GENERATION OF HIGH PURITY CW PROTON BEAMS FROM MICROWAVE DRIVEN SOURCES *

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We describe a technique we have developed to significantly increase the proton fraction extracted from high pressure (mTorr) electron cyclotron resonance (ECR) sources of the type developed by Chalk River Laboratories (CRL)[1]. Specifically, this proton enhancement is achieved by the addition of environmentally benign additives (H_2O being the most effective) to the plasma, in molecular concentrations of the order of 1%. Typically, operating under non-resonant source conditions, this technique will enhance the proton fraction from about 75% to greater than 95% for a power input of 700W at 2.45 GHz. Similar results are achieved for deuteron beams. We believe this technique is capable of similar results in arc-discharge (bucket) sources, Penning sources and any other gas discharge sources, under suitable conditions.

I. INTRODUCTION

High current cw proton sources of high reliability are a current requirement for several proposed accelerator applications, including spallation neutron sources and accelerator production of tritium. A desirable property of such sources is that the proton fraction of the extracted beam be as high as possible so as to avoid the need for selection of the desired ion, i.e., to enable direct injection into an accelerating structure. A number of sources have been described in the literature that yield proton fractions of the order of 80% of the extracted beam, the other unwanted beam components being H_2^+ and H_3^+. These advanced sources include the arc-driven multi-cusp generator developed for the Basic Technology Accelerator (BTA) at JAERI [2] and the high pressure ECR source developed at CRL. Although the CRL source has generated a beam with a proton fraction under resonant conditions of 90%, most experiments reported by the CRL group [3] have been performed when operating off-resonance where proton fractions of 75 - 80% were obtained. Normal operation for this source is off resonance because of problems in maintaining long term plasma stability when operating on resonance, an observation also noted by ourselves using an identical source purchased from CRL. Similarly, the CRL ECR source supplied to Los Alamos National Laboratory (LANL)[4] generally produces beams with a proton fraction of about 80%. While beams with a proton fraction of 80% have been shown by the CRL group to be suitable for direct injection into a room-temperature radio frequency quadruple (RFQ) [5], they would certainly not be suitable for injection into a superconducting structure because of the possible unacceptable thermal loading caused by the deleterious H_2^+ and H_3^+ ion species. Unless beam purity of the order of 99% or so can be achieved, direct injection into a superconducting structure does not appear likely, thus requiring magnetic separation before injection. Magnetic separation inevitably leads to emittance growth and loss of beam brightness, a situation that is also undesirable for high current cw superconducting accelerators. An additional benefit of very high purity proton beams has been pointed out by Sherman, [5] i.e., the higher the proton fraction, the less is the effective mass of the beam. Hence, for a given beam current density, the electric field can be reduced, thus reducing voltage breakdown and yielding a more reliable injector.

II. BACKGROUND

It has long been known that the addition of minor constituents to microwave generated plasmas can greatly modify the species composition of the plasma, and, specifically, increase atomic neutral fractions with respect to molecular species [6]. This technique has sometimes been used by those in atomic and molecular physics to produce high purity atomic hydrogen beams [6]. Because the molecular fraction of the additive required is generally so small (<1%), it seems unlikely that its catalytic action is a gas phase property and more likely that it results from some surface action, though for a long time controversy existed on this point. Systematic studies [6] of atomic hydrogen fractions from microwave driven plasmas, however, strongly indicate that any catalytic action of the additive results from (largely unknown) surface phenomena by preventing atomic recombination on the surface. This is analogous to the prevention of recombination by fused-alumina ion source liners. Neutral atomic hydrogen sources with close to 100% purity have been made using this technique, leading us to recognize that this may be a viable technique for the production of high purity ion beams.

