DOPPLER-SHIFT PROTON FRACTION MEASUREMENT ON A CW PROTON INJECTOR

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Abstract

A spectrometer/Optical Multi-channel Analyzer has been used to measure the proton fraction of the cw proton injector developed for the Accelerator Production of Tritium (APT)[1] and the Low Energy Demonstration Accelerator (LEDA) at Los Alamos. This technique, pioneered by the Lawrence Berkeley National Laboratory (LBNL), was subsequently adopted by the international fusion community as the standard for determining the extracted ion fractions of neutral beam injectors. Proton fractions up to $95 \pm 3\%$ have been measured on the LEDA injector. These values are in good agreement with results obtained by magnetically sweeping the ion beam, collimated by a slit, across a Faraday cup. Since the velocity distribution of each beam species is measured, it also can be used to determine beam divergence. While divergence has not yet been ascertained due to the wide slit widths in use, non-Gaussian distributions have been observed during operation above the design-matched perveance. An additional feature is that the presence of extracted water ions can be observed. During ion source conditioning at 75 kV, an extracted water fraction >30% was briefly observed.

1 INTRODUCTION

A diagnostic developed by the magnetic fusion energy community has been successfully utilized on the LEDA injector test facility[2] at Los Alamos. The technique was developed in the late 1970s at LBNL[3] as a means of determining the composition of neutral beams used to heat magnetic fusion plasmas. Extracted H^+, H_2^+, and H_3^+ interact with background gas to produce fast, excited hydrogen atoms with energies of E, E/2, and E/3, where E is the ion source extraction potential. By observing the beam at an angle relative to the direction of propagation, the Doppler-shift separates the light from the three species. The wavelength of the Doppler-shifted light is $\lambda = \lambda_0 (1 - \beta \cos \theta)$, where λ_0 is the unshifted wavelength, $\beta = v/c$, and θ is the angle between the viewing line of sight and the beam's direction of propagation. Beam composition is determined from the quantity of light associated with each Doppler-shifted line. Cross sections for Balmer-α (Hα) production from H^+, H_2^+, and H_3^+ incident on hydrogen gas have been measured[4], permitting a quantitative measure of the beam composition. In addition to the Doppler shift due to the differing β's, the light from each species is broadened due to $\cos \theta$. For small beam divergence, and neglecting broadening due to the instrument, the line shape is a direct measure of the velocity distribution. In principle, a quantitative measure of the divergence can be made[5]. Collisions of extracted water ions with the background gas produce excited hydrogen atoms with energy E/18, where E is the extraction potential. Water contamination becomes apparent at a level of <1%

Experiments carried out at Los Alamos have been a successful proof-of-principle test on a proton injector, even though photon fluences from the injector are orders of magnitude below that of large fusion ion sources. The photon production rate is proportional to the beam current, the background gas density, and the Hα production cross sections. While the current densities of fusion and APT ion sources are similar, fusion ion sources have much larger extraction areas. Fusion ion source currents are of order 100 A versus 100 mA for the LEDA/APT injector. Another significant difference is the background gas density. In neutral beam injectors, the goal is to convert the extracted ions into neutrals by collisions with background gas. For a proton injector, it is important to avoid proton loss via charge exchange to H^0. Near the ion source, the background gas density is ~10 times lower than in a fusion neutral beam injector. The net result is that the Hα production rate in a proton injector is ~10^4 times less than in a fusion neutral beam injector.

Several factors favor the proton injector. The APT ion source is cw compared to pulse-lengths of a few seconds for fusion ion sources; long integrations are therefore possible. Another advantage is that the neutralization and dissociation of the extracted ion beam, that takes place in the neutral beam injector before the beam reaches the observation point, occurs to a much smaller degree in a proton injector. The problem created by changing the state of the beam is that the Hα production cross sections are different for the daughters than for their parents. Therefore, the composition of the beam at the observation point must be known to deduce the composition at the extraction plane. Due to the low gas pressure between the ion source and observation point in a proton injector, a beam composed of H^+, H_2^+, and H_3^+ can be assumed.

Initial data collection occurred at 50 kV, during experiments supporting a 1.25 MeV cw radio-frequency quadrupole (RFQ)[6]. The RFQ for LEDA and APT has been designed to accept a 75 keV proton beam. A small amount of data was obtained after the ion source was regapped for operation at 75 keV.

