycle, antihydrogen is produced by mixing around 10^5 antiprotons ($\bar{\mathrm{p}}$) with a cold plasma of 3×10^6 positrons (e^+) inside a nested Penning-Malmberg trap. The $\bar{\mathrm{p}}$ and e^+ are initially confined in separate Penning traps several metres apart, and must be transferred into one of ALPHA's two $\overline{\mathrm{H}}$ mixing traps before antihydrogen synthesis can take place. At ALPHA, charged particles are transferred between Penning traps as low-energy (50 eV) pulsed beams, produced by rapidly (1 μs) manipulating the electric potential along the axis of one trap so that particles are ejected in one direction. These $\bar{\mathrm{p}}$ and e^+ beams are born in strong axial magnetic fields, and have a number of properties that make them difficult to transport using conventional magnetic or electrostatic beamlines. Instead, positrons and antiprotons are guided between ALPHA's various particle traps through a series of solenoid magnets, which provide continual steering and focusing in the transverse plane. At low energies, the $\bar{p}$ and e^+ will adiabatically follow the direction of the magnetic field, and so steering can be achieved using a region of curved magnetic field lines [3].

In order to produce hydrogen atoms using techniques similar to those described above, a source of low-energy protons or H^- ions would need to be added to the ALPHA apparatus. This ion source should be compatible with ALPHA's existing magnetic beamlines, so that low-energy ions can be transported into either of the $\overline{H}$ mixing traps and and used to form atomic hydrogen. The PELLIS ion source [4], previously developed at the University of Jyväskylä (JYFL), is a 5 keV filament-driven source that generates H^- beams with low emittances and currents of up to 50 μA. PELLIS could potentially be used as an H^- source for ALPHA due to its modest beam current and low extraction energy. However, this ion source cannot be connected directly to the existing ALPHA experiment, and its integration presents a number of challenges.

In this work, we explore the feasibility of using an electrostatic beamline to transport H^- ions from a PELLIS-type ion source into ALPHA's various particle traps. We present SIMION simulations that were used to develop and characterise the proposed beamline design, focusing on key elements including an electrostatic quadrupole deflector and decelerating drift tube section.

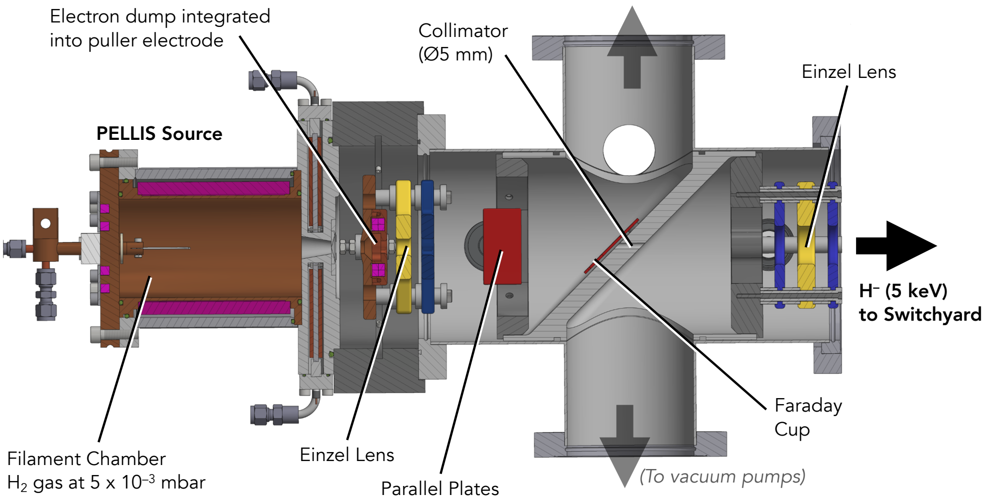

Figure 1. Diagram showing a cross-section of the PELLIS ion source, together with its extraction optics installed inside the differential pumping chamber.

2. PELLIS Source

The PELLIS ion source (shown towards the left of Figure 1) was originally developed by Kalvas et al. [4] to provide low-emittance H^- beams for the Pelletron accelerator at JYFL. A detailed description and characterisation of the PELLIS source itself is beyond the scope of this work, and has already been given elsewhere. However, we will give a brief overview of the H^- source parameters and extraction optics as pertains to this study.