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III. EXPERIMENTAL SETUP

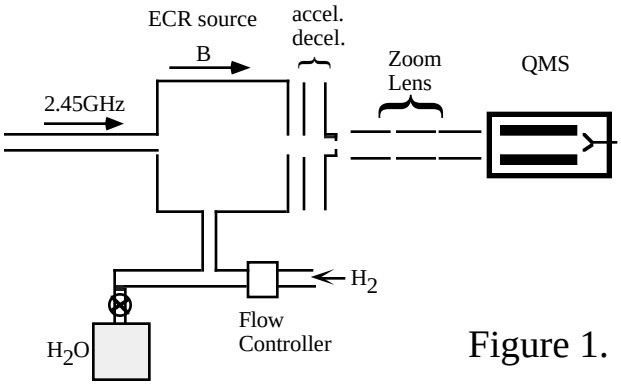


Figure 1.

A schematic of our experimental setup and beam diagnostic is shown in Fig. 1. The major components of our apparatus include an ECR source purchased from CRL which is powered by a 2.45 GHz microwave generator rated at 2.0 kW. The microwave generator is coupled to the source via a circulator and a four-stub autotuner. The ion source is attached to a large, flexibly designed, high-vacuum, oil-free diagnostic chamber that is pumped by three cyropumps and a turbo pump giving a base pressure of 1.0×10^{-8} Torr without baking. When operating the ion source at a hydrogen-feed flow rate of 1 sccm, the base pressure in the diagnostic chamber rises to about 6×10^{-6} Torr as measured on an (uncorrected) ion gauge. The catalytic additive (generally H_2O) is introduced to the plasma downstream of the hydrogen flow control unit via a leak valve as shown in figure 1. The molecular fraction H_2O/H_2 is estimated from the ion gauge measurements taking into account the very different gauge constants for these two gases. This fraction is generally of the order of 1% or less and the ion gauge measurements are consistent with the fraction of O^+ we see in the extracted beam as described below.

In the present experiment, 5 to 15 mA of beam current is extracted from the source at a few hundred volts by an accel-decel arrangement, with the main beam being collected and monitored on the decel electrode. A small hole in the decel electrode allows a portion of the beam to be imaged at the entrance plane of a quadrupole mass spectrometer (QMS) by means of a three element zoom lens whose design is based on focal properties tabulated by Harting and Read [7]. The zoom lens gradually decelerates the beam which emerges from the decel electrode to the 10-20 eV required by the QMS for quantitative analysis. The beam trajectories for the zoom lens were calculated using SIMION [8]. With the typical operating voltages shown in Fig. 1, 50% of the sampled beam lies in a circle of only 0.25 mm dia. at the entrance plane of the QMS, and the resulting rays within this circle easily meet the parallelicity requirements for quantitative mass spectrometry[9].

IV. RESULTS

All of the measurements reported here are conducted with the ECR source operating slightly off resonance, as chosen by the magnitude of the magnetic confining field. Similar results were obtained with the source magnetic field operating either 10% above or below the resonant field. Though operation off-resonance usually produces a smaller fraction of protons, such is not the case in the present experiment with H_2O as an additive.

Figure 2 shows the mass analysis of a beam extracted from the source with 1 sccm H_2 flow and 700 W microwave power to the source. Under these conditions, the proton fraction of the total beam (consisting of $H^+ + H_2^+ + H_3^+$) is about 0.75, consistent with the measurements of Taylor [1] under similar non-resonant conditions.

Figure 2.

