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Development and commissioning of a hydrogen ion source for the CERN ALPHA experiment

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Abstract: The CERN ALPHA experiment makes precision measurements of antihydrogen atoms held in a superconducting magnetic minimum trap. Recent studies of the antihydrogen spectrum have provided unique tests of fundamental physics, and to improve on these studies ALPHA is now proposing upgrades to directly compare hydrogen and antihydrogen within their existing atom trap. One route towards producing cold, neutral hydrogen atoms is the integration of a hydrogen ion source into the experiment. Ideally, this should provide both positive (H^+, H_2^+, H_3^+) and negative (H^-) ions to facilitate different schemes for producing and trapping hydrogen atoms. For compatibility with ALPHA's existing beamlines, the source must produce modest (~ 10 μA) beam currents at very low final energies (< 100 eV). PELLIS, previously developed at JYFL, is a filament-driven ion source

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that generates 5–10 keV H^- beams with small emittances and tens of microamps of beam current. Here, we present a modified PELLIS design to provide both positive and negative hydrogen ions for ALPHA. The use of an electromagnet filter field in PELLIS allows for the optimisation of H^- volume production, and also tuning of the positive ion species fraction. We present simulations of H^- (and similarly H^+) transport through the initial extraction optics, which have been configured for a lower beam energy of 5 keV and designed to match a proposed beamline to interface with ALPHA. We present the results of detailed vacuum simulations that were used to guide the optics design, allowing the source (at 10^{-2} mbar) to interface with a transport beamline ~ 0.5 m downstream that has strict vacuum requirements of $< 10^{-9}$ mbar. We present experimental results from commissioning of the source, and show that it broadly performs as designed for both positive and negative hydrogen ions.

Keywords: Ion sources (positive ions, negative ions, electron cyclotron resonance (ECR), electron beam (EBIS)); Beam Optics

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1 Introduction

The ALPHA experiment, based at the CERN Antiproton Decelerator, makes precision measurements of antihydrogen ($\overline{\mathrm{H}}$) atoms confined in a superconducting magnetic minimum trap. Comparisons between the hydrogen atom and its antimatter counterpart provide unique tests of fundamental symmetries and theories of new physics [1], and may help to explain why our universe contains so little antimatter. In recent years, ALPHA has made landmark studies of the antihydrogen atom, advancing to a point where many $\overline{\mathrm{H}}$ can now be trapped simultaneously [2], held over long timescales, and subsequently probed with lasers and microwaves to determine their properties [3, 4]. Recent developments, including the demonstration of laser cooling in antihydrogen [5], may facilitate future measurements of the antihydrogen spectrum at hydrogen-like precision. In this regime, $\overline{\mathrm{H}}$ spectroscopy measurements made at ALPHA are likely to be dominated by systematic uncertainties that will complicate efforts to compare these measurements against similar studies of hydrogen made elsewhere. Consequently, there are significant motivations for ALPHA to also pursue hydrogen spectroscopy, enabling direct, model-independent comparisons between both species within the existing ALPHA-2 atom trap.

At ALPHA, antihydrogen is synthesized by slowly merging cold populations of positrons (e^+) and antiprotons ($\bar{p}$) inside a cylindrical Penning trap. In a typical experimental sequence, around 3×10^6 e^+ are cooled to ~20 K and mixed with approximately 10^5 $\bar{p}$, yielding around 20 trapped $\overline{\mathrm{H}}$ per mixing attempt [2]. Ideally, hydrogen spectroscopy at ALPHA should involve atoms prepared through a similar process, ensuring that comparable populations of hydrogen and antihydrogen are used in experiments. One route towards producing neutral hydrogen atoms in this manner is the integration of a low-energy source of negative hydrogen ions (H^-) or protons into the experiment.

