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The Extraction of Negative Carbon Ions from a Volume Cusp Ion Source

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Abstract. Acetylene and carbon dioxide gases are used in a filament-powered volume-cusp ion source to produce negative carbon ions for the purpose of carbon implantation for gettering applications. The beam was extracted to an energy of 25 keV and the composition was analyzed with a spectrometer system consisting of a 90° dipole magnet and a pair of slits. It is found that acetylene produces mostly C_2^- ions (up to 92 μA), while carbon dioxide produces mostly O^- with only trace amounts of C^-. Maximum C_2^- current was achieved with 400 W of arc power and, the beam current and composition were found to be highly dependent on the pressure in the source. The beam properties as a function of source settings are analyzed, and plasma properties are measured with a Langmuir probe. Finally, we describe testing of a new RF H^- ion source, found to produce more than 6 mA of CW H^- beam.

INTRODUCTION

Negative ion source research at the new Ion Source Test Facility (ISTF) [1] designed by D-Pace Inc. has recently started, following completion in March 2016 when the beam was first analyzed through the spectrometer system consisting of a 90° dipole magnet and slits. It is used as a test bed for both filament-powered and RF-powered volume-cusp ion sources, as well as beam diagnostic hardware.

We investigate the production of negative ions heavier than hydrogen with volume-cusp ion sources; a subject that has received little attention in the literature. Heavy negative ions are currently used in tandem accelerators and in the semiconductor industry for ion implantation since negative ions are known to reduce the charge-up voltage of the samples [2]. Acetylene and carbon dioxide were used in our TRIUMF licensed filament-powered ion source [3] with a goal of extracting C^- or C_2^- at an energy of 25 keV. Carbon is used as a getter for impurities in silicon [4], and previous studies have shown that gettering efficiency increases with the dose of MeV implanted carbon [5]. High current carbon ion sources are therefore required to achieve a reasonable semiconductor manufacturing time frame, a goal of 1 mA C^-, or 0.5 mA C_2^- has been set.

A disadvantage of filament-powered sources is the short lifetime of the filaments, so efforts are being made to commercialize RF ion sources with an antenna external to the plasma chamber. A 13.56 MHz RF H^- ion source licensed from the University of Jyväskylä [6] has recently been tested at the ISTF. The beam properties and the beam current as a function of the RF power are presented.

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FIGURE 1. D-Pace/Buckley Systems Ion Source Test Facility at Buckley Systems in Auckland, New Zealand.

EXPERIMENTAL DETAILS

The volume-cusp ion source used for this study is described in [3] and can be modified to be RF powered. The plasma is confined by 10 rows of Sm_2Co_{17} magnets, and a permanent magnetic dipole of 0.012 T is located 20 mm from the plasma electrode, creating a "cold" plasma region. The co-extracted electrons are dumped on the extraction electrode by a dipole magnetic field (a dipole magnetic field of the opposite sign follows this to correct the ion trajectories), so the current on the electrode is approximately the co-extracted electron current. The beam energy can be set to up to 30 keV and beam diagnostic equipment consists of a mass spectrometer, a TRIUMF licensed emittance/phase space intensity distribution scanner whose underlying technology follows Allison [7], a fiber-optic beam intensity profile monitor [8], and a Faraday cup. The emittance scanner was scanning in the *y* direction and was mounted 368 mm from the ion source's plasma electrode while the Faraday cup was installed 590 mm from the same electrode. To measure the beam composition, the Faraday cup was replaced by a spectrometer system composed of a 90° bending magnet with an effective length of 300 mm, a pair of slits and a Faraday cup, giving it an energy resolution of up to 1:656. The beam was first collimated by an aperture with a diameter of 3 mm located 557 mm from the ion source's plasma electrode to eliminate beam loss in the spectrometer, and the first slit was located 1248 mm from the collimator. A schematic of the ISTF with the spectrometer system is presented in Fig. 2. Pumping is achieve with two turbo molecular pumps with pumping speeds of 4500 L/s each, giving a base vacuum pressure of around $1x10^{-6}$ Pa.

