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

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1. Introduction

The ALPHA experiment, based at the CERN Antiproton Decelerator, makes precision measurements of **antihydrogen atoms** held in a superconducting magnetic minimum trap. ALPHA has recently made several landmark measurements of the antihydrogen spectrum, providing unique high-resolution tests of fundamental symmetries [1]. To improve on these studies, ALPHA is pursuing an ambitious upgrade programme to carry out high-precision **spectroscopy of both hydrogen and antihydrogen** in its existing atom trap.

This upgrade would require the development of a **low-energy (~50 eV) proton or H⁻ ion source** that is compatible with ALPHA's existing magnetic charged particle beamlines. Here, we explore the feasibility of using a proposed electrostatic beamline design to transport H⁻ ions from a **PELLIS-type ion source** into ALPHA's various particle traps.

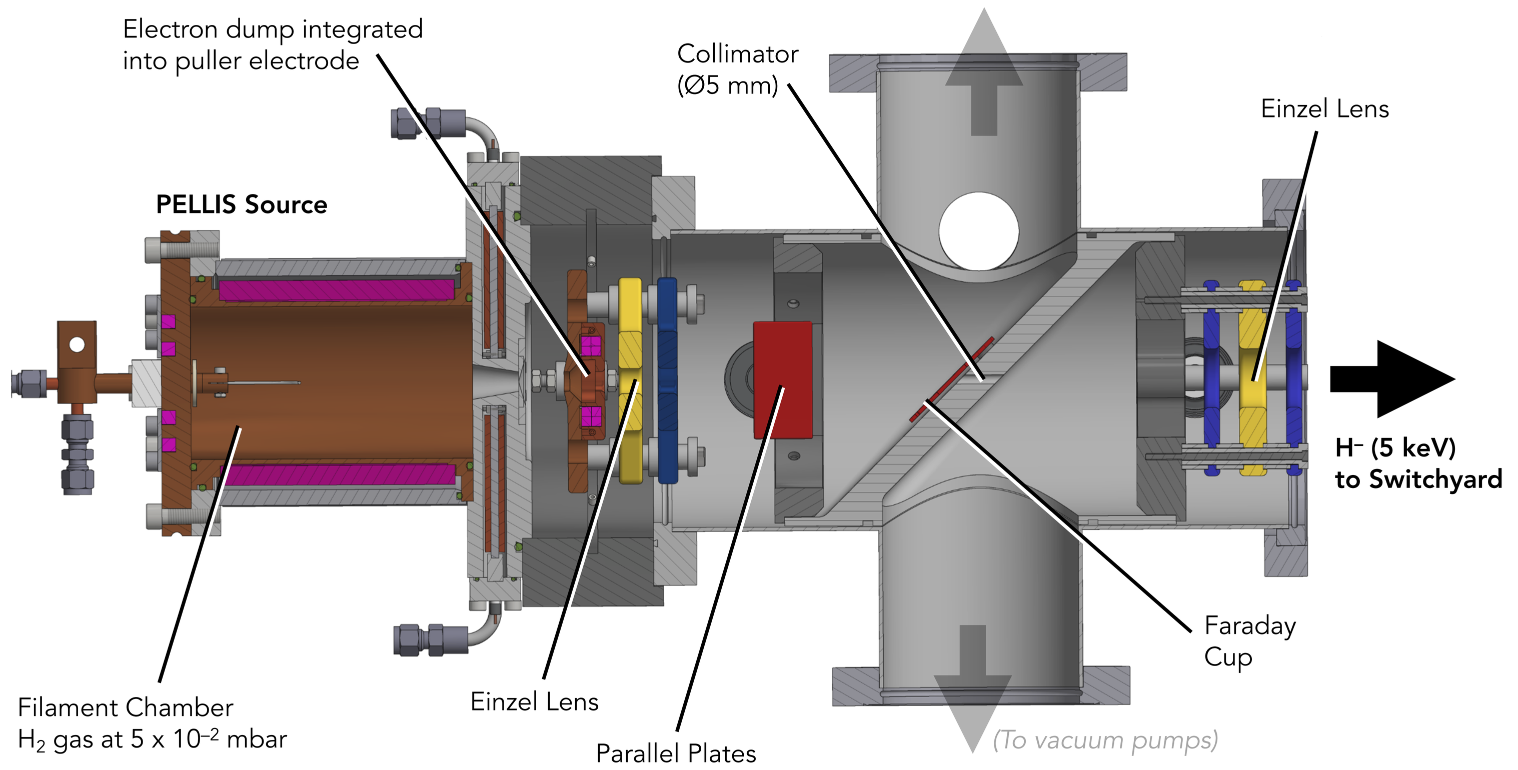

Figure 1. Diagram showing a cross-section of the PELLIS ion source, together with its extraction optics installed inside the differential pumping chamber.