For compatibility with ALPHA's existing charged particle traps and beamlines [6], this ion source should produce beams with similar properties to those of our existing antiproton source. Prior to antihydrogen synthesis, the $\bar{p}$ and e^+ are initially prepared in separate Penning traps approximately 12 m apart. Around 10^7 $\bar{p}$ are received from the CERN ELENA decelerator every 100 s at energy 100 keV, and directed through a degrader foil so that 5% of each bunch can be captured in a high-voltage (5 kV) Penning trap with a magnetic field of 3 T. The resulting antiproton cloud is cooled and compressed to a radius of ~0.4 mm, before being extracted for transport into one of ALPHA's two $\overline{\mathrm{H}}$ synthesis traps. Charged particles are transferred between ALPHA's Penning traps as low-energy ($\lesssim$ 100 eV) bunches, formed by quickly (1 µs) manipulating the electric potential along the trap axis so that particles are ejected in one direction.

PELLIS, previously developed at The University of Jyväskylä (JYFL) [7], is a 10 keV H^- ion source that generates beams with low emittances and currents of up to 50 µA. Due to its modest beam current, low extraction energy and high brightness, PELLIS is well-suited to ALPHA's requirements for a negative hydrogen ion source. In principle, positive ions (H^+, H_2^+ and H_3^+) can also be extracted from a PELLIS-type source by simply inverting the applied voltages, facilitating a range of schemes for neutral hydrogen production at ALPHA. Previous work [8] has explored the proposed integration of such an ion source into the ALPHA experiment via a low-energy electrostatic beamline, showing that such a beamline could deliver bunches of up to 3×10^8 H^- at energies below 100 eV.

Here, we describe a modified PELLIS source that has been developed to provide both H^- ions and protons to ALPHA. In section 2, we present simulations of the source extraction optics, which have been optimised for a reduced (5 keV) extraction energy and tightly integrated into a differential pumping system. In section 3, we present an analysis of experimental data collected during commissioning of the source at STFC ISIS, and show that it already exceeds ALPHA's requirements in terms of extracted beam current for both H^- and positive ions.

2 Ion source design

A detailed description and characterisation of the original JYFL PELLIS source is presented in ref. [7]. This section will describe modifications to the original PELLIS design that were implemented for compatibility with the proposed transport beamline to ALPHA [8]. A brief review of the ion source design and relevant beam parameters is given below.

Figure 1 shows a cross-section of the ALPHA PELLIS source. PELLIS is a filament-driven multicusp ion source, originally designed for the volume production of H^- beams with very small emittances. Typically, the filament chamber (to the left in figure 1) is filled with H_2 gas at 5×10^{-3} mbar, such that a filament (arc) current of 5.6 A can generate 50 µA of H^- beam current at 10 keV. Based on studies of the original JYFL PELLIS source [7], H^- beams are extracted from the 2 mm plasma electrode aperture with a 95% normalised emittance of 0.015 mm mrad.

The PELLIS filter field is created by a pair of electromagnets built into the front plate of the source, which can be tuned to optimise the volume production of H^- within the extraction region. Together, these magnets produce peak fields ranging from 0–30 mT perpendicular to the beam axis when energised with currents up to 5 A. In principle, the filter magnets can also be used to tune the species fraction of the beam when the source is configured to produce positive ions. Previous works have shown that strong filter fields can suppress the extraction of molecular hydrogen ions in small multicusp ion sources such as PELLIS [9], with some authors achieving proton ratios as high as 90% [10]. Here, we define the proton ratio as the fraction of the total beam current carried by protons rather than molecular hydrogen ions.

The extraction optics (section 2.1), consisting of two Einzel lenses, a set of parallel plates and a collimator, were configured for a lower initial beam energy (5 keV) and for matching into the