PELLIS is a filament-driven multicusp ion source that produces H^- beams with energies in the range of 5 – 15 keV. Typically, the filament chamber is filled with H_2 gas at a pressure of 5 $\times 10^{-3}$ mbar, such that a filament (arc) current of 5.6 A will produce 50 μA of H^- beam current. In this study, the source and its extraction optics have been configured to operate at a nominal energy of 5 keV. The H^- beam emerges from the 2 mm plasma electrode aperture with a 95% normalised rms emittance of 0.015 mm mrad.

Figure 1 shows the PELLIS source and its associated extraction optics, which have been modified slightly for this application. Beam extraction simulations were carried out using IBSimu [5]. Several electrostatic elements are integrated into a custom vacuum chamber, which acts as the first stage of a differential pumping system between PELLIS and ALPHA's existing beamline. A 20 mm long, 5 mm aperture at the centre of the chamber acts as both a collimator for the H^- beam and a pumping restriction between the ion source and the rest of the beamline.

Electrons that are co-extracted with the H^- beam are deflected into an electron dump using a pair of permanent magnets, which produce opposing dipole-antidipole fields. The ion beam is largely unaffected by these deflector magnets, but emerges from the puller electrode at a small ($\sim$5 mrad) angle to its original velocity. This offset will be corrected using a set of parallel plates approximately 128.5 mm from the plasma electrode. Pulsing the voltage on the parallel plates will chop the H^- beam into short pulses, so that ions are only delivered to ALPHA when required. A typical pulse will be around 1 μs in duration, corresponding to a bunch charge of 50 pC or $\sim 3.1 \times 10^8$ H^- ions. A Faraday cup mounted around the collimator will be used to monitor the beam current between shots.

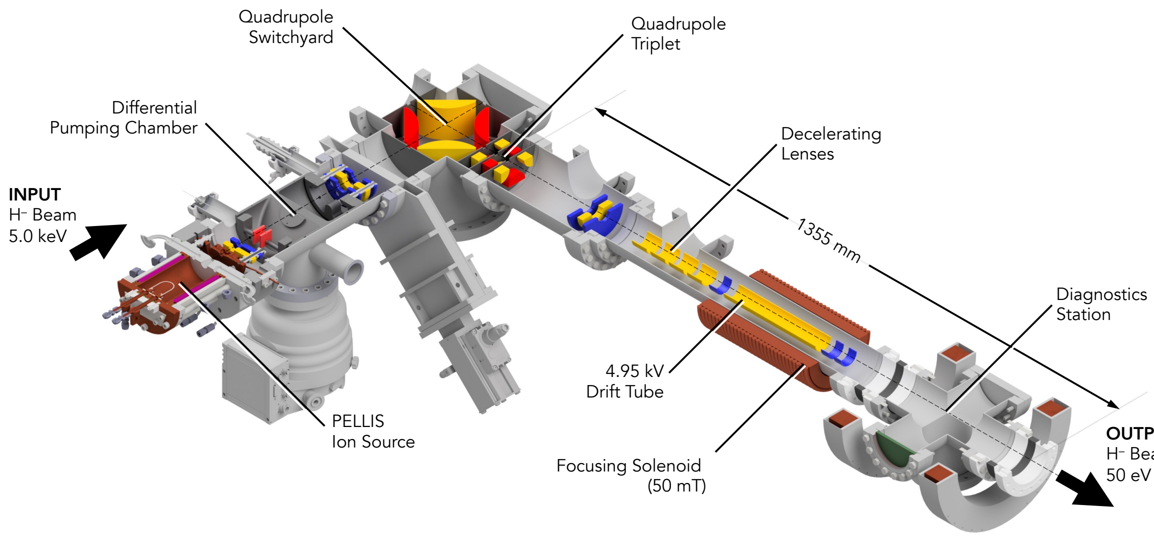

Figure 2. Diagram showing a cross-section of the proposed beamline design to transport H^- ions into the ALPHA experiment from a PELLIS-type ion source.

