Beam Current Stability Improvements of Negative Carbon Ions Extraction from a Multi-Cusp Ion Source

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Abstract. Ion implantation requires a high beam current stability to ensure a uniform implantation dose across the wafers. This requires ion sources with a stable extraction system to achieve a high beam current stability. Our goal is to extract 0.5 mA of C_2^- with less than 10 glitches per hour, with a glitch defined as any variation greater than +/- 5% of the nominal beam current. The beam energy should be between 10 keV and 30 keV while the normalized 4 RMS emittance should be less than 1 mm·mrad. We've shown that high negative carbon ion current densities could be obtained with a multi-cusp ion source when acetylene was used as the feed gas (0.27 mA of C_2^-), but there was significant sparking between the electrodes, which led to frequent beam current glitches (>1000/hour). In this study, we investigate the different factors that contribute to the sparking between the electrodes. We found that the sparking is highly correlated to the dumping of the co-extracted electrons and the beam strike on the electrodes. Extraction simulations were completed to determine how the electron dumping can be improved and how the beam strikes on the electrodes can be reduced. Furthermore, we modified the magnetic configuration in the plasma chamber to decrease the electron density close to the extraction aperture, which reduced the co-extracted electron current by a factor of almost 5 and reduced sparking frequency to about 20 glitches per hour. However, there was a corresponding decrease in the extracted beam current due to the smaller aperture sizes needed to reduce the sparking, with only 0.05 mA of C_2^-.

INTRODUCTION

The extraction of negative carbon ions from a volume cusp ion source when acetylene was used as the injection gas was found to be unstable due to frequent voltage breakdowns between the electrodes of the ion source. Consequently, the ion source is unusable for ion implantation applications since an unstable beam would lead to non-uniform dose in the wafers. To quantify the stability of the beam current, we introduce the concept of glitches, where a glitch is described as any beam current deviation of more than +/-5% of the nominal beam current. Ion implanter applications require an ion source glitch rate of less than 10/hour to limit the defects in the wafers[1].

The ion source used for this study is a hybrid design between a TRIUMF licensed multi-cusp ion source[2] and the RADIS RF ion source developed by the University of Jyväskylä[3]. The ion source uses the body and the extraction system of the TRIUMF design, but the back plate of the ion source was replaced with an aluminum nitride (AlN) window. Power is coupled into the plasma by a flat spiral antenna connected to a 13.56 MHz RF amplifier[4]. The RF components of the ion source are taken from the RADIS ion source design. The plasma is confined with Sm_2Co_{17} magnets forming a cusp field configuration. The cusp configuration is interrupted at 40 mm from the front plate of the ion source to form a dipole magnetic field, which was optimized for the production of H^- ions. The extraction system is composed of three electrodes, the first electrode (plasma electrode) is commonly biased positively at a few volts above the plasma chamber wall potential. The second electrode (extraction electrode) is used as an electron dump and is commonly biased between 1-3 kV. Two sets of opposite sign dipole magnetic fields are located in the electrode to first dump the electrons and then to correct the deflection of the negative ions being extracted. Finally, the third electrode (ground electrode) is at electrical ground potential. A schematic of the ion source is presented in Fig. 1.