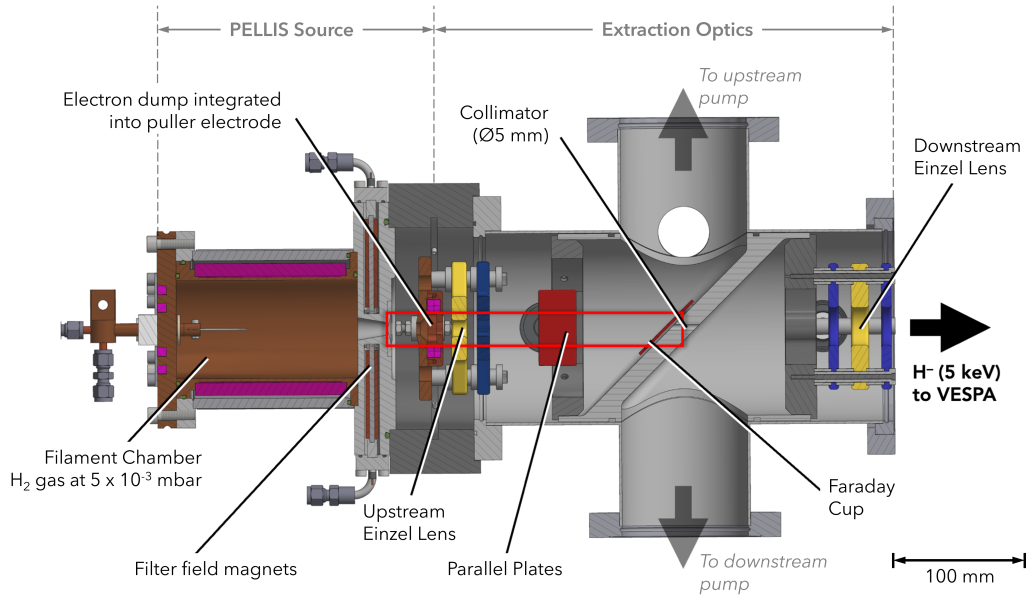

Figure 1. Schematic showing a cross section of the ALPHA PELLIS source, including the differential pumping chamber and extraction optics. The red outline indicates the region shown in figure 2.

proposed transport beamline [8]. As shown in figure 1, the extraction optics are tightly integrated into a differential pumping system (section 2.2), which protects the ultra-high vacuum (UHV) environment of the ALPHA experiment (< 10^{-9} mbar) from the H_2 gas load inside the ion source.

2.1 Extraction optics

The revised extraction optics were developed and optimised based on extensive IBSimu [11] simulations. For clarity, this section will only describe simulations of H^- beams extracted from the ion source; however, very similar dynamics were found in calculations where positive ions (H_n^+) were transported through the extraction optics. Figure 2 shows the simulated trajectories of 5 keV H^- ions from the plasma electrode up to the midplane of the differential pumping chamber, for an initial beam current of 50 µA.

As in the original PELLIS source, electrons that are co-extracted with the H^- beam are deflected into an electron dump by a set of permanent magnets, which are integrated into the puller electrode in a dipole-antidipole configuration. The ion beam is largely unaffected by these magnets, but nonetheless emerges at a small (5 mrad) angle to the nominal beam axis. In our source, the residual deflection is corrected using a set of parallel plates 128.5 mm from the plasma electrode. By quickly switching the voltage on these plates, the H^- beam can be chopped into 1 µs pulses, so that ions are only delivered to ALPHA when required (see figure 2b). Assuming an initial beam current of 50 µA, the bunch charge is 50 pC (3×10^8 ions), far in excess of ALPHA's likely requirements for neutral hydrogen production.

A 20 mm long, 5 mm aperture at the centre of the differential pumping chamber (see figure 1) acts as both a collimator for the H^- beam and a pumping restriction between the ion source and transport beamline. The aperture dimensions were chosen with input from vacuum calculations

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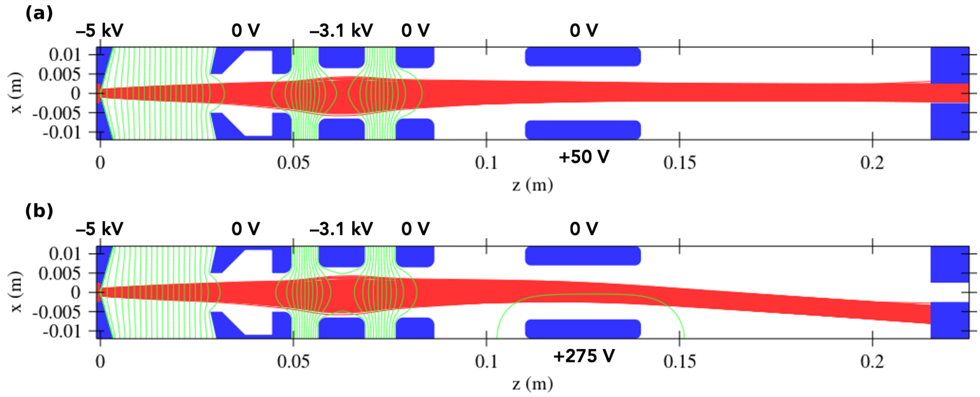

Figure 2. IBSimu simulation showing the trajectories of 5 keV H^- ions through the revised extraction optics, within the highlighted region of figure 1. Simulations are shown with the parallel plates set to a) align the beam through the collimator, or b) deflect the beam into a Faraday cup mounted around the aperture.

