High current $H_2^+$ beams from a filament-driven multicusp ion source

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Recently, the use of $H_2^+$ ions instead of protons to overcome space charge challenges in compact cyclotrons has received much attention. This technique has the potential to increase the available beam current from compact cyclotrons by an order of magnitude, paving the way for applications in energy research, medical isotope production, and particle physics, e.g., a decisive search for sterile neutrinos through the IsoDAR experiment. For IsoDAR we go a step beyond just using $H_2^+$ and add pre-bunching through a Radio-Frequency Quadrupole (RFQ) embedded in the cyclotron yoke. This puts beam purity and beam quality constraints on the ion source that no published ion source has simultaneously demonstrated so far. Here, we report results from a new multicusp ion source (MIST-1) that produces the world’s highest steady-state current of $H_2^+$ from this type of ion source (1 mA), with exceptionally low emittance (0.05 $\pi$-mm-mrad, RMS, normalized) and high purity (80% $H_2^+$). This result shows the feasibility of using a multicusp ion source for IsoDAR and the RFQ direct injection prototype, and paves the way to record breaking continuous wave (cw) beam currents of 5 mA $H_2^+$ (equivalent to 10 mA protons) from compact cyclotrons, ideal for underground installation. This represents a significant advance, with impact on neutrino physics specifically and high power cyclotron design in general.

I. INTRODUCTION

Compact cyclotrons that can produce 10 mA proton beams with energy $>50$ MeV, and that can be mass-produced, would provide a powerful tool for basic [1–3] and applied science [4–6]. This is an order of magnitude higher current than is available from on-market cyclotrons. It has recently been shown that the solution to many of the challenges of achieving this goal lies in accelerating 5 mA of $H_2^+$ ions [3]. In this paper we report on an important first step in the development of such an accelerator: The design of the MIST-1 ion source and its commissioning at reduced power, which nonetheless already yielded record $H_2^+$ currents.

MIST-1 is an integral part of the IsoDAR project, and the requirements of this experiment have set the ion source specifications. IsoDAR is planned as a definitive search for anti-electron-flavor disappearance due to eV scale sterile neutrinos, a beyond Standard Model particle, as described in Refs. [1–3]. The novelty of IsoDAR is in constructing an intense low energy anti-neutrino source near a kiloton scale neutrino detector, KamLAND [7], that is located underground, to reduce backgrounds (see Fig., FIG. 1). The anti-neutrinos are produced by a 10 mA, 60 MeV continuous wave (cw) proton beam impinging on a $^8$Be target surrounded by $^7$Li. To save on space and costs, IsoDAR will use a compact cyclotron as a driver instead of a linear accelerator. Commercially available cyclotrons in this energy range typically have maximum proton beam currents around 1 mA, with space charge the primary limiting factor. In order to reduce space charge effects, IsoDAR will accelerate $H_2^+$ instead of protons or $H^-$ (note that $H_2^+$ was also investigated, but the higher rigidity would make the cyclotron larger and more expensive). With this, and additional innovations described in Ref. 3 (axial injection through an RFQ, high accelerating gradient, vortex-motion), the IsoDAR cyclotron will accelerate 5 mA of $H_2^+$ to 60 MeV/amu, which, after charge-stripping, yields 10 mA of protons at 60 MeV on target.

The ion source requirements for RFQ direct axial injection into the compact cyclotron are:

1. Low emittance ($<0.1\,\pi$-mm-mrad, rms, norm.)
2. Low contamination ($>80\%\, H_2^+$ fraction)
3. High current (10 mA of $H_2^+$)

These stem from the desire to keep the system compact, and utilize the RFQ’s ability to separate by mass in addition to its highly efficient bunching and pre-acceleration. In FIG. 1, the entire low energy beam transport is contained within the 6-way cross on top of the cyclotron. The status of high current $H_2^+$ and $H_3^+$ sources was recently reviewed in [10], which lists 2.45 GHz Electron