2. PELLIS H⁻ Source

The PELLIS ion source [2], originally developed at JYFL, is a **filament-driven multicusp ion source** that produces H⁻ beams with **low emittances** and energies of 5 – 15 keV. PELLIS could be used as an H⁻ source for ALPHA due to its **modest beam current** (up to 50 μA) and **low extraction energy**. In this study, the source has been configured to operate at 5 keV.

Figure 1 shows the **PELLIS source and its extraction optics**, which were modified slightly for this modification. The H⁻ beam leaves the puller electrode at a small angle (~5 mrad) and is steered through a 20 mm long, 5 mm aperture using a set of parallel plates. This aperture acts as both a collimator for the H⁻ beam, and the first stage of a **differential pumping system**. Pulsing the voltage on the parallel plates will chop the ion beam into short (1 μs) bunches of around 3 x 10^8 H⁻ (approximately 50 pC).

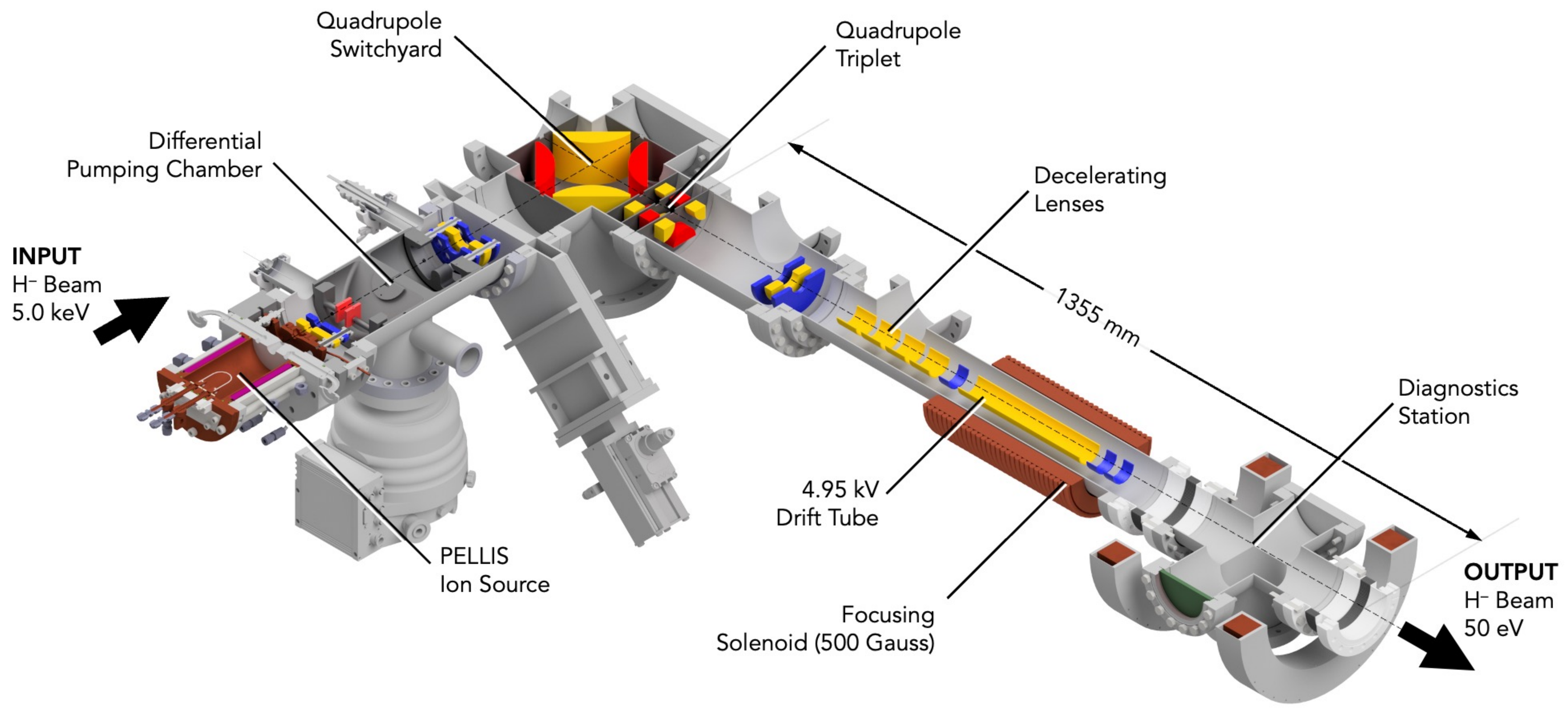

Figure 2. Diagram showing a cross-section of the proposed beamline design to transport H⁻ ions into the ALPHA experiment from a PELLIS-type ion source.