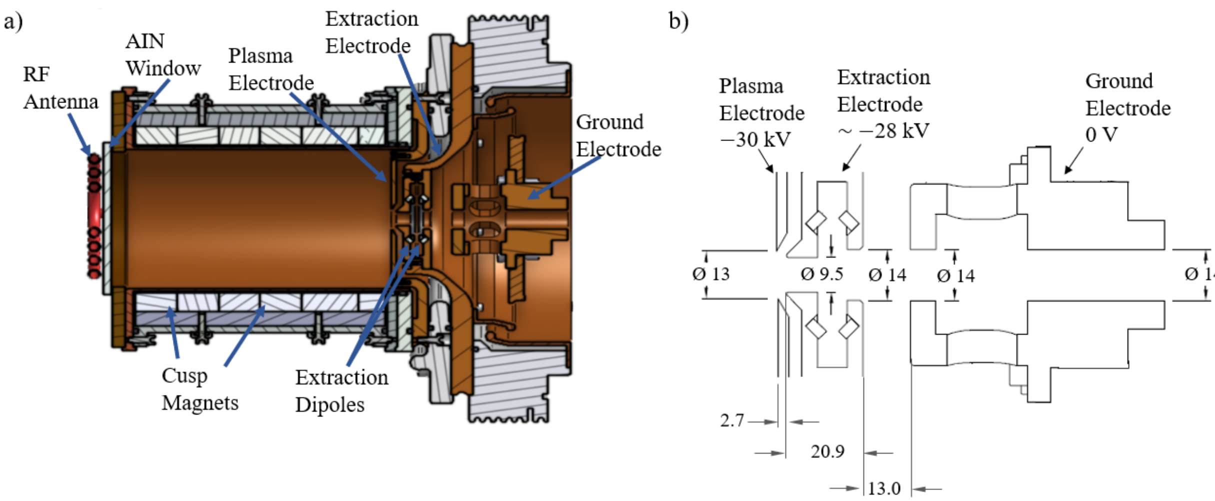

FIGURE 1. a) Cross section of the Hybrid RF ion source used in this study[2,3] and b) schematic of the extraction system with the default voltages on the electrodes.

Negative carbon ions can be extracted from the ion source if acetylene is used as the feed gas[5]. The beam composition is analyzed with a mass spectrometer system consisting of two slits and a 90° dipole magnet with a resolution of 1:500[4]. The four main negative ions that are extracted are H^-, C_2^-, C_2H^- and $C_2H_2^-$ with a relative composition of about 5% of H^-, 30% of C_2^-, 55% of C_2H^- and 10% of $C_2H_2^-$[5]. Figure 2 presents the C_2^- beam current extracted with the baseline ion source configuration presented in Fig. 1 as a function of the RF power for various gas flows.

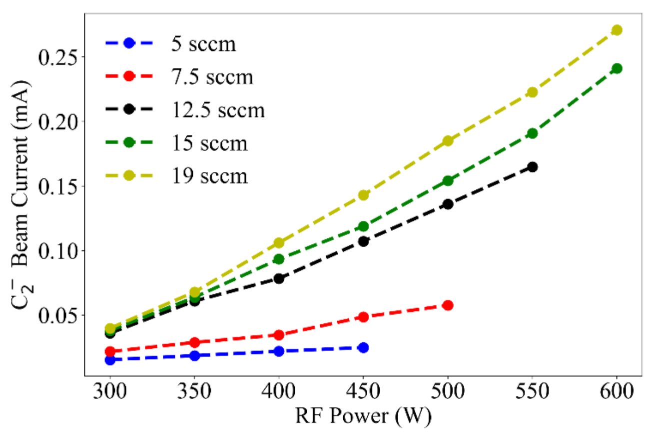

FIGURE 2. C_2^- beam current as a function of the RF power for various acetylene gas flow rates. The bias voltage was set at 25 kV.

Up to 0.27 mA of C_2^- was extracted, which is more than half of our goal of 0.5 mA of C_2^-. However, the glitch rate was much higher than our goal of less than 10 glitches per hour at more than 1000/hour. The instabilities in the beam current are due to voltage breakdowns on the extraction electrode. Figure 3 presents the beam current and the extraction electrode voltage over time. We can see how the glitches in the beam current are associated with breakdowns on the voltage of the extraction electrode.