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Cyclotron Resonance (ECR) ion sources [11, 12] and filament-driven discharge sources, with the plasma either confined by a solenoid [13] or by a multicusp field [14]. For IsoDAR, the 2.45 GHz ECR versatile ion source (VIS) [15, 16] was first tested by the MIT group in collaboration with INFN-LNS and Best Cyclotron Systems, Inc. While the performance for protons was excellent, the finding was that the maximum \( \text{H}^+ \) fraction was limited to 50% at the required total beam currents [17, 18]. In [10] similar fractions are reported. In Ref. [19], a filament discharge source with solenoid confinement was presented that showed > 91% \( \text{H}^+ \) fraction and 2.84 mA of \( \text{H}^+ \), however, the energy spread was on the order of 120 eV (reported for a \( \text{He}^+ \) beam). In Ref. [14], a multicusp ion source, developed at LBNL, capable of producing extractable total current densities of 50 mA/cm\(^2\), with up to 80% of the beam being \( \text{H}^+ \) ions was presented. Combined with typically low emittances (e.g. < 0.04 \( \pi \)-mm-mrad for Ar+ [20]), low energy spread (< 2 eV [21]), and ease of operation, this type was deemed the best choice for a new source. It is important to note that the results of the LBNL source were for sub-mm diameter extraction apertures and pulsed beams. To fulfill the IsoDAR requirements, MIST-1 was designed to deliver 10 mA of \( \text{H}^+ \) beam current in DC mode, requiring significant design changes and cooling upgrades.

In this early commissioning phase, MIST-1 has already set a new record for this type of ion source: a 1.08 mA DC \( \text{H}^+ \) beam. At full power, MIST-1 must deliver a 10 mA DC \( \text{H}^+ \) beam to the RFQ and cyclotron. With a demonstrated plasma density of 11 mA/cm\(^2\) and doubling the aperture size from 4 mm to 8 mm diameter, the scaled \( \text{H}^+ \) current of 4 mA \( \text{H}^+ \), when run through our detailed cyclotron simulations, would already allow building a compact cyclotron that can deliver 4 times the current of a commercial system. Additional development is ongoing that will bring us to the nominal current of 10 mA \( \text{H}^+ \). In addition to the beam currents, we show very low emittances of 0.05 \( \pi \)-mm-mrad (1-rms, normalized), which are in good agreement with simulations. Section II contains a detailed description of the source and diagnostic setup. Section III covers simulations of extraction system and test beam line. Measurements are in Section IV.

### II. EXPERIMENTAL SETUP

#### A. Ion Source

The MIST-1 ion source is a filament-driven multicusp ion source and is described in detail in Refs. [2] [3] [22]. A CAD rendering is shown in FIG. 2, and a cross section view in FIG. 3 (right). A stainless-steel chamber with samarium-cobalt permanent magnets creates a multicusp field that confines the plasma around the extraction aperture. Hydrogen enters the source through the cowl. The hydrogen undergoes electron-impact-ionization by electrons from the tungsten filament, which are being accelerated towards the anode. The filament is a tungsten alloy, mixed with small amounts of copper and nickel for corrosion resistance. The ions are then extracted through a hole in the center of the front-plate. The source is on a high voltage platform that can be lifted to a maximum...
potential of 20 kV. Ions leaving the source are focused and accelerated in the extraction system. The ion source parameters described here are summarized in Table I.

The amount of hydrogen entering the source is controlled by a mass flow controller (MFC), (MKS Instruments, Model: GV50A, with 5 sccm full range). The MFC is controlled via a RS485/USB with optical interface connected to our control system PC.

The filament is connected to two power supplies (see Fig. 3): The filament heating power supply (8.4 V, 300 A max), to raise the temperature of the filament for thermionic electron emission; and the plasma discharge power supply (140 V, 24 A max), to maintain a potential difference between the filament (cathode) and the source body (anode), facilitating the discharge. The source body, back plate, and front plate are all electrically insulated. This will allow each component to be maintained at a different potential in order to test the effects of varying the anode arrangements in future studies. For this study, all components are maintained at the same potential. The filament emits electrons that ionize the gas to form a plasma. H$_3^+$ is a fragile ion that easily recombinates to H$_2^+$ or dissociates into protons through further collisions in the plasma. Its mean free path is short at 1-2 cm [14, 22]. MIST-1 accounts for this with a short source body (low aspect ratio), producing the bulk of H$_3^+$ within a few centimeters of the extraction aperture, not giving the ions enough time to undergo a significant number of collisions before drifting out of the source.