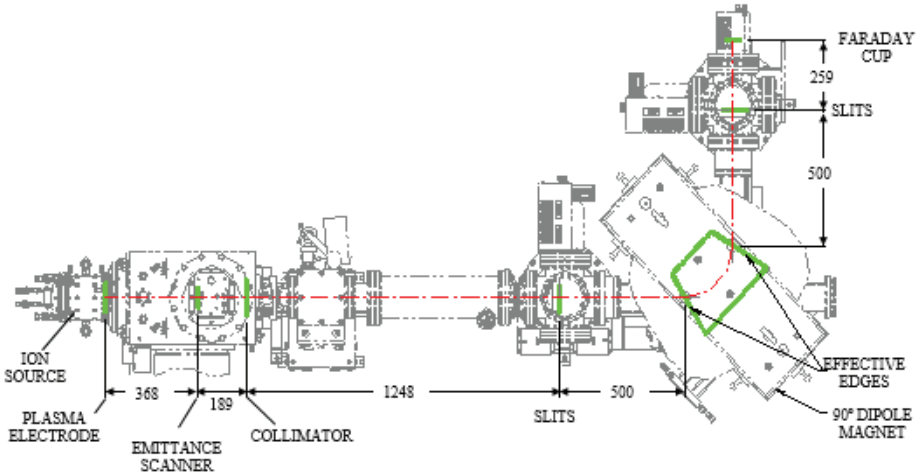

FIGURE 2. Schematic of the ISTF.

ACETYLENE

High purity acetylene (C_2H_2) was used in the filament-powered ion source with the source operating with two half-circle tantalum filaments. Up to 330 μA of total beam current was extracted from the source, including 92 μA of C_2^- current, but the source was found to be unstable at higher arc current and higher gas flows due to arcing between the plasma electrode and extraction electrode. To reduce the arcing, the plasma electrode aperture diameter was reduced to 6 mm from 13 mm, while the extraction electrode aperture diameter was increased to 16 mm from 9.5 mm. This improved the stability but arcing was still observed when the arc current was set above 2 A. Tune data for the highest current tune is presented in Table 1, a best mass spectrum for C_2^- is presented in Fig. 3, and a typical y-y' phase space scan is presented in Fig. 4. No magnetic steering was used for these measurements however, the two magnetic dipoles used to deflect the co-extracted electron give a stronger net deflection to the H^- ions. The separation of the H^- from the heavier carbon ions can be seen in the phase space plot.

TABLE 1. Tune data for the highest beam current obtained with acetylene.

Total Beam Current (mA)	Arc Current (A)	Arc Voltage (V)	Bias Current (mA)	Bias Voltage (kV)	Extraction Electrode Current (mA)	Extraction Electrode Voltage (kV)	Plasma Electrode Current (A)	Plasma Electrode Voltage (V)	Gas Flow (sccm)	Filament Current (A)	Filament Voltage (V)
0.33	3.30	120	0.70	24.97	24.48	2.88	3.00	20.0	5.00	163.4	5.11

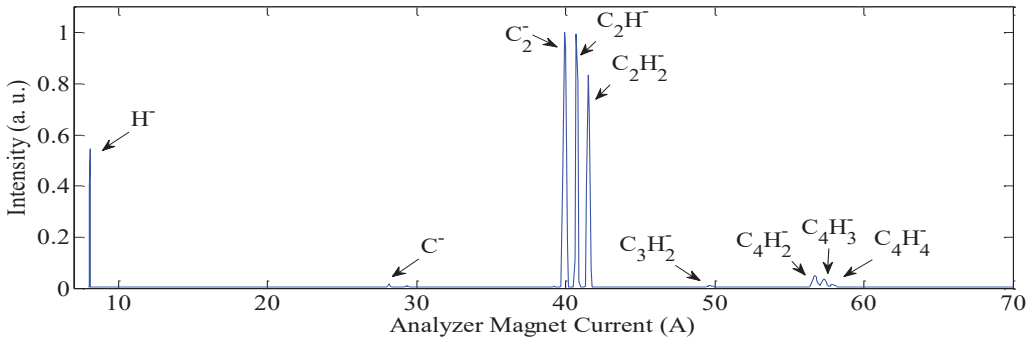

FIGURE 3. Mass spectrum of a negative beam extracted from an acetylene plasma from our volume-cusp ion source. The arc current was set at 1 A, the arc voltage as set at 120 V, and the gas flow was set at 10 sccm.