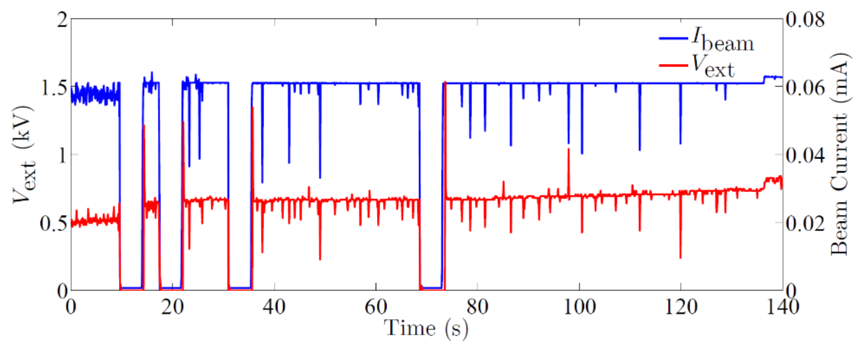

FIGURE 3. Beam current and extraction voltage stability over time. The RF power was set at 500 W, the acetylene gas flow rate was set at 10 sccm, the plasma electrode voltage was set at 20 V, and the bias voltage was set at 30 kV.

EXTRACTION MODIFICATIONS

We found that increasing the size of the extraction electrode aperture greatly improved the stability of the beam current. The baseline ion source configuration for the extraction of H^- uses a plasma electrode with an aperture diameter of 13 mm and an extraction electrode with an aperture diameter of 9.5 mm. The plasma meniscus needs to be highly convex to focus the beam through the smaller extraction electrode aperture. If the plasma meniscus shape is not optimized, this could lead to considerable beam strike on the extraction electrode and could lead to the voltage breakdowns that are seen. Various electrode apertures were tested and the measure glitch rates for the various configurations are presented in Table 1.

TABLE 1. Glitch rate and C_2^- beam current measure for various aperture sizes. $\O_{plasma}$ and $\O_{extraction}$ denote the diameter of the plasma electrode aperture and of the extraction electrode aperture respectively, while V_{PE} and V_{EE} denote the potential on the plasma electrode and the extraction electrode respectively. The RF power was set at 400 W, the acetylene gas flow rate was 30 sccm, bias voltage was 30 kV, and the plasma electrode to extraction electrode spacing was 2.7 mm, and the extraction electrode to ground electrode spacing was 13.0 mm.

$\O_{plasma}$ (mm)	$\O_{extraction}$ (mm)	V_{PE} (V)	V_{EE} (kV)	Glitch Rate (h^{-1})	C_2^- Beam Current (mA)
13	9.5	20	1.5	~1100	0.055
13	16	20	1.5	~700	0.057
8	14	20	1.5	~150	0.017
10.5	14	20	1.5	~390	0.060
10.5	16	20	1.5	~410	0.036

As can be seen, increasing the extraction electrode aperture diameter leads to a decrease in the glitch rate and the effect is amplified when the ratio between the plasma electrode aperture diameter over the extraction electrode aperture diameter is lowered. However, when a smaller plasma electrode is used there is also a decrease in the beam current. With an 8 mm plasma electrode aperture diameter and a 14 mm extraction electrode aperture diameter the glitch rate was reduced to about 150 glitches per hour, but only 0.017 mA of C_2^- was extracted. The beam current was not directly proportional to the plasma electrode aperture size but also depended on the extraction electrode aperture diameter. The emittance was improved with the smaller aperture, decreasing from a normalized 4 RMS value of 1.1 mm·mrad with the original configuration to 0.7 mm·mrad with a 10.5 mm plasma electrode aperture and a 14 mm extraction electrode aperture. To reduce the glitch rate while also keeping a large beam current, we decided to use a 10.5 mm plasma electrode aperture diameter with a 14 mm extraction electrode aperture diameter while at all times keeping the lens to lens spacings held constant.

The bias voltage was also found to have a great influence on the beam stability. The H^- ion source is usually biased at 30 kV, but the target C_2^- application can have a beam energy of as low as 10 keV. Figure 4 presents the glitch rate and the beam current as a function of the bias voltage on the ion source. The extraction electrode voltage was set to 2 kV for every measurement.