The size, shape and position of the filament have an effect on the properties of the plasma. We have found that using a filament that is less than 0.8 mm thick does not provide sufficient electrons to generate a dense plasma. A systematic study for optimal filament shape, thickness, and position is forthcoming. The specific parameters of each filament used in the studies presented here will be described in the measurement section.

The ions drift out of the source through the extraction aperture where they are shaped and accelerated by a tetrode extraction system. The extraction system is a series of four copper electrodes that shape the beam upon leaving the ion source (see Fig. 5) through static voltages applied by Matsusada power supplies AU-20P7 and AU-20N7, for positive and negative voltages, respectively. The electrodes following the source plate are the screening electrode, or “puller” (typically kept at a low, negative voltage of -2 kV) and the einzel lens. The puller prevents electrons from the beam line from streaming back into the ion source, and increases the electric field that shapes the meniscus. The einzel lens is made up of a total of three electrodes. The outer ones are grounded and the larger central piece is adjustable up to 20 kV. This feature is mostly unused in the presented measurements. The electrodes are aligned via the compression of several ceramic balls. The extraction system is modeled using the IBSimu code [23], discussed in Section II.

### B. Low Energy Beam Transport and Diagnostics

The ion source extraction system is followed by a low energy beam transport line (LEBT) used for beam diagnostics (see Fig. 4). The LEBT consists of three electromagnets: 2 quadrupoles and 1 dipole. The arrangement of the magnets, beamline, and diagnostics 6-way-crosses (designated as DB1 and DB2 in the text below) are shown in Fig. 4. Parameters for the magnets are listed in Table II. Both quadrupoles can be used for vertical focusing of the beam, however only the first quadrupole is used for the studies presented here. When a mass spectrum is being taken, the quadrupole current is increased in a constant ratio with the dipole current. The dipole is used for horizontal focusing and ion species separation. Following the second quadrupole magnet is the analysis 6-way-cross (DB2), which contains a second Faraday cup and two Allison scanners with perpendicular axes.

The Faraday cup (FC1) in DB1, which follows the extraction system, is used to measure the total current coming from the source without separation of species. A second Faraday cup (FC2) is located at the end of the beamline to measure the relative species fractions after separation by the dipole (see Fig. 5). Each Faraday cup is equipped with a negative suppression electrode to prevent secondary electrons from escaping, which would ar-

| Parameter       | Value (nominal) |
|-----------------|-----------------|
| Plasma chamber length | 6.5 cm          |
| Plasma chamber diameter | 15 cm          |
| Permanent magnet material | Sm$_2$Co$_17$   |
| Permanent magnet strength | 1.05 T on surface |
| Front plate magnets | 12 bars (star shape) |
| Radial magnets | 12 bars         |
| Back plate magnets | 4 rows of magnets, 6 bars tot. |
| Front plate cooling | embedded steel tube |
| Back plate cooling | embedded copper pipe |
| Chamber cooling | water jacket     |
| Water flow (both) | (1.5 l/min)     |
| Filament feedthrough cooling | water cooled |
| Filament material | W mixed with Cu and Ni |
| Filament diameter | ≈ 0.8 mm        |
| Discharge voltage | max. 180 V       |
| Discharge current | max. 24 A        |
| Filament heating voltage | max. 8 V         |
| Filament heating current | max. 100 A       |

### Table II Parameters for the beam line magnets.

| Dipole Parameter | Value | Quad Parameter | Value |
|------------------|-------|----------------|-------|
| Manufacturer     | Bruker | Manufacturer    | BNIP  |
| B$_{max}$ (center) | 0.7 T  | B$_{max}$ (pole tip) | 0.085 T |
| I$_{max}$         | 125 A  | I$_{max}$       | 200 A  |
| U$_{max}$         | 47 V   | U$_{max}$       | 2 V    |
| Bending radius    | 300 mm | Pole tip radius | 37.5 mm |
| Pole gap          | 75 mm  | Aperture diameter | 90 mm |
FIG. 4. CAD model of the LEBT and diagnostic system. Starting with multiple species coming from the ion source, the species are then focused in the beamline by quadrupole magnets, and separated by the dipole magnet. Their currents and emittances can then be measured by the Faraday cup and emittance scanners in DB2.

Artificially increase the measured positive ion current. The necessary suppression voltage for our Faraday cups has been experimentally determined to be -350 V.