3. Beamline Design

Figure 2 shows a cross-section of our proposed beamline design to decelerate H^- bunches and transport them into the ALPHA experiment. The PELLIS source is connected to the main beamline through an electrostatic quadrupole deflector (the 'switchyard'). The switchyard is intended to maximise the flexibility of the beamline, so that additional ion sources and particle traps can be installed in future without further modifications to the apparatus.

The four electrodes that form the quadrupole switchyard each have a radius of 80 mm, and an inscribed radius of 53.3 mm. Based on an analytical model for an ideal quadrupole deflector [6], the required field strength for a 5 keV H^- beam is 0.864 V/mm^2, corresponding to electrode voltages of $\pm$2.46 kV. Simulations of the transport beamline, including the switchyard, were carried out using SIMION [7]. Figure 3 shows the simulated trajectories of 5 keV H^- ions through the quadrupole deflector. Within the switchyard, space charge effects were modelled

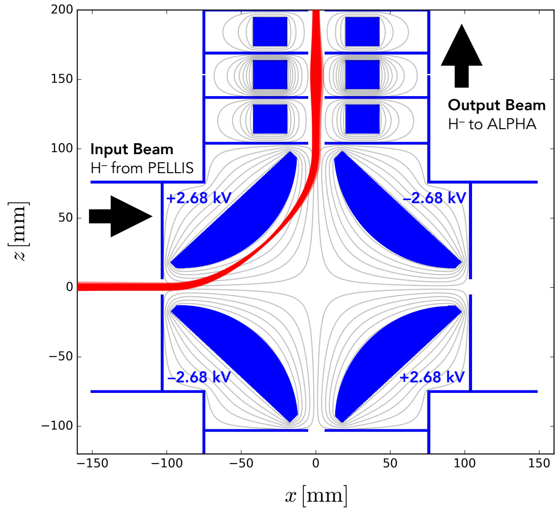

Figure 3. SIMION simulation showing the trajectories of 5 keV H^- ions through the quadrupole switchyard. The contour lines show the electric potential in 400 V intervals.

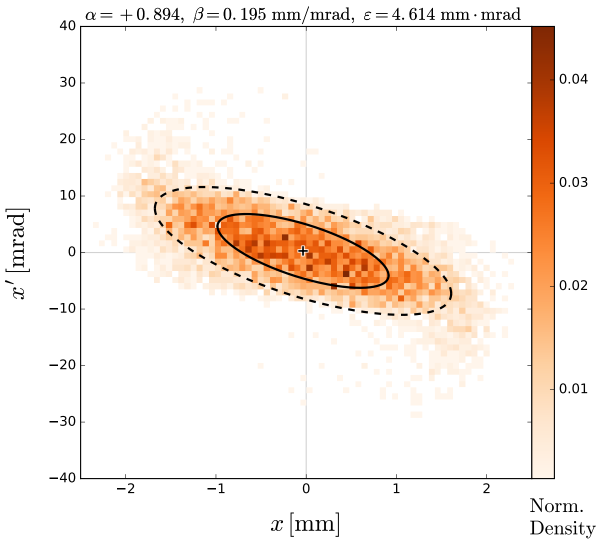

Figure 4. Simulated transverse (horizontal) phase space of the H^- beam after the final focusing quadrupole.

using SIMION's built-in beam repulsion method. In this simulation, the electrode voltages were increased to ±2.68 kV to compensate for field errors around the input and output of the deflector, so that the beam is well-aligned as it leaves the switchyard.

Upon leaving the switchyard, the H^- beam is no longer circular, with an rms radius of 0.86 mm along its horizontal axis, and 1.40 mm along its vertical axis. An electrostatic quadrupole triplet was added after the switchyard to correct this, and to match the two transverse phase spaces of the beam. The beam emerges from the quadrupole triplet with a slightly converging envelope and an rms beam radius of 0.96 mm. Figure 4 shows the transverse (horizontal) phase space immediately after the final quadrupole.