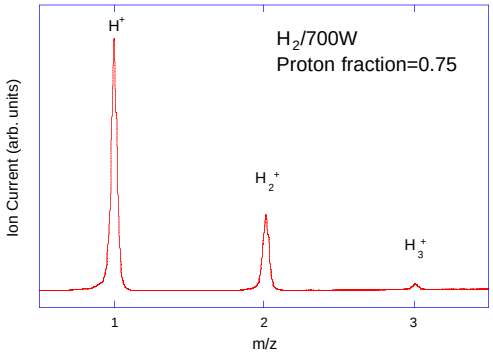


Figure 3 shows a beam composition obtained under the same conditions as figure 2, but with ~ 1% H_2O added to the source. In this case the proton fraction is slightly higher than 0.95. Notable in figure 3 is the absence of H_3^+. This is expected since H_3^+ is produced via the reaction $H_2^+ + H_2 \rightarrow H_3^+ + H$ and is thus quadratic with respect to the H_2 partial pressure in the source. Reduction of the H_2^+ peak by a factor of about 5 by the addition of 1% H_2O thus reduces the H_3^+ intensity by a factor of 25. The increase in concentration of hydrogen atoms in the source by the addition of H_2O is dramatically visual to the eye, the plasma changing color from pale bluish-pink to a dramatic deep violet characteristic of Balmer ($H\alpha$ and $H\beta$) radiation. The addition of H_2O to the source appears to have the added benefit of significantly stabilizing the plasma and producing a less noisy beam.

Figure 3.

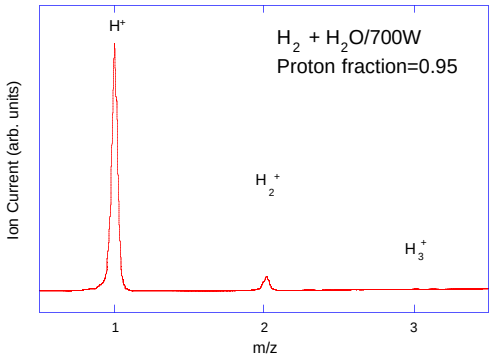
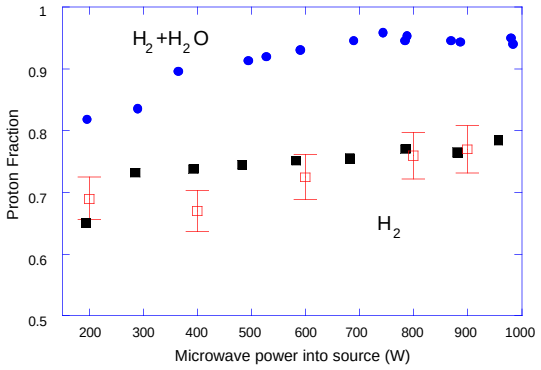


Figure 4 shows the proton fraction obtained as a function of microwave power to the source for 1 sccm H_2 flow rate, both with (solid circles) and without (solid squares) H_2O additive and operating under non-resonant conditions. Alternate data points in figure 4 were taken under conditions of increasing and decreasing power so as to illustrate the absence of any long term drift. Figure 4 also shows the reproducibility of Taylor's earlier results [1] (open squares) under similar non-resonant conditions.

Figure 4.



Under the conditions of figure 4, measurements of other impurities introduced into the beam by admitting H_2O to the source show these to be O^+ (0.4%) and OH^+ and H_2O^+ (each at the level of a few parts per thousand). Finally, we have obtained a similar improvement in deuteron (D^+) enhancement by use of either H_2O or D_2O, each being equally effective but producing extraneous peaks (H^+, HD^+ and HD_2^+) in the case of H_2O + D_2 , as expected.

V. SUMMARY AND FUTURE

We have demonstrated significant enhancement in the proton and deuteron fractions of beams extracted from high pressure ECR sources by the addition of about 1% of H_2O or D_2O to the source under non-resonant conditions. An additional benefit seems to be a more stable operation of the source. We believe this technique may be applied to any type of gas discharge proton source, provided that the source may be made to operate thermally cool. Further, we believe that with minor modifications the source may realistically yield proton fractions of 98 to 99%, the remaining part consisting primarily of O^+, OH^+, and H_2O^+ resulting from the H_2O.

Finally, a preliminary analysis of collaborative experiments by ANL and LANL[10] performed on the CRITS injector located at LANL, indicate higher proton fractions and lower proton beam emittances at 40-45keV beam energies using this technique.

VI. ACKNOWLEDGMENTS

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