To measure horizontal and vertical emittance (separately), DB2 houses two Allison-type electrostatic emittance scanners [24]. A model for the identical Allison scanners, designed and constructed at MIT, is shown in Figure 5. They are equipped with a water-cooled copper front plate and are able to handle proton beam currents of up to 50 mA and 80 keV. Further details are provided in Ref. [25].

C. Measurement Parameters

Systematic studies during commissioning of this source are done varying the following parameters:

- Discharge voltage,
- Filament heating current,
- \( \text{H}_2 \) gas flow into source,
- Filament shape and position.

Beam line parameters like source high voltage potential, einzel lens setting and quadrupole settings are then adjusted for each data point to give the best transmission to FC2.

The filament discharge current strongly affects the plasma density. In order for the discharge current to be kept constant and stable, the heating current can be used to compensate for the changes in the plasma (e.g. temperature of the filament, pressure fluctuations, etc.). This is controlled by a proportional–integral–derivative control-loop, or “PID loop” [26]. As the filament heating and discharge voltage are varied, the total current is measured in FC1. The platform and puller voltages are adjusted to keep the beam focused into FC1, which is monitored by measuring the current on its front plate. When taking an ion mass spectrum, the dipole current is varied while current measurements are taken in FC2. The first quadrupole's current is set proportional to the dipole current, for vertical focusing. FC2 currents are then plotted as a function of dipole field (see Sec. IV). As ions with different mass-to-charge ratio have different magnetic rigidity, a different dipole field strength is necessary to transport them to FC2, thus leading to individual peaks in the spectrum. The magnets are controlled, and mass spectra are recorded, via an automated LabVIEW program run on the PC.

FIG. 5. CAD rendering of DB2, housing the Allison scanners (vertical scanner shown) and FC2. The Allison scanners can be retracted so that beam current can be measured in FC2 to obtain mass spectra.
III. SIMULATIONS

Ions extracted from MIST-1 are simulated using two publicly-available software packages: IBSimu [23] and Warp [27, 28]. IBSimu is used initially because it accurately models ions traversing the plasma sheath. However, IBSimu would be too computationally expensive to use for a simulation of the entire test beamline. On the other hand, Warp accurately models space-charge effects and beam transport, with less computing power than IBSimu, but the plasma sheath modeling in Warp is not well-established. This led to the decision to combine the packages in series. IBSimu simulates ions from the ion source to midway through the first 6-way cross, Warp then simulates ions from the first 6-way cross to the end of the beamline.

A. Ion Source Extraction (IBSimu)

The extraction system was designed and simulated using IBSimu, a particle-in-cell code developed at Yvãskylã, which uses iterative processes to calculate the particle trajectories through electromagnetic fields. IBSimu has successfully been used to design and simulate several extraction systems and is well-benchmarked against experimental results [29–32]. IBSimu uses electrode geometries that are imported from CAD files. The electrodes, set to static potentials, are then used to calculate the external fields in the system. The particle trajectories are simulated by ray-tracing of the particles through the superposition of the external field and the beam’s self-field (space-charge). This process is repeated until the simulation converges. Multiple species can be simulated simultaneously, accounting for the space-charge effects of each. IBSimu is used for the first 14 cm of beam line.

B. Low Energy Beam Transport (Warp)

Warp is a particle-in-cell Python package that has been developed since the 1980s at Lawrence Livermore National Laboratory and Lawrence Berkeley National Laboratory [27, 28]. The particle distributions from IBSimu simulations are loaded as the initial distributions for the Warp simulations. Particles are propagated using the wxy-slice package. The wxy-slice package calculates the transverse space-charge effects at each step, but ignores longitudinal space-charge effects, which is a good approximation for slow-changing DC beams, and brings significant simulation speed-up. Space-charge compensation (from residual gas ionization in regions free from electrostatic fields) is treated as a free parameter and simulated by modifying each species’ current: \( I_{comp} = I_i \cdot (1 - f_e) \) with \( f_e \) the space-charge compensation factor from literature [33]. A more accurate space-charge compensation model will be implemented in future simulations [34]. Simulations are done for the entire beam line, and individual sets of parameters, matching emittance measurements and mass spectrometer measurements.