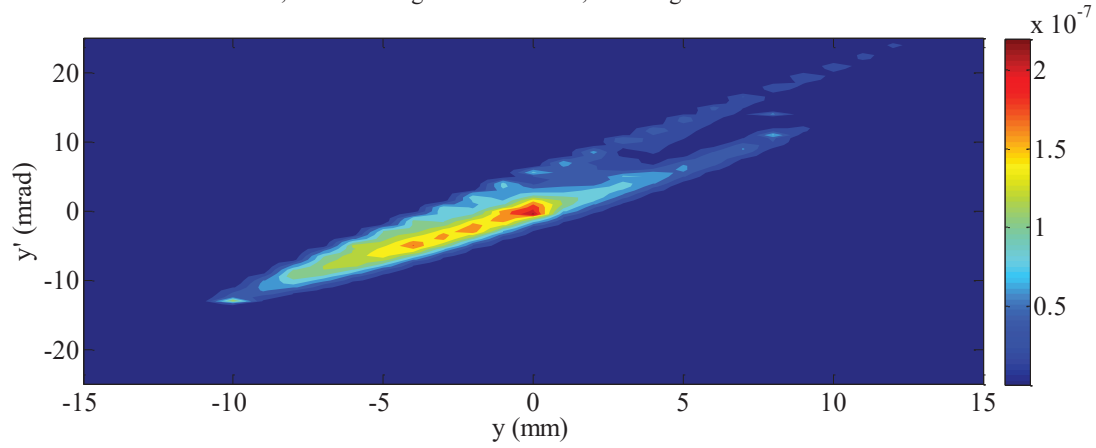

FIGURE 4. A y-y' phase space scan obtained of the total beam with acetylene. The arc current was set at 1 A, the arc voltage was set at 120 V and the beam energy was set at 25 keV. The normalized 4-RMS emittance is 0.23 mm·mrad and contained 88% of the beam.

We see strong C_2^-, C_2H^-, and $C_2H_2^-$ signals, due to the strength of the triple bond (C≡C) between the two carbon atoms in these species [9]. The beam composition was found to be only slightly dependent on the various source parameters, with variation of gas flow giving the biggest variation. Figure 5 shows the effect of gas flow on the beam

composition. We see how the increase in gas flow causes the relative H^- current to drop significantly. The pressure inside the source was not measured however, pressure measurements outside the extraction region of the ion source increased linearly from $3x10^{-4}$ Pa to $3x10^{-3}$ Pa when the gas flows was increased from 1 sccm to 19 sccm.