3. Electrostatic Transport Beamline

Figure 2 shows our proposed electrostatic beamline design to **decelerate H⁻ ions** to 50 eV and **transport them into ALPHA's various particle traps**. The PELLIS source is connected to the transport 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 transport beamline, including the switchyard, was **simulated using SIMION** [4]. Figure 1 shows the simulated trajectories of H⁻ ions through the quadrupole deflector. A **quadrupole triplet** was added immediately after the switchyard to circularise the beam. Figure 4 shows the transverse phase space of the beam immediately after the final quadrupole.

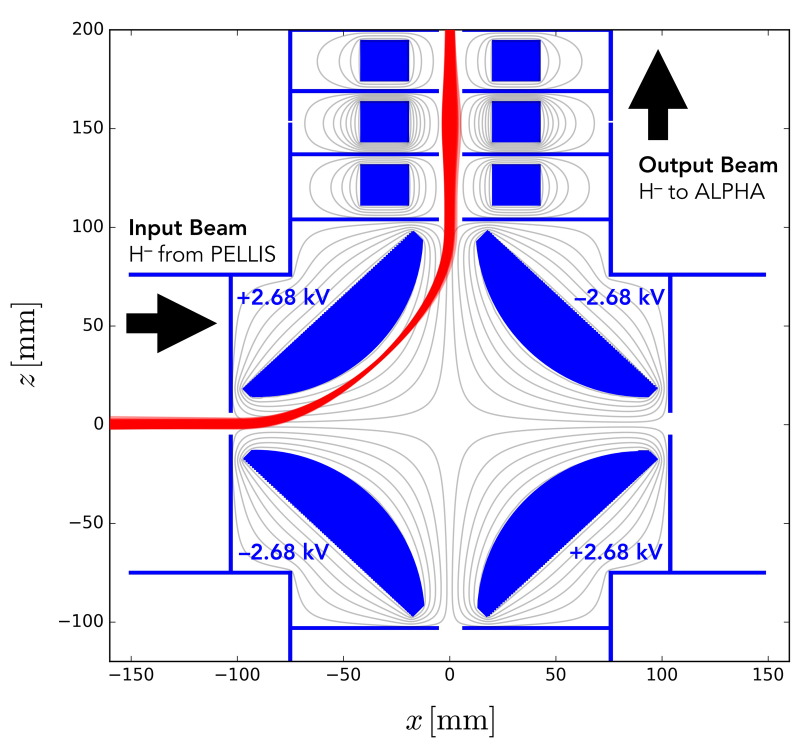

Figure 3. SIMION simulation showing the paths of 5 keV H⁻ ions through the quadrupole switchyard. The contour lines show the electric potential in 400 V intervals.

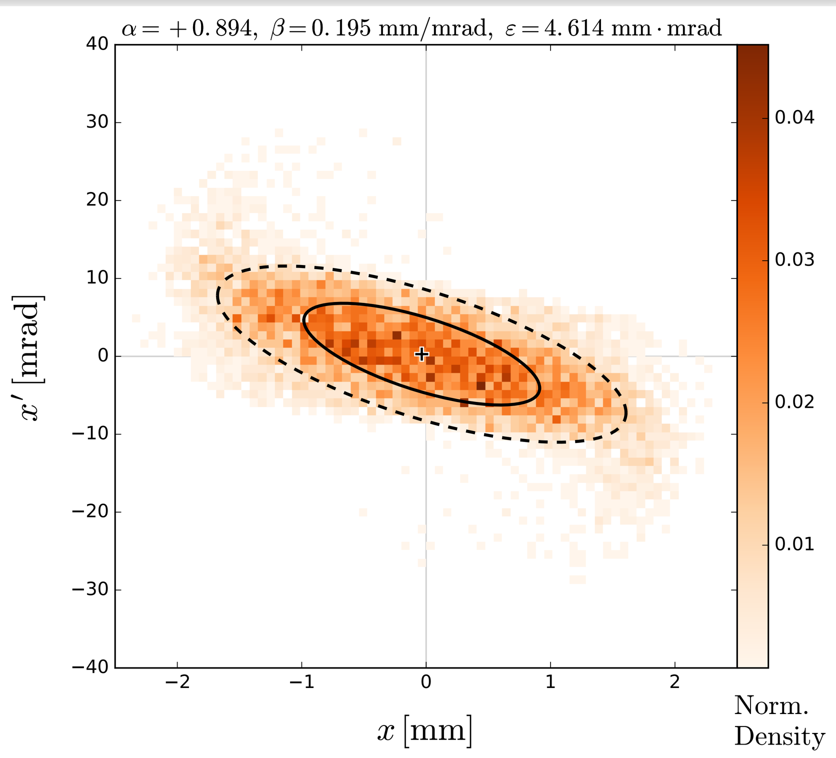

Figure 4. Simulated transverse (horizontal) phase space of the H⁻ beam after the final focusing quadrupole.

