THE PRODUCTION OF NEGATIVE CARBON IONS WITH A VOLUME CUSP ION SOURCE

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Abstract

Recent progress has been made at the newly commissioned Ion Source Test Facility (ISTF) [1]. Phase II, the final phase of the project, was completed in March 2016. First measurements were performed with D-Pace's TRIUMF licensed H^- ion source [2]. The source was first characterized with H^- and an extraction study of the H^- ions was performed. A study of the production of heavy negative ions with volume cusp sources was started. Measurements with helium revealed no negative ions were extracted. Negative carbon ions were produced with acetylene. The beam composition has been analysed with a spectrometer.

INTRODUCTION

A new Ion Source Test Facility (ISTF) designed by D-Pace Inc. has recently been commissioned at Buckley Systems Ltd. in Auckland New Zealand [1]. The ISTF's main purpose will be to research and develop ion sources, beam diagnostic devices and beamline components. The final phase of the installation was completed in March 2016. D-Pace's TRIUMF licensed filament-powered H^- source [2] as well as D-Pace's University of Jyvaskyla 13.56 MHz RF powered H^- source [3] can be installed at the ISTF. The diagnostic devices include a pneumatic and a fixed Faraday cup, an emittance scanner, a mini beamline, an analyser/spectrometer set up for 100:1 mass resolution, an optical fibre beam profile monitor licensed from the University of Bern [4], a residual gas analyser and an optical spectrometer.

Initial characterization of the filament-powered source was performed with hydrogen and a study of the extraction of the ions is also ongoing. The ISTF will also be used to study the production of heavy negative ions with volume-cusp ion sources. Initial tests with helium show that no negative helium ions are being extracted from the source. Negative carbon ions were extracted from the source when acetylene was used. The different species extracted are analysed as a function of the various source settings.

HYDROGEN

Initial measurements at the ISTF were performed with D-Pace's TRIUMF licensed filament-powered H^- volume-cusp ion source. The source was tested up to 16.1 mA DC of H^- beam with a normalized 4 rms emittance of 0.77 mm-mrad.

The extraction of the source was studied. The ion source extraction system is composed of three lenses. The front plate of the source, called the plasma lens, is biased at a few volts. The second lens, called the extraction lens, is usually biased between 1 kV and 4 kV also serves as an electron dump due to an added magnetic dipole field. Finally, the third lens is the ground lens.

For large ion production rates, the extraction is space charge limited and will follow the 3/2 Child-Langmuir power law [5]. For two species, the Child-Langmuir law still applies for the defined total current [6]:

$$I_{Tot} = I_{H^-} + \sqrt{\frac{m_e}{m_H}} I_e, \quad (1)$$

where I_{H^-} is the H^- current, m_e is the electron mass, m_H is the H^- mass and I_e is the electron current. I_{H^-} is taken as the bias current, not the Faraday cup current to include all the ions that are extracted from the source. The electron current is the extraction lens current since all the electron are deflected onto the lens by the dipole field. We assume here that no H^- ion hits the extraction lens.

For the emission from a flat surface at zero initial velocity, the Child-Langmuir law states [7]:

$$J = PV^{\frac{3}{2}} = \frac{1.74}{d^2} V^{\frac{3}{2}} \text{ mA·mm}^2, \quad (2)$$

where J is the current density, d is the distance between the plasma lens and the extraction lens and V is the potential applied to the extraction lens. The perveance of the beam, P, is only dependent on geometry. For a circular aperture of radius r, the relation between the current and the current density is given by: $I_{tot} = \pi r^2 J$.

The extraction lens potential was incremented from 1.5 kV to 3.7 kV. The arc in the ion source's plasma chamber was set at 20 A and 130 V, the beam energy was set at 30 keV and the gas flow was set at 15 sccm. The results are presented in Figure 1. The data is fitted to Eq. (2) with different perveance values P.

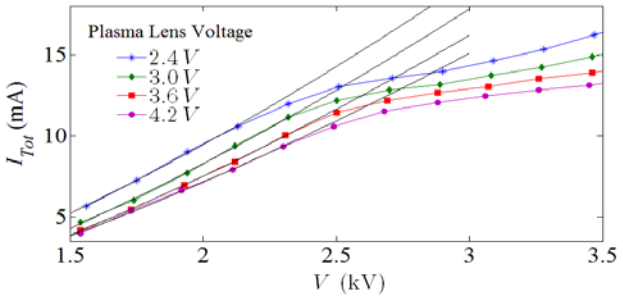

Figure 1: Perveance plot of a 30 keV H^- beam for various plasma lens voltages. The arc current was set at 20 A and 130 V and the gas flow was set a 15 sccm. The data was fitted with the 3/2 power law over the extraction limited region.

We see that the source follows the 3/2 power low for low extraction voltages. At higher extraction voltage the source becomes production limited and the extracted current is

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saturated. One will notice that the plasma potential changes the perveance. The plasma lens plays a crucial part in negative ion sources because it is thought to help the transport of negative ions to the extraction region and it depletes the electron from the extraction region [8]. Furthermore, Figure 1 shows that the plasma potential has an effect on the perveance of the beam.