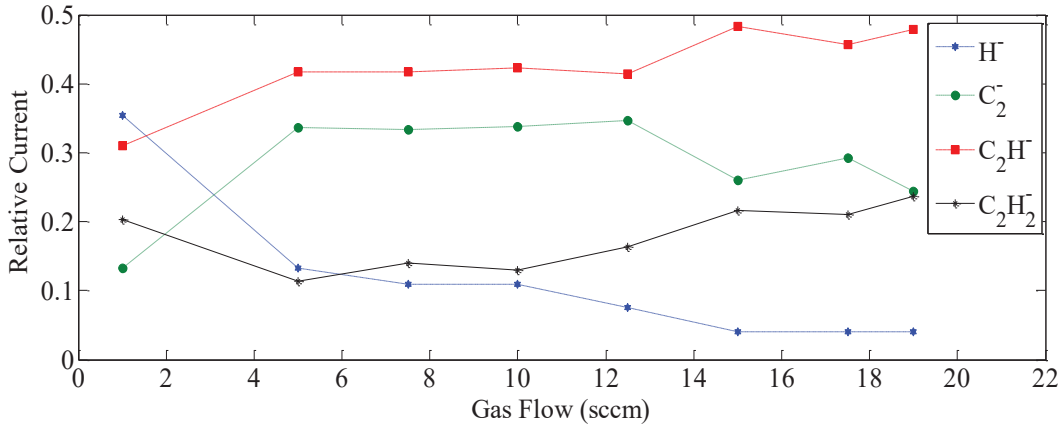

FIGURE 5. Data set from one run showing relative beam composition as a function of the acetylene gas flow. The arc current was set at 1 A and the arc voltage was set at 120 V. The beam energy was set at 25 keV.

Total beam current was also found to be dependent on the gas flow in the source. Figure 6 shows the total and C_2^- beam current as a function of the gas flow. The error bars correspond to the standard deviation of consecutive measurements. We found that an increase in gas flow caused an increase in beam current, even at lower arc currents. With hydrogen gas feeding the ion source instead of acetylene, we found low gas flows produced higher H^- output currents as compared to higher gas flows at low arc currents. We surmise that higher pressures found with increased gas flow rates reduces H^- beam current due to stripping in the extraction region at lower arc current, though at high arc currents higher flow rates were required to maximize H^- current.

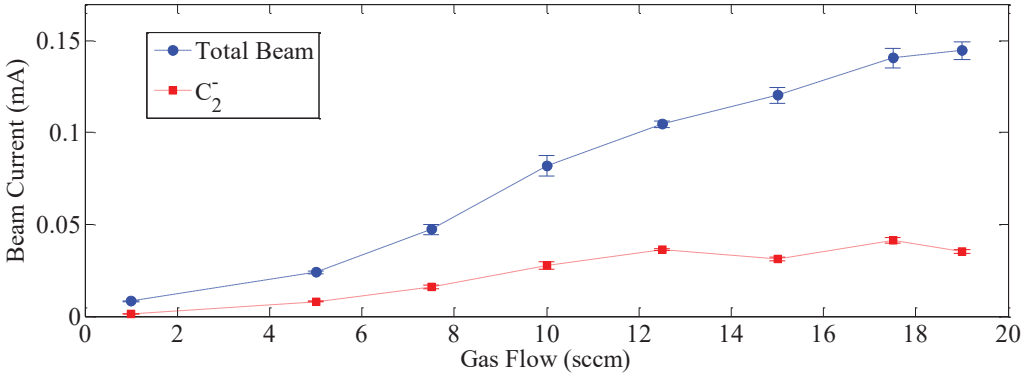

FIGURE 6. Total beam and C_2^- current as a function of acetylene gas flow. The arc current was set at 1 A, the arc voltage was set at 120 V and the beam energy was set at 25 keV.

A Langmuir probe was used to investigate the plasma properties of the acetylene plasma inside the filament-powered ion source. The probe consisted of a single cylindrical tantalum tip with a length of 5 mm and a diameter of 1.4 mm. The probe was inserted on the central-axis of the ion source through the extraction system apertures, with the probe tip 10 mm from the plasma electrode. The probe was in the "cold" plasma region, created by a magnetic dipole field which is 160 G at this location. The Langmuir probe measurements were completed without any bias voltage on the source since the probe was inserted through the extraction apertures. Also, the conductance and thus the pressure in the source is affected by the probe. Figure 7 presents the electron temperature and the electron density as a function of the gas flow. The electron temperature was obtained by fitting the I-V curve of the Langmuir probe with an exponential function and the error bars correspond to the 95% confidence intervals from the fit. The electron density, n_e, was found by measuring the probe current at the plasma potential and using [10]

$$n_e = 4\frac{I_p}{eA}\left(\frac{\pi m}{8kT_e}\right)^{1/2}, \quad (1)$$

where I_p is the probe current at the plasma potential, A is the probe surface area, k is the Boltzmann constant and e, m and T_e are the electron charge, mass, and temperature respectively. The plasma potential was taken as the potential where the second derivative of the I-V curve is zero. The error bars were calculated assuming an error of ± 0.5 mA in the measurement of the current and using the 95 % confidence interval from T_e.