(see section 2.2) to maximise the pressure drop across the differential pumping chamber while minimising beam losses. As shown in figure 2, the upstream Einzel lens voltage (−3.1 kV) was optimised to focus ions through the collimator.

The downstream Einzel lens (shown to the right in figure 1) will be used to match the H^- beam into the proposed transport beamline. IBSimu was used to track H^- beams from the collimator to the exit of the differential pumping chamber for a range of Einzel lens voltages. The resulting particle distributions were used to initialise separate simulations of the transport beamline, which have been described elsewhere [8]. Figure 3 shows the transverse phase spaces of a simulated H^- beam observed 134 mm after the downstream Einzel lens, for the optimal lens voltage of 9 kV. The beam has a normalised emittance of 0.021 mm mrad in both planes, only slightly larger than the emittance reported for the original JYFL PELLIS source operating at 10 keV.

2.2 Differential pumping

To maximise the lifetimes of trapped antiparticles, ALPHA is subject to strict vacuum requirements, with a maximum pressure of 10^{-9} mbar in room temperature parts of the experiment's beamlines. The integration of PELLIS-type source, with a pressure of 10^{-2} mbar in the filament chamber, therefore requires a differential pumping system to reduce the residual H_2 pressure by six orders of magnitude within several metres. Apertures built into the plasma electrode and extraction optics are used as the first pumping restrictions in this system, as shown in figure 1.

The H_2 pressure within the ion source and transport beamline was calculated using Molflow+ [12]. Figure 4 shows the residual pressure as a function of longitudinal distance from the ion source backplate, with the filament chamber held at 5×10^{-3} mbar. In each simulation, H_2 gas is evacuated from the differential pumping chamber using a pair of vacuum pumps arranged on either side of the pumping restriction. For our chosen pumping rate of 500 L/s (provided by two Pfeiffer HiPace 400 turbomolecular pumps, installed on either side of the chamber), we expect to achieve pressures of 3×10^{-5} mbar within the upstream section of the chamber, and $\sim 10^{-7}$ mbar after the pumping restriction. As evidenced by the calculation, the pressure in the transport beamline is ultimately $\sim 10^{-9}$ mbar, meaning that negligible gas load is introduced to ALPHA from the ion source.

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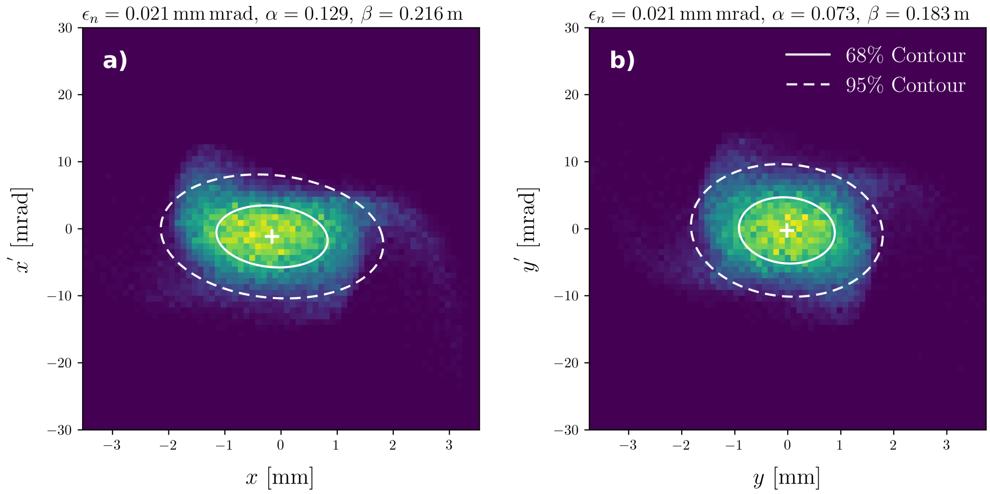

Figure 3. Simulated transverse phase spaces for a 50 µA H^- beam measured 134 mm from the second Einzel lens. The solid (dashed) white line shows the one (two) sigma RMS phase space ellipse for the Twiss parameters annotated above each phase space.