Before entering ALPHA's existing beamline, H^- pulses are decelerated to ∼50 eV using a 250 mm long drift tube, as shown in Figure 2. The drift tube voltage is switched from 4.95 kV to ground within 100 ns as the beam transits along its length. Since the ions lose 99% of their initial kinetic energy upon entering the drift tube, care must be taken to avoid blow-up of the beam profile inside the narrow (20 mm radius) electrode. A series of decelerating lenses were added before the drift tube to prevent large transverse electric fields from rapidly defocusing the beam. Figure 5 shows the configuration of these lenses and their effect on the H^- trajectories calculated using SIMION. Within the drift tube, space charge effects were represented using SIMION's built-in particle-in-cell solver.

To produce atomic hydrogen using H^-, ions must be introduced into one of ALPHA's two $\overline{\mathrm{H}}$ mixing traps, where there is a strong (1 T) axial magnetic field. To avoid losses due to magnetic mirroring, H^- pulses must therefore transit from the electrostatic portion of the beamline into ALPHA's existing magnetic beamlines with very small transverse velocities. As shown in Figure 2, the drift tube is enclosed by a solenoid magnet that generates an axial field of ∼50 mT. This solenoid provides transverse focusing for H^- bunches in transit along the drift tube, and also helps to guide ions into the magnetic field of ALPHA's existing beamline. The voltages applied to the decelerating lenses were optimised to limit the transverse energies of H^- within the drift tube, thereby minimising the number of ions lost due to magnetic mirroring.

Upon leaving the drift tube, each 50 eV H^- pulse has a normalised emittance of

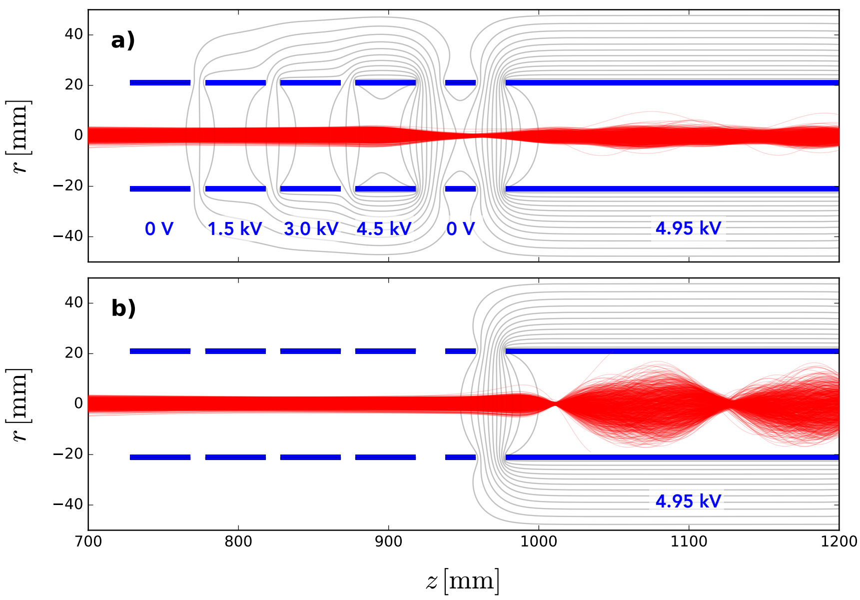

Figure 5. SIMION simulation showing H^- ion trajectories through the decelerating lenses and drift tube a) with the lenses turned on and b) with the lenses grounded. The contour lines show the electric potential in 400 V intervals.

0.019 mm mrad, indicating some emittance growth during deceleration. The final beam radius is on the order of 1 mm and can be adjusted by changing the magnetic field within the drift tube section. Extending the simulation to track ions into either of ALPHA's $\overline{\text{H}}$ mixing traps suggests that only $< 1\%$ of ions are lost in transit, primarily due to magnetic mirroring effects and ballistic losses within the drift tube section.

4. Summary and Outlook

In these proceedings, we have briefly outlined the motivations for adding an H^- source to the ALPHA antihydrogen experiment. We have explored the feasibility of an electrostatic beamline design to transport 5 keV H^- ions from a PELLIS-type ion source into ALPHA, and to decelerate the beam to a final energy of just 50 eV. Using extensive SIMION simulations, we have shown that the beamline meets its design criteria and maintains the low emittance of the PELLIS source. Initial assembly of the ion source and differential pumping chamber are scheduled for November 2021, with commissioning to take place on the VESPA test stand at STFC ISIS [8].

References

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