2 DESCRIPTION OF THE HARDWARE

A complete Doppler-shift spectroscopy system[7] was borrowed from the Princeton Plasma Physics Laboratory (PPPL). It consists of a 135-mm Canon lens to focus collimated light onto a 600-μm glass fiber; an Instruments S.A. 640-mm Czerny-Turner spectrometer; a Princeton Applied Research Corp. vidicon detector; a detector controller; and a computer control console.

The beam was observed 34 cm downstream from the extractor as it exits the cone that follows the accelerator. The 7-cm exit diameter of the cone equals the 7-cm diameter of the light collection cylinder. At this location the 4-rms beam diameter is 2.2 cm. Since light is collected from the entire horizontal extent of the beam, all of x phase space is observed.

Each pixel in the 500x500 square detector is 25 μm. When integrating light from a 43-cm tall PPPL neutral beam injector, the slits of the spectrometer were set at 3 μm. In the present case, they were opened to 50 μm, providing additional light. Opening the slits beyond the 50-μm size of the pixels caused broadening of the lines and merging of the two molecular lines. 50 μm is a compromise between signal and resolution.

3 DATA AND ANALYSIS

Figure 1 is a spectrum obtained at 50 kV with 120 mA of ions measured at the first DC current toroid. (All quoted beam currents were measured with this toroid.) The viewing angle, θ, was 60°, the entrance slit of the spectrometer was 50 μm, and light was integrated for 16 s. Since the beam came towards the line of sight, the Doppler shift was in the blue direction. Left to right, the first three lines are the Doppler-shifted lines from incident H^+, H_2^+, and H_3^+. The rightmost, and tallest, line is unshifted Hα (656.3 nm).
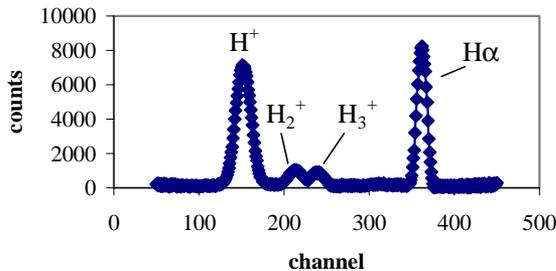
Figure 1. Spectrum at 50 kV and 120 mA with 50 mm slits.

Light falls on a portion of the height of the detector corresponding to the diameter of the fiber. Each channel was defined to be one pixel wide by 60 pixels tall (sufficient to include all pixels illuminated by the fiber). The wavelength corresponding to a particular channel can be determined by assigning 656.2 nm to channel 362 and

using a dispersion of 0.016 nm/channel. The ordinate represents the number of counts detected in each channel.

Proton fractions were obtained by fitting the three Doppler-shifted lines to Gaussians. Error bars of ±3% for the proton fraction, 17% for H_2^+, and ±20% for H_3^+ are based on uncertainties of ±10% in calculating the line areas, ~±5% in cross sections[4], and assuming that the gas line density between the ion source and observation point could be as high as 1.5×10^{14} cm^{-2}.

4 RESULTS

Proton fractions have been measured for scans of the ion source microwave power and gas throughput. In both cases, the spectrometer and detector were operated in the as in figure 1. Figure 2 shows the results of scanning the 2.45 GHz microwave power to the source over the range of 500 to 1500 W while the beam energy and gas throughput were fixed at 50 keV and 2.22 standard cubic centimeters per minute (sccm). Beam current varied from 36 mA to 140 mA. Due to the wide range over which the beam current changed, the currents to the two electron cyclotron resonance (ECR) solenoids needed to be varied to maintain stable operation.
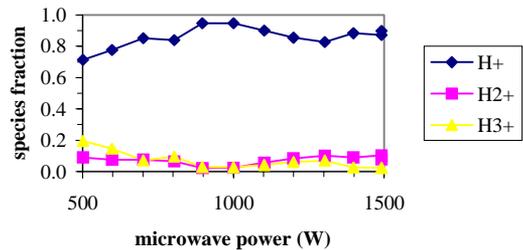
Figure 2. Beam composition as a function of microwave power.