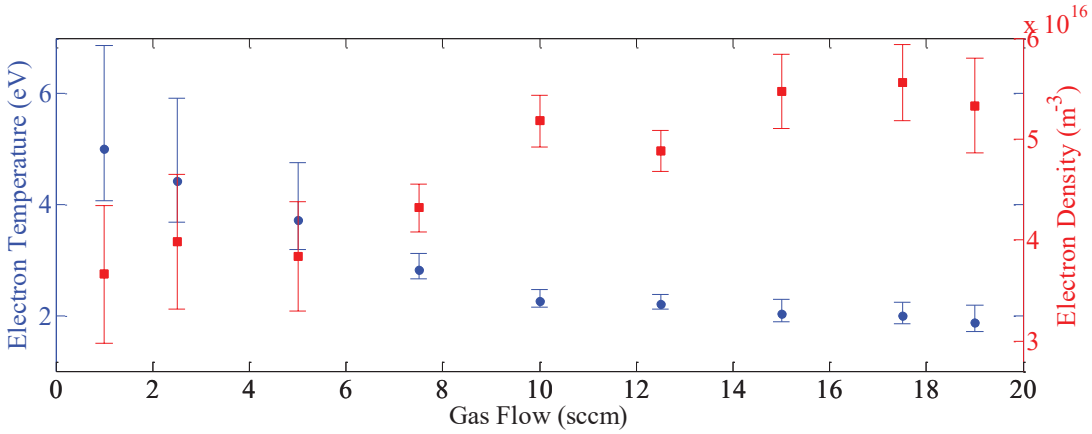

FIGURE 7. Electron temperature (circles) and electron density (squares) at the extraction of the ion source as a function of acetylene gas flow. The arc current was set at 1 A, the arc voltage was set at 120 V.

We see a decrease and then flattening of the electron temperature at around 2 eV, while the electron density increases only slightly. Comparing Figs. 6 and 7, the increase in negative carbon ion current with gas flow could be explained by the lowering of the electron temperature. A study by Szymańska *et al*. [11] reveals that there is a peak in the interaction cross section corresponding to the production of $C_2H_x^-$ at about 2.5 eV of electron energy. This compares well with our observations; however, further analysis is needed with the Langmuir probe installed so as not to affect the gas conductance. Also, further testing is required at a stable pressure to determine how the electron temperature and the pressure affect the production of negative ions separately.

The plasma electrode voltage had no effect on the beam current when acetylene was used in the source. However, as is the case with hydrogen, increasing the voltage on the plasma electrode reduced the co-extracted electron current by a factor of about 30% when the plasma electrode voltage was increased from 0 V to 20 V.

CARBON DIOXIDE

Carbon dioxide was used in the filament-powered ion source in an effort to produce C^- ions. The main ion produced was O^- with small amounts of CO^- and trace amounts of C^-, O_2^- and CO_2^-. This compares well with previous studies [12, 13]. Oxygen has a larger electron affinity at 1.401 eV than carbon at 1.246 eV [14]. In addition, it has been shown that the production of C^- by dissociative attachment in CO_2 only starts at electron energies above 15 eV and the maximum cross section of the reaction is on the order of $2\text{x}10^{-21}$ cm^2 [15]. The highest current tune is presented in Table 2, and a typical spectrometer scan with CO_2 is presented in Fig. 8.

TABLE 2. Tune data for the highest beam current obtained with carbon dioxide.