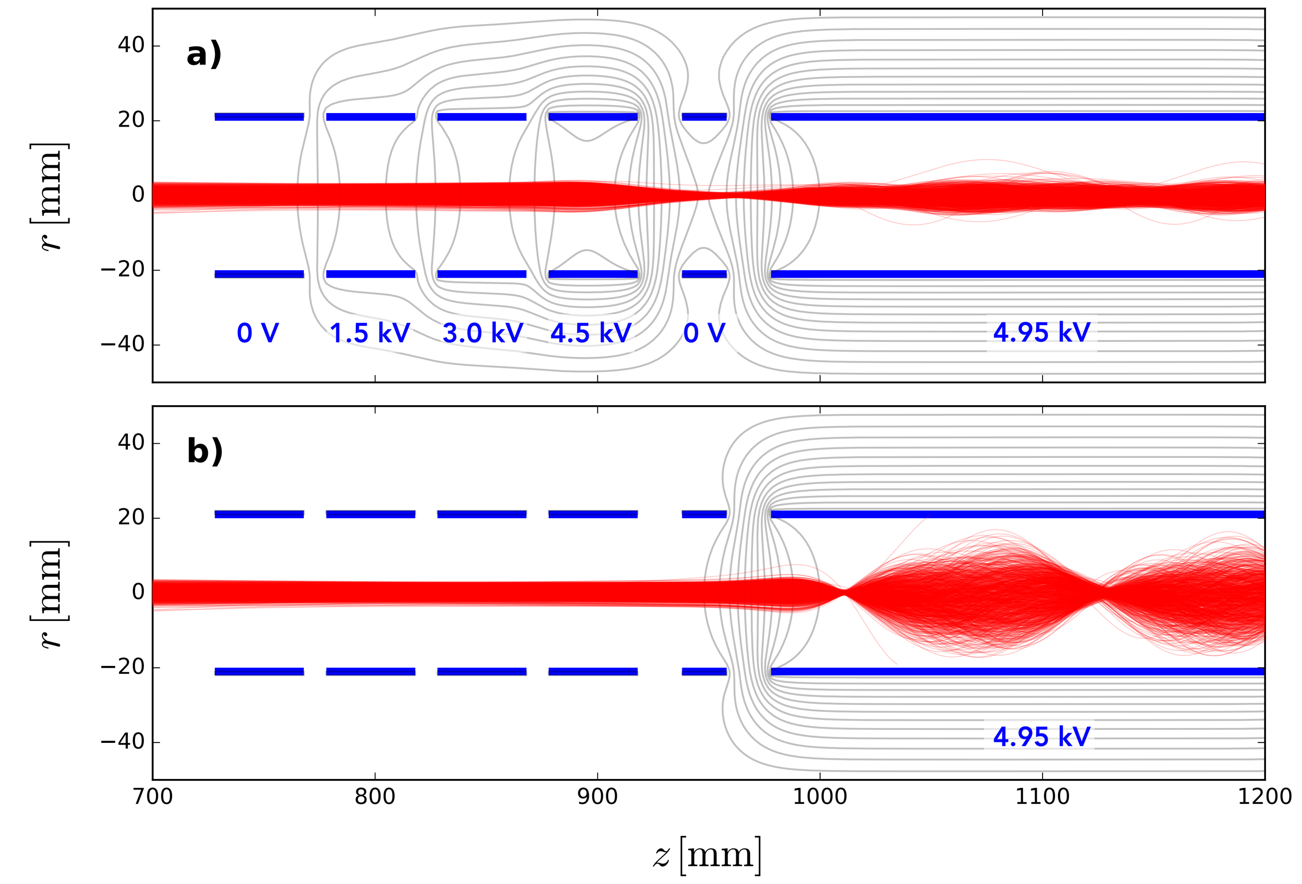

Figure 5. SIMION simulation showing H– ion trajectories through the decelerating lenses and drift tube a) with the lenses turned on and b) with the lenses grounded. The contour lines show the electric potential in 400 V intervals.

4. Beam Deceleration

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.

Upon leaving the drift tube, each 50 eV H– pulse has a **normalised emittance of 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 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.

References

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