3 Commissioning results

The ALPHA PELLIS source was commissioned on the VESPA test stand [13] at STFC ISIS in April and May 2022. Prior to beam commissioning, H_2 gas was introduced to the filament chamber to validate the design of the differential pumping system. For consistency with the Molflow+ modelling in figure 4, an additional 10 mm square aperture was installed between the ion source and VESPA (approximately 0.53 m from the source plasma electrode), representing the interface to the proposed transport beamline. With the filament chamber at its nominal pressure, the upstream (downstream) portion of the differential pumping chamber ultimately reached a pressure of 2×10^{-5} mbar (3×10^{-7} mbar), consistent with the modelled performance of the system.

For beam commissioning, the source was initially configured to extract H^- ions, and later reconfigured for positive ion production. Beam current measurements were primarily made using VESPA's large-bore Faraday Cup (FC), located approximately 0.94 m from the PELLIS plasma electrode. The filter magnets, parallel plates and upstream Einzel lens were coarsely optimised to maximise the beam current transported to the FC at 5 keV. The filter magnets were set to 1.9 A (12 mT) to extract H^- ions, and initially turned off during positive ion production. The optimal Einzel lens voltage was around −3.2 kV, consistent with the IBSimu simulations detailed in section 2.1.

Figure 5 shows the extracted beam current measured as a function of arc current, for both positive and negative hydrogen ions. The ALPHA PELLIS source achieved a maximum beam current of 32 µA for H^- ions, and 22 µA for positive hydrogen ions. As shown in figure 5, these values are somewhat lower than the 50 µA of H^- current achieved by the original JYFL PELLIS source, which is operated at 10 keV. We expect that the reduced beam current is primarily due to the lower extraction energy; however, the coarse optimisation of other parameters and increased distance to the FC through two limiting apertures may also result in some particle losses. Nonetheless, the achieved beam currents exceed ALPHA's likely requirements for neutral hydrogen production using either H^- or protons (at least 10^6 ions per 1 µs bunch).

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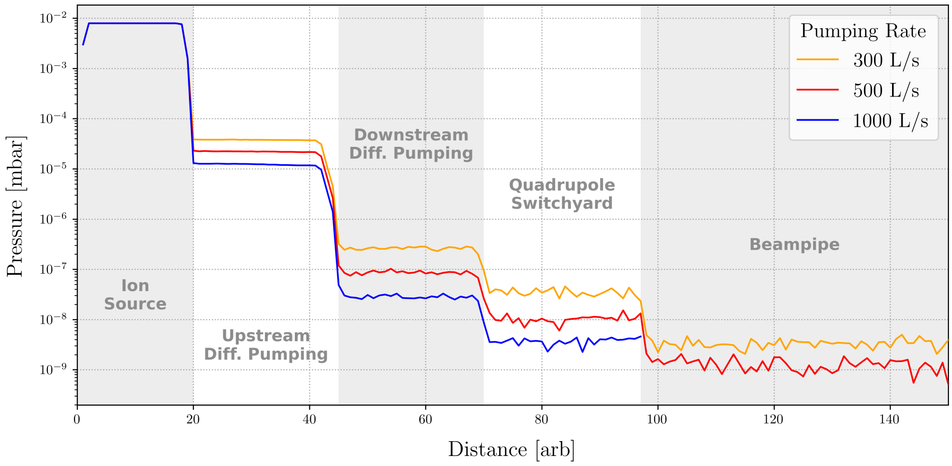

Figure 4. Molflow+ calculation showing the vacuum pressure as a function of distance from the PELLIS plasma electrode, for different pumping speeds within the differential pumping chamber (see figure 1). The layout of the proposed transport beamline is described in ref. [8].