Included in the simulations are models of the magnetic fields and vacuum components. In order to accurately model the quadrupole and dipole magnets, CAD models of the yokes and coils were imported to COMSOL [35] to calculate 3d fields using finite elements methods. These fields are imported into Warp with a scaling factor to simulate different field strengths. Vacuum components are accounted for by using Warp’s internal functions to generate conductor data from Boolean operations on primitive shapes. Conducting cylinders are used for the vacuum tubes and 6-way crosses; a rectangular box is used for the dipole chamber. Particles coming into contact with conductors are removed from the simulation and the currents are adjusted after each simulation step.

At the beginning of the Warp simulations, the beam has a circular cross-section and nearly identical phase spaces for xx’ and yy’. During simulations, the maximum and 2-rms beam envelopes are saved at each step and the phase space of all remaining particles is saved at the end of each simulation (see FIG. 7 for a typical output plot). The final currents are calculated by multiplying the initial currents by the fraction of particles transmitted for each species. To determine the beam composition (species and currents) for the simulations, mass spectrometer measurements were used. By varying the dipole scaling factor in Warp, the current measured in FC2 during an actual dipole sweep can be simulated. Good mass separation is achieved by placing a 1 cm wide slit between dipole magnet and FC2 in the experiment as well as in the simulations. Emittance scans can be matched at the z position of the Allison scanners by creating a 2D histogram of the simulated particle phase spaces in the same location.

The simulated dipole scans show good qualitative agreement with measured spectra. The simulated phase spaces show excellent qualitative and good quantitative

![IBSimu simulation of the low energy extraction system. The electrodes are in blue, and the equipotential lines are in green. The electrode voltages are shown at the top. This simulation includes all species listed in the text.](image-url)
agreement with emittance scans using the Allison scanners. As an example, the experimental settings used to obtain the emittance scans shown in Section IV D were used in the described simulation deck and results are plotted in FIG. 7. The species considered in this simulations are H\(^+\), H\(_2\)\(^+\), H\(_3\)\(^+\), N\(^+\), O\(^+\), H\(_2\)O\(^+\), N\(_2\)\(^+\), and O\(_2\)\(^+\), with ratios obtained from the respective mass spectrum. The higher mass ions are due to insufficient pumping time (air and water that had gotten into the source chamber during a filament change) and not due to the contamination described in Section IV A. The space charge compensation factor \(f_e\) was set to 0.5. The phase space plots on the right side of FIG. 7 should be compared to the emittance plots in FIG. 13.

IV. MEASUREMENTS

This section presents first measurements of ion species from the MIST-1 ion source. This establishes the base level of performance for this device, which can be further tuned as needed for future applications. Note that the ion source front plate has an exchangeable disc that lets us use different extraction aperture diameters. During the presented measurements, we used two diameters, 3 mm and 4 mm, hence currents are usually reported as densities in mA/cm\(^2\).

A. Source Contamination

The first systematic tests during early commissioning of the MIST-1 ion source showed a number of contaminants that persisted through all measurements. As an example, FIG. 8 shows a typical mass spectrum with prominent species indicated. Using M/Q for the mass-to-charge-state ratio in units of amu, we have not found significant contamination above M/Q = 40 (a small Ar peak can occasionally be seen) and restrict our dipole scans to M/Q = 0 to M/Q = 45 typically. The M/Q of the peaks that were found in the recorded spectra hinted at water contamination (O\(^+\), OH\(^+\), H\(_2\)O\(^+\)), a small air leak (O\(^+\), O\(_2\)\(^+\), N\(^+\), N\(_2\)\(^+\), Ar\(^+\)), and a third source of contamination, related to outgassing of the silicone rubber O-rings (F\(^+\), Si\(^+\)). Replacement of the back plate O-rings with Viton and removal of a cracked ceramic insulator reduced the source contamination significantly. Measurements that were taken prior to the O-ring replacement will be indicated as such.
FIG. 9. Mass spectrum for H₂ flow = 0.275 sccm and 125 V discharge voltage. The H₃⁺ fraction is 76%. Note that contaminants are reduced to virtually zero after O-ring replacement.

B. Performance Tests

The first results we are reporting here are of the ion source peak performance to date: The highest extracted current density, the highest H₂⁺ fraction, and the highest total extracted H₂⁺ current density (a balance between H₂⁺ fraction and total extracted current density).