Beam Current (mA)	Arc Current (A)	Arc Voltage (V)	Bias Current (mA)	Bias Voltage (kV)	Extraction Electrode Current (mA)	Extraction Electrode Voltage (kV)	Plasma Electrode Current (A)	Plasma Electrode Voltage (V)	Gas Flow (sccm)	Filament Current (A)	Filament Voltage (V)
0.22	8.51	120.00	2.75	24.99	143.83	3.34	6.29	20.00	2.50	153.4	4.03

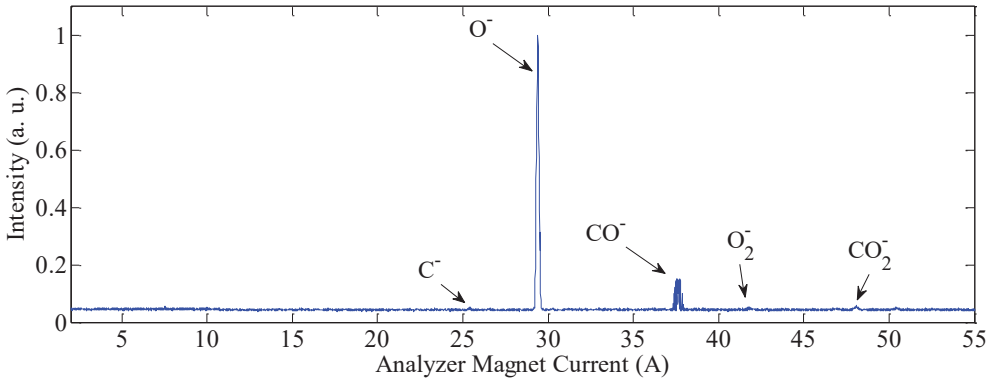

FIGURE 8. Spectrometer scan obtained with CO_2 in the ion source. The arc current was set at 2 A, the arc voltage was 120 V and the gas flow was at 2 sccm.

RF ION SOURCE

Tests of a new 13.56 MHz RF powered H^- ion source licensed from the University of Jyväskylä [6] were undertaken at the ISTF with pure hydrogen gas. The source uses a flat external antenna, which couples RF to the plasma chamber via an aluminum nitride (AIN) window. The TRIUMF licensed filament-powered ion source's body and extraction system were used, with the back plate changed to the AIN window with the RF antenna. The plasma electrode had an aperture diameter of 13 mm. An L-network of two variable capacitors was put in place to tune the load impedance to match the output impedance of the generator. Table 3 presents the tune data for the highest beam current obtained, and Fig. 9 shows the H^- current as a function of RF power.

TABLE 3. Tune data for the highest beam current obtained with the RF ion source.

Beam Current (mA)	RF Power (kW)	Bias Current (mA)	Bias Voltage (kV)	Extraction Electrode Current (mA)	Extraction Electrode Voltage (kV)	Plasma Electrode Current (A)	Plasma Electrode Voltage (V)	Gas Flow (sccm)	X Steer (A)	Y Steer (A)
6.11	2.68	11.20	30.00	43.52	2.79	2.78	24.75	15.00	0.1	0.9

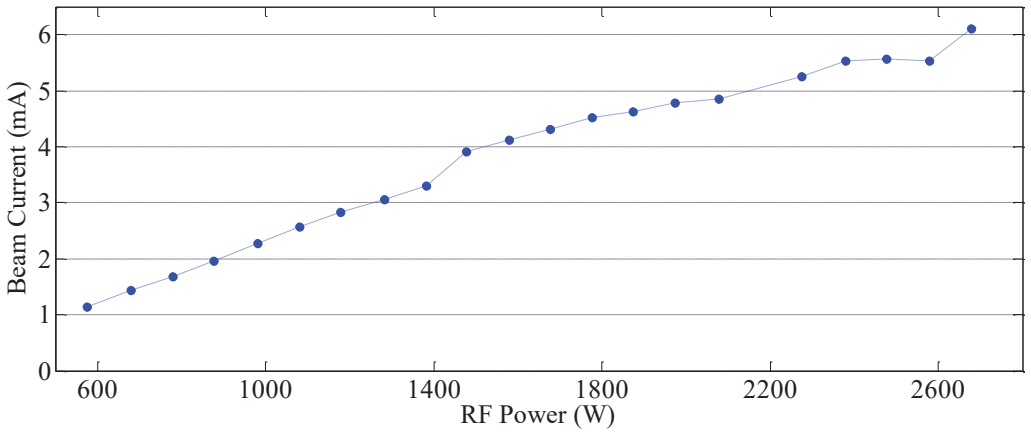

FIGURE 9. H^- beam current obtained as a function of RF power. The gas flow was set at 15 sccm and the beam energy was set at 30 keV.