After establishing positive ion production at 5 keV, the strength of the filter magnet was scanned to investigate its effect on the H_n^+ beam current. As discussed in section 2, a strong filter field should suppress the extraction of molecular ions and result in a beam with a high proton ratio [9, 10]. Figure 6 shows the total H_n^+ beam current as a function of the PELLIS filter magnet current. As expected, the beam current is initially reduced as the strength of the filter field increases, consistent with the extraction of fewer molecular ions from the plasma meniscus. However, the total beam current does not decrease monotonically nor converge to a constant value at strong filter fields, suggesting that the species fraction varies continually across the range of filter fields investigated here.

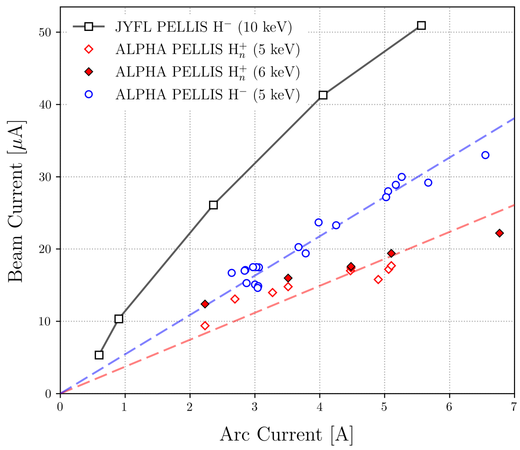

Figure 5. Beam current as a function of arc current, for both positive and negative hydrogen ions. Similar measurements from the 10 keV JYFL PELLIS source are shown for comparison [7].

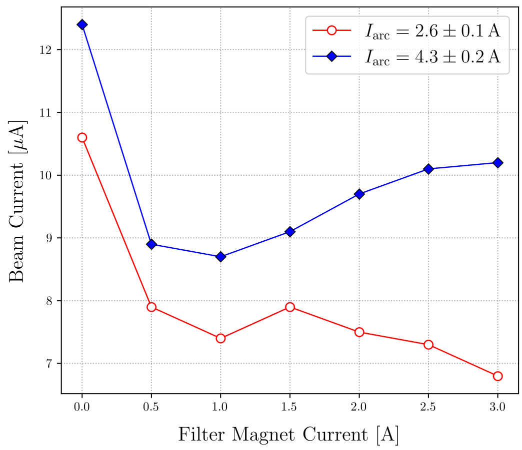

Figure 6. Positive ion current measured on the VESPA Faraday cup as a function of the PELLIS filter magnet current.

Further measurements or detailed modelling of the plasma dynamics within the source are required to fully characterise the beam species fraction at different operating points. While it is desirable to produce high-purity proton beams directly from the PELLIS source, protons can ultimately be selected by their charge-to-mass ratio using the steering magnets that interface the proposed transport beamline with the ALPHA experiment [6].

4 Outlook and conclusions

In this paper, we have briefly described the development of a hydrogen ion source for the CERN ALPHA experiment, based on the PELLIS design originally developed at JYFL. Using extensive IBSimu simulations, the source extraction optics have been adapted for a reduced (5 kV) beam energy, and tightly integrated into the first stage of differential pumping system. The performance of the differential pumping system agrees well with Molflow+ simulations that were used to inform its design. By analysing experimental data collected during commissioning of the ion source at STFC ISIS, we have shown that it achieves beam currents up to 32 µA for H^- ions, or 22 µA for positive hydrogen ions (comprising H^+, H_2^+ and H_3^+). Based on studies of other ion sources [9, 10] and measurements presented here (see section 3), we anticipate that high proton ratios can be obtained from the ALPHA PELLIS source by optimising its electromagnet filter field.

The ion source described in this work has now been delivered to CERN, where it will undergo further in-situ testing in preparation for its proposed integration onto ALPHA. Two additional PELLIS-type sources have also been fabricated, and will be used for Fixed-Field alternating gradient Accelerator (FFA) [14] prototyping on the STFC ISIS Front End Test Stand (FETS) [15] in future.

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