Highest total current. With 5 mA of total beam current measured in Faraday cup 1, the highest current density recorded so far was ≈ 40 mA/cm² (4 mm diameter aperture). This was with a discharge voltage of 150 V and a H₂ flow of 1 sccm. Accordingly (see discussion below) the species balance was shifted towards H₃⁺, with an H₂⁺ fraction of ≈ 22% and H₃⁺ fraction of ≈ 51%. This measurement was taken before O-ring replacement and, consequently, suffered from contamination with higher mass species.

Highest H₂⁺ contribution. With a lower H₂ flow of 0.275 sccm, V_discharge = 125 V, and I_discharge = 7 A, the highest fraction of H₂⁺ was recorded as 76%. The total extracted current was 1.42 mA (11.4 mA/cm²). The corresponding mass spectrum is shown in FIG. 9. Coincidentally, this is also the highest current recorded with H₃⁺ being the dominant species. 470 μA were transported to the end of the beam line, constituting a beam line transmission efficiency of 44%, which agrees with Warp.

C. Systematic Parameter Variations

The ion source is designed to allow several parameters to be varied. Here we provide information on the total current and species composition of the beam for each set of parameters.

Hydrogen flow. In this study, the total extracted beam current was held stable at 0.5 mA. The mass flow was varied from 0.25 to 3.0 sccm. The results are plotted in FIG. 10. Notably, the H₂⁺ contribution rises towards lower pressures. This is quite typical, as with higher flow rates the probability for collisions of the already formed H₂⁺ ion with other molecules, plasma ions, and electrons increases. The contribution from the contaminant species (not shown in the plot) is nearly constant at ≈ 50%. Throughout our measurements, the optimal mass flow for H₂⁺ production has been between 0.15 and 0.25 sccm.

Discharge voltage. Here we varied the discharge voltage from 70 V to 140 V, while keeping the H₂ flow rate constant at 0.2 sccm. The total extracted current in Faraday cup 1 was 0.75 mA and dropping. This reduction stems from the adjustment of the filament heating current to keep the discharge current constant at 4 A throughout this measurement. As can be seen in FIG. 11, the contribution of the remaining contaminants...
FIG. 12. Variation of discharge current. Here the discharge voltage was kept at 120 V and H\textsubscript{2} flow at 0.2 sccm. No strong dependency is observed at these values.

is reduced, while H\textsuperscript{+}\textsubscript{2} slightly increases up to 110 V. After that, all contributions remain near constant.

**Discharge current.** Here we varied the discharge current from 2 A to 5 A, while keeping the H\textsubscript{2} flow rate constant at 0.2 sccm. While increasing the discharge current, the total extracted current increased almost linearly. This is not surprising as a higher discharge current usually indicates higher plasma density. No strong dependence of the species ratios is observed in this regime.

**D. Emittance Measurements**

An example of the results from the two Allison emittance scanners can be seen in FIG. 13, for a mass-separated H\textsuperscript{+}\textsubscript{2} beam, allowing a demonstration of good qualitative agreement with the IBSimu/Warp simulation of the setup (cf. Section III). The measured 1-RMS, normalized emittances at the end of the beam line were 0.37 \unit{\pi-mm-mrad} and 0.29 \unit{\pi-mm-mrad} for the horizontal and vertical scans, respectively. The total current from the source was 850 \unit{\mu A} and the H\textsuperscript{+}\textsubscript{2} current arriving at the scanner location was 200 \unit{\mu A}.

**E. Discussion**

As H\textsuperscript{+}\textsubscript{2} has a short mean free path (3-5 cm) before it either combines with an H to H\textsuperscript{+}\textsubscript{3} or is dissociated into protons, the H\textsubscript{2} gas flow must be in balance with discharge voltage, and filament position, with the filament position close to the extraction aperture being a critical aspect that is reflected in the design through the short source body.