The source was only tested to 2.7 kW, as thermal problems caused a crack in the ceramic window. Further testing will be completed once replacement parts are obtained. The chamber walls had a thin tantalum coating remaining from

operation with the tantalum filaments. Further testing with a tantalum free source is planned to investigate the contribution of surface enhanced volume production in this source configuration.

The plasma electrode potential was set between 20 V and 25 V, which is considerably higher than what is usually applied to the electrode when the filament-powered version of the source is used (3-4 V). This higher value may be explained by a higher plasma potential. Further testing with the Langmuir probe will be done to verify this. The electron to H^- ratio was found to be consistently higher for the RF-powered source at 6-7 while the filament-powered source's ratio is of 4-5. Figure 10 presents emittance scans for the 6.11 mA tune described in Table 3. Early results show that the measured emittance was found to be slightly smaller than the filament powered version of the source at the same beam current.

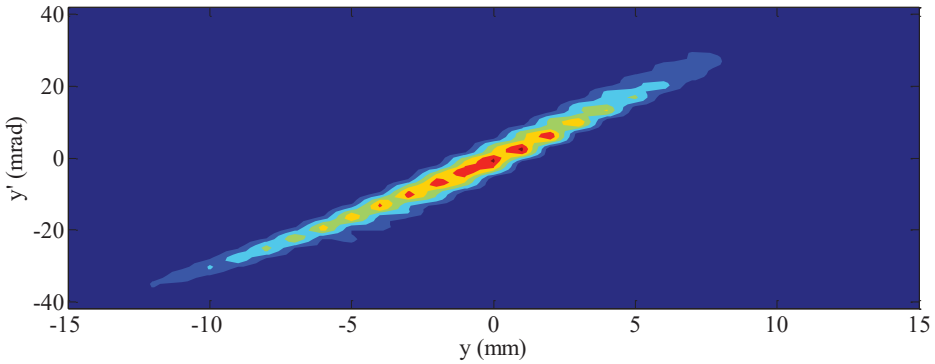

FIGURE 10. y-y' phase space scans obtained with the RF ion source for the 6.1 mA H^- beam tune. The normalized 4-RMS emittance is 0.41 mm·mrad and contained 85% of the beam.

CONCLUSION

A TRIUMF licensed filament-powered volume-cusp ion source was used to produce negative carbon ions. Acetylene was first used in the source, and C_2^- ions were the most common pure carbon ions due to the high bond strength between the carbon atoms in the acetylene molecule. To date the largest C_2^- current obtained was 92 µA. The beam current and composition was found to be highly dependent on the pressure in the source, and it is thought that this might be due to a peak in the production of $C_2H_x^-$ ions at an electron temperature of 2.5 eV which occurs at gas flows greater than 10 sccm. Carbon dioxide was also used in the source, and it was found that O^- was the most abundant negative ion produced with only trace amounts of C^-, which is consistent with previous studies on electron attachment of CO_2. We intend to modify our extraction system to reduce arcing and improve stability as we progress towards 0.5 mA of C_2^- with acetylene.

A new RF powered ion source licensed from the University of Jyväskylä was also tested with pure hydrogen gas. Up to 6.1 mA of H^- beam at 2.7 kW of RF power was achieved with a hybrid configuration using the Jyväskylä RF back plate and the TRIUMF style body and extraction system. Further testing to higher powers will follow and the production of negative carbon ions with the RF powered source will be investigated.

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