The Child-Langmuir law is only valid for flat emission surfaces. Therefore, Eq. (2) is invalid for a curved plasma meniscus. If we assume that the meniscus is spherical and that the curvature remains constant as a function of the extraction potential, we can solve Poisson's equation in spherical coordinates to better describe the geometry.

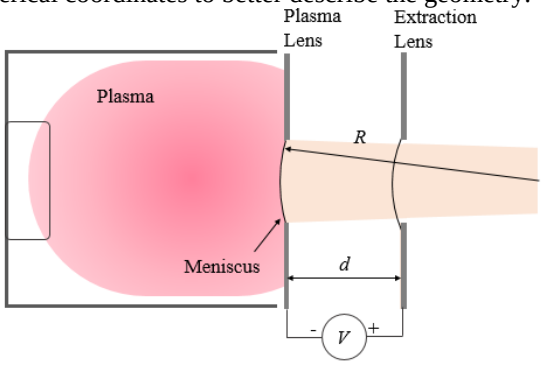

Figure 2: Schematic of the extraction geometry with a concave spherical meniscus. R is the radius of curvature of the meniscus and d is the distance between the lenses.

Figure 2 presents a schematic of the geometry for a concave meniscus. A convex meniscus can be described by setting the radius R to the left of the plasma lens. We will assume radial symmetry of the electric potential and in the velocity of the particles. Using the same procedure as with the planar case[5], we obtain the following differential equation.

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial \varphi}{\partial r}\right) = \frac{J}{\varepsilon_0}\sqrt{\frac{m}{2q}}\varphi^{-\frac{1}{2}} \qquad (3)$$

Equation (3) can be solved numerically. Changing the solving interval varies the radius of curvature of the meniscus. The equation was solved for positive (convex) and negative (concave) radii of curvature. The solution for $R \gg d$ converges with equation (2) for both positive and negative radii of curvature. The results are presented in Figure 3.

We see how a curved plasma meniscus reduces the current extracted from the source for concave surfaces and does the opposite for convex surfaces. We also notice that the relation between the curvature of the emission surface and the current extracted is non-linear. Relating the results back to Figure 1, it seems like we have a convex emission surface that is approaching a flat surface as the plasma lens voltage is reduced. An extraction study of our source will be completed to compare the simulated curvature to the one predicted here.

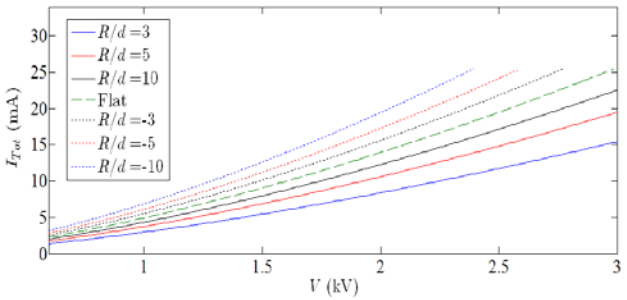

Figure 3: Calculated extraction limited current for various emission surfaces. The negative curvature represents a concave emission surface while the positive curvatures are for convex surfaces.

A proper fit to the data using Eq. (3) could not be done because the perveance values obtained from Figure 1 are lower than predicted since we believe some H^- current is lost on the extraction. This causes the measured I_{Tot} to be lower than the actual value. Therefore, an estimation of the meniscus curvature couldn't be calculated.

HELIUM

Helium was used as the injection gas in the filament-powered volume-cusp ion source. Helium forms a metastable negative ion with a lifetime of 18.2 µs [9]. Negative helium ions are commonly produced by charge exchange through alkali vapour chambers [10]. No measurable beam could be measured from our ion source. The large plasma volume is thought to give transit times that are larger than the lifetime of the negative helium ions that would be created in the plasma. Therefore, any negative ion produced in the plasma would lose its extra electron before being extracted from the source.

CARBON

In an attempt to obtain negative carbon ions from D-Pace's TRIUMF licensed H^- source, acetylene was used as the injection gas in the source. Acetylene was chosen because it has the highest carbon to hydrogen content (1:1) out of any organic gases. Furthermore, acetylene is known to produce negative ions through interactions with electron [11, 12]. These studies found that the two most abundant negative ions produced were C_2^- and C_2H^-.

Using four half-circle tantalum filaments, a plasma was generated at about 320 A of filament current. The ion source extraction and cusp configurations remained unchanged from the H^- case. Arcing between the extraction and the plasma lenses became a problem at higher flow rates and higher arc currents. Such arcing has never appeared while using hydrogen, even though the lens are only 2.7 mm apart. It might suggest that the plasma meniscus is convex when using acetylene and is protruding in the extraction region. Further study needs to be done to completely eliminate the problem.