The dominant process for H\textsuperscript{+}\textsubscript{2} production is

\[ \text{H}_2 + \text{e}^- \rightarrow \text{H}^+ + \text{H} + \text{e}^- \]

with the three main processes reducing the available H\textsuperscript{+}\textsubscript{2} being:

\[ \text{H}_2^+ + \text{e}^- \rightarrow \text{H}^+ + \text{H} + \text{e}^- , \]
\[ \text{H}_2^+ + \text{H}_2 \rightarrow \text{H}_3^+ + \text{H} , \]
\[ \text{H}_2^+ + \text{e}^- \rightarrow 2\text{H}^+ + 2\text{e}^- . \]

The corresponding cross-sections are plotted in FIG. 14. Our measurements indicate that H\textsuperscript{+}\textsubscript{2} becomes the dominant species at low H\textsubscript{2} mass flow (0.25 sccm and below) and low discharge voltage (80 V to 120 V). This is also in agreement with earlier findings by Ehlers and Leung [14, 37]. In the next measurement period, the filament position will be varied to find the maximum extracted current with high H\textsuperscript{+}\textsubscript{2} fraction. Other planned improvements to the source include better water cooling and a plasma aperture made from a tungsten alloy (75% W, 25% Cu) to improve heat transfer away from the source aperture and to provide better thermal stability.

The quality (emittance) of beam extracted from the ion source is very good, as is typical for filament-driven multicusp ion sources. Currently, we only have emittance scans after the beam has gone through the non-ideal LEBT, but as the agreement with the simulations is good, we can extrapolate back to the ion source, which yields
normalized 1-rms emittances below 0.05 $\pi$-mm-mrad at extraction. The large emittance growth in the LEBT can be attributed to the strong multipole components in the dipole fringe fields. Borrowed equipment was used to assemble the test stand. Furthermore, the dipole magnet has no vertical focusing and a pair of quadrupole magnets were used to compensate for this. In a future measurement, the Allison scanners will be moved into DB1 to measure the combined emittance of the beam (at $>80\%$ $H_2^+$) right after extraction, which will decouple the emittance measurement from the shortcomings of the LEBT, albeit at the expense of having some proton and $H_2^+$ contamination in the scans.

Contamination of the source with heavier-mass species in a previous commissioning run was significantly reduced by replacing a pair of O-rings and a cracked ceramic insulator. Once the source has warmed up, contaminants are virtually non-existent. The source now operates stably over periods of several hours without significant changes in beam current and composition.

As a final point of discussion, we would like to mention that the stainless steel body of the source, while robust, turned out not to be ideal in terms of transferring heat away through the water cooling channels. Particularly, the plasma aperture shows distortions after long running times (several hours) at high power. We are beginning to replace individual source parts with a high yield-strength copper alloy like Elmedur.

V. OUTLOOK AND CONCLUSION

We have presented a new filament-driven multicusp ion source, designed to produce high currents of $H_2^+$ in DC mode for long-time operation, and established simulations that provide good qualitative agreement with the constructed device. We reported maximum currents of 1.42 mA from a 4 mm aperture consisting of 76% $H_2^+$, which corresponds to a current of 1.08 mA of $H_2^+$. To our knowledge, this is the highest $H_2^+$ current published to date from a multicusp ion source in DC mode, while $H_2^+$ was the dominant species. This is an important milestone for MIST-1 and, as described below, we have a clear path for further improvement.

For the novel RFQ Direct Injection method that is being proposed for the IsoDAR experiment [3, 38, 39], the nominal goal is 10 mA of $H_2^+$ delivered by the ion source. If our 4 mm diameter aperture results are scaled up to an 8 mm aperture (assuming constant plasma density), 4.3 mA of $H_2^+$ can currently be delivered from this source. This is only a factor 2.5 short of the goal. With the ongoing systematic tests of filament material, shape, and position as well as a stronger magnetic confinement field, the available $H_2^+$ beam current will be significantly increased. Furthermore, improved cooling will allow higher discharge currents, also leading to higher plasma densities and thus, higher currents. Even with the currently reachable 4.3 mA of $H_2^+$, a compact cyclotron of the IsoDAR design could be built that delivers 4 times more proton current (2 mA of $H_2^+$ corresponds to 4 mA of protons after charge-stripping) than commercially available machines, and also beats record holder PSI Injector II, which delivers a maximum of 2.7 mA protons [40].

In addition to construction of the source, we developed an accurate simulation model of the ion source and beam line, that was compared with mass spectra and emittance measurements in the second 6-way cross (DB2) with good agreement. Thus, although the LEBT itself has certain shortcomings (due to the use of borrowed equipment), we understand the beam dynamics well and can extrapolate the beam quality directly after the source from the measurements at the end of the LEBT. The extrapolated emittance at extraction is $<0.05\pi$-mm-mrad (1-rms, normalized), which is well below the IsoDAR requirements.

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