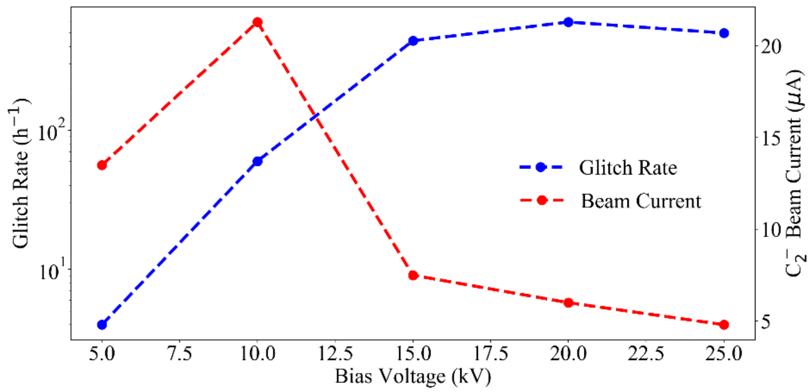

FIGURE 4. Glitch rate and C_2^- beam current at various bias voltages. The extraction electrode voltage was set at 2 kV, the RF power was set to 350 W, the acetylene gas flow rate was set at 15 sccm and the original electrodes were used.

A bias voltage of 10 kV gives a maximum beam current and has a lower glitch rate than the higher bias voltages. The reason for the greater stability is thought to be due to a lower electric field between the extraction and ground electrodes, which would reduce the probability of breakdowns between the two electrodes. The beam current decreases with the higher bias voltages because there are more beam losses on the ground electrode as the bias current remained relatively constant for all bias voltages.

EXTRACTION SIMULATIONS

Our study of the stability of the extraction of negative carbon beam with the standard ion source configuration revealed slightly lower glitch rates with higher gas flows, even though the beam current was also higher. There is a decrease in the co-extracted electron current as the gas flow is increased and we believe that the electrons could lead to voltage breakdowns if they are not properly dumped. The extraction system used is designed to dump the electrons on the extraction electrode. Beam extraction simulations in IBSimu[6] show that the electrons are dumped on the front face of the extraction electrode, creating a high electron density zone between the plasma and the extraction electrodes. This is mainly due to the magnetic filter field in the plasma that extends into the extraction region and adds to the first magnetic dipole on the extraction electrode. The large magnetic field deflects the electrons before they reach the extraction electrode.

To prevent the electrons from being dumped on the front face of the extraction electrode, the first set of dipole magnets on the extraction electrode was removed. Figure 5 presents the IBSimu simulation of the original electron dumping configuration as well as with the modified configuration.