Up to 250 µA of beam has been extracted from the source at 5 A of arc current. Additional analysis with the spectrometer show that the beam is mostly composed of

C_2^-, C_2 H^- and $C_2H_2^-$, as can be seen in the spectrometer scan presented in Figure 4. This compares well with previous measurements done on the interaction between acetylene and electrons [11] except for the strong $C_2H_2^-$ signal. H^- was also found in large proportions in our beam. This is not surprising since our source is optimized for H^- production and the bond dissociation energy of the C-H bond at 298 K is 132.8 kcal/mol while the dissociation energy of the C≡C at the same temperature is of 230.6 kcal/mol [13]. This also explains why we get a larger proportion of C_2H_x compared to CH_x ions. There is also a considerable current of C_4H_x in the beam. These ions are likely the result of a polymerisation of the acetylene [14].

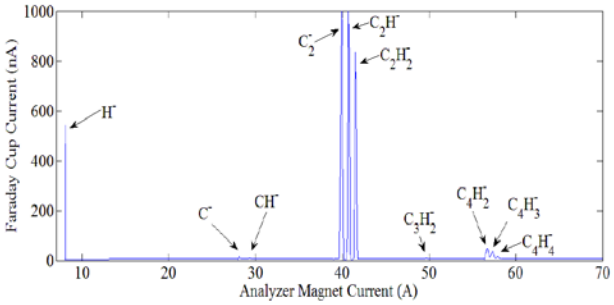

Figure 4: Spectrometer scan obtained with acetylene. The arc was set at 1.5 A and 120 V and the gas flow was set at 10 sccm.

Acetylene has also shown to cause some cleanliness issues. When the source is running with hydrogen, tantalum is being sputtered from the filaments and forms a thin coat on the plasma chamber walls. However, when running acetylene, the plasma strips the thin film from the wall and forms flakes that land at the bottom of the plasma chamber. These flakes could potentially cause the plasma lens to short against the body. Cleaning the plasma chamber before running acetylene has been shown to greatly reduce the concentration of flakes in the source. Using a non-hydrogenated gas such has carbon monoxide might improve cleanliness and will be tested in the future.

Future work will include analysis of the beam composition and current as a function of plasma parameters. The source will then be optimize for maximum production of C^- and C_2^-. The goal is to achieve more than 1 mA of C^- and C_2^- with higher arc currents and an optimized source configuration.

CONCLUSION

A new ion source test facility has recently been commissioned. The ISTF was first used to analyse H^- ion production with a filament-powered volume-cusp ion source. A study of the extraction revealed that the plasma lens potential changes the curvature of the plasma meniscus. Heavy negative ions are also being investigated. No negative helium ions were produced with the filament-powered volume-cusp source. Negative carbon ions were extracted from the source when acetylene was used as the injection gas. The source will be optimize for the production of C^- and C_2^- with a goal of obtaining up to 1 mA once the physics is better understood.

ACKNOWLEDGMENTS

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REFERENCES

[1] Melanson, S., et al. "A negative ion source test facility." *Review of Scientific Instruments* 87.2 (2016): 02B109.

[2] Kuo, T., et al. "On the development of a 15 mA direct current H− multicusp source." *Review of scientific instruments* 67.3 (1996): 1314-1316.

[3] Kalvas, Taneli, et al. "Power efficiency improvements with the radio frequency H− ion source." *Review of Scientific Instruments* 87.2 (2016): 02B102.

[4] Braccini, S., et al. "A beam monitor detector based on doped silica and optical fibres." *Journal of Instrumentation* 7.02 (2012): T02001.

[5] Child, C. D. "Discharge from hot CaO." *Physical Review (Series I)* 32.5 (1911): 492.

[6] Midttun, O., et al. "A magnetized Einzel lens electron dump for the Linac4 H− ion source." *AIP Conf. Proc.*. Vol. 1515. No. CERN-ATS-2013-012. 2013.

[7] Lawrie, S. R., et al. "Plasma meniscus and extraction electrode studies of the ISIS H− ion sourcea)." *Review of Scientific Instruments* 81.2 (2010): 02A707.

[8] Bacal, M., and M. Wada. "Negative hydrogen ion production mechanisms."*Applied Physics Reviews* 2.2 (2015): 021305.

[9] Nicholas, D. J., C. W. Trowbridge, and W. D. Allen. "Lifetime of a negative helium ion." *Physical Review* 167.1 (1968): 38.

[10] Ennis Jr, R. M., et al. "Production of Negative Helium Ions by Nearly-Resonant Charge Exchange in Potassium." *Nuclear Science, IEEE Transactions on* 14.3 (1967): 75-77.

[11] Melton, C. E., and P. S. Rudolph. "Negative ion mass spectra of hydrocarbons and alcohols." *The Journal of Chemical Physics* 31.6 (1959): 1485-1488.

[12] Tate, John T., and P. T. Smith. "The efficiencies of ionization and ionization potentials of various gases under electron impact." *Physical Review* 39.2 (1932): 270.

[13] Ervin, Kent M., et al. "Bond strengths of ethylene and acetylene." *Journal of the American Chemical Society* 112.15 (1990): 5750-5759.

[14] Kobayashi, H., A. T. Bell, and M. Shen. "Plasma polymerization of saturated and unsaturated hydrocarbons." *Macromolecules* 7.3 (1974): 277-283.