Proton fractions of 0.95 ± 0.03 were found at 900 and 1000 W. These values agree with measurements made using an emittance measuring unit modified with a deflection magnet preceding the Faraday cup[2].
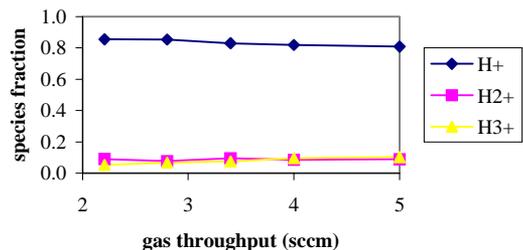
Figure 3. Beam composition as a function of gas throughput.

Figure 3 is the result of a scan where the gas throughput was varied from 2.2 to 5 sccm, at a constant

microwave power of 1000 W. As the throughput increased from 2.2 to 5 sccm, beam current decreased from 92 mA to 71 mA. As above, the currents to the two ECR solenoids were adjusted to maintain stable source operation.

It is important to note that the proton fraction corresponding to the 2.2-sccm data point in figure 3 (85%) does not agree with the 1000 W data point in figure 2 (95%). Source microwave power and throughput were the same in these two cases, but the proton fractions differ by 10%. Inspection of the raw data supports the measured difference. ECR solenoid settings were slightly different. This observation, together with the variations in figure 2, indicates that the proton fraction is sensitive to minor variations in ion source setpoints.

Figure 4 is a spectrum from 50 kV, 132 mA source operation. The source is operating above its design-matched perveance (110 mA at 50 kV). An important difference between the way this spectrum was acquired and all of those discussed so far is that the slit width was reduced to 20 μm.
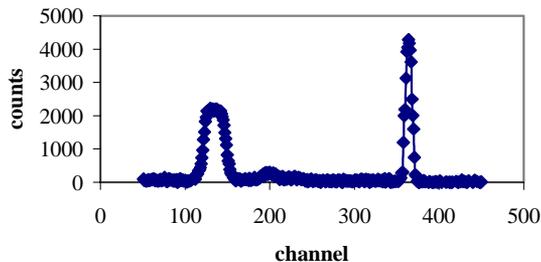
Figure 4. Spectrum taken at 132 mA with 20 μm slit width showing a non-gaussian proton peak.

Note the non-Gaussian shape of the proton line. Such a distribution is indicative of poor beam optics. In this case, it can be attributed to overdense beam extraction. Other data taken with 20-μm slits show a return to Gaussian shape as the current was reduced to 110 mA. The data taken with 50-μm slits is more Gaussian because the natural line width is convolved with a wider instrument function.

Data were also taken during several hours of ion source operation at 75 keV. Immediately prior to when this data was taken, the ion source was exposed to air for accelerator maintenance. The spectrometer slit width was back to 50 μm.

An interesting spectrum was noted and is shown in figure 5. Situated at channel 300 is a line due to hydrogen atoms extracted as water ions. The presence of significant water in the beam is attributed to the fact that the ion source was just beginning to be conditioned and that water became absorbed on the source walls during its exposure to air.

Cross sections for the production of Hα from water incident on hydrogen have not been measured. To estimate the water fraction, the required cross sections

were estimated from cross sections for the production of Hα for hydrogen atoms incident on water[8].
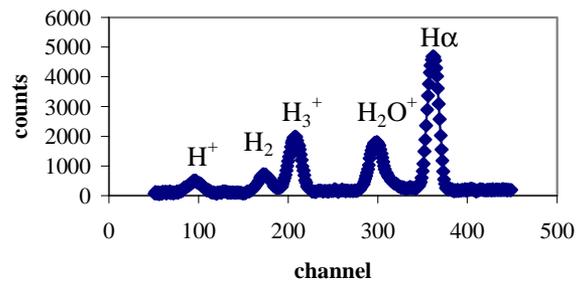
Figure 5. Spectrum at 75 kV, just after the ion source was open to air.

The proton fraction is estimated to be in the range of 30 to 40% while water is 40 to 25%, respectively. There is a large uncertainty in the beam fractions in this case due to the facts that protons are no longer the dominant line and that estimates of the water cross sections differ by a factor of two.

After approximately 10 minutes of cw operation, the water level in the beam decreased by over an order of magnitude. However, the proton fraction was still poor due to the low source power. Residual gas analysis of the injector vacuum always indicates the presence of water contamination for several days after exposure to air. Water in the ion source cleans up at a more rapid rate due to its active removal by the plasma and the beam.

ACKNOWLEDGMENTS

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