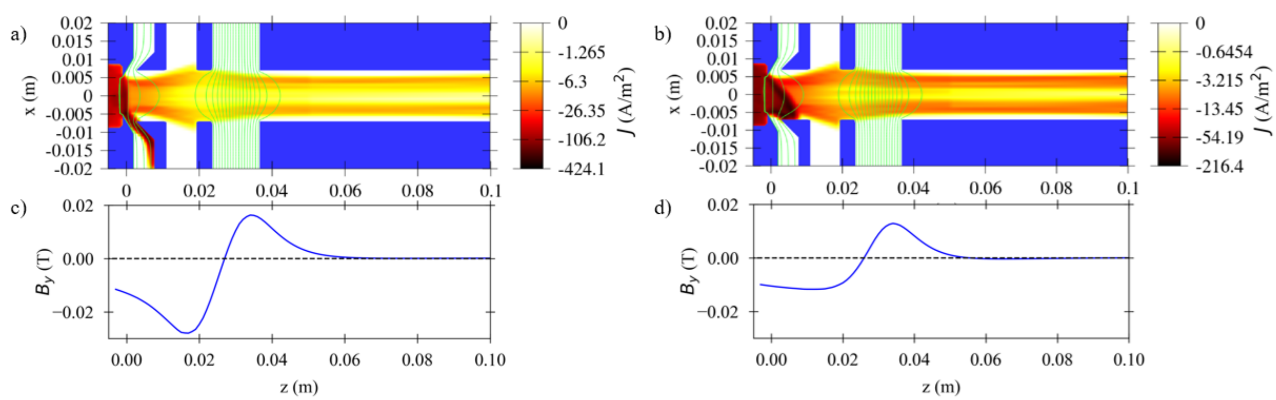

FIGURE 5. IBSimu simulations of a) the original extraction configuration and b) a modified extraction configuration with the first set of magnets removed from the extraction electrode aperture. The simulations were done at a bias voltage of 10 kV and an extraction electrode voltage of 1.5 kV. 0.1 mA of C_2^- and 30 mA of electrons were simulated. Magnetic field on the central axis for c) the original configuration and d) the modified configuration.

The first set of magnets on the extraction electrode were removed, creating the magnetic configuration presented in Fig. 5d), and the performance of the ion source was measured. A plasma electrode aperture diameter of 10.5 mm and an extraction electrode aperture of 14 mm were used. The bias voltage was also set at 10 kV. The results are presented in Fig. 6. There is a slight decrease in the glitch rate and this is more pronounced at higher RF powers.

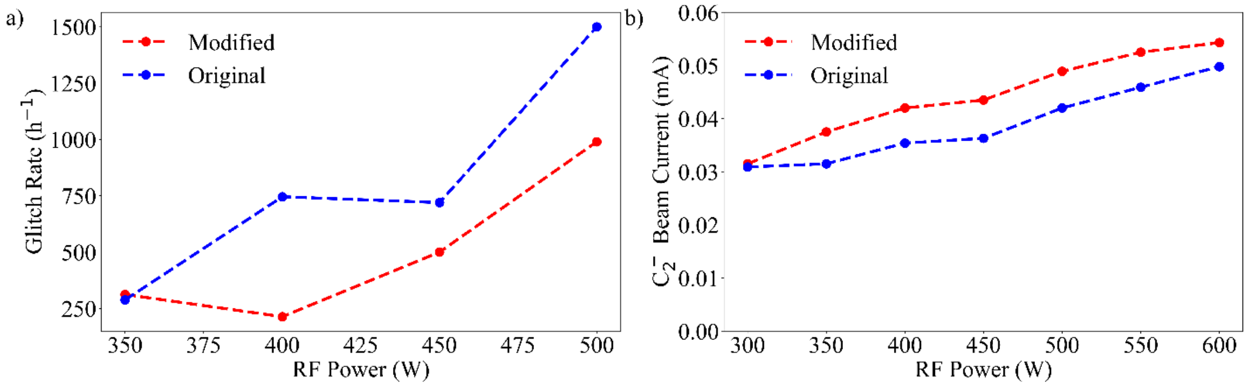

FIGURE 6. a) Glitch rate and b) C_2^- beam current measured with the original magnetic configuration and without the first set of magnets. The gas flow was set at 20 sccm, the bias voltage was set at 10 kV and aperture diameters of 10.5 mm and 14 mm were used for the plasma and extraction electrodes respectively.

PLASMA VARIATIONS

Along with modifications to the extraction system, we found that reducing the co-extracted electron current also affected the glitch rate. To reduce the co-extracted electron current, the magnetic dipole filter in the plasma chamber was varied. The magnetic filter field is created by replacing the cusp magnet configuration with a dipole at the plasma electrode end of the plasma chamber. The filter field can be varied by modifying the permanent magnet configuration in the ion source body. Five magnetic field configurations were tested, and the magnetic field for each configuration was simulated with Opera[7]. The magnetic field on the central axis was compared with measurements, with a good agreement found. The magnetic field on axis for the different configurations is presented in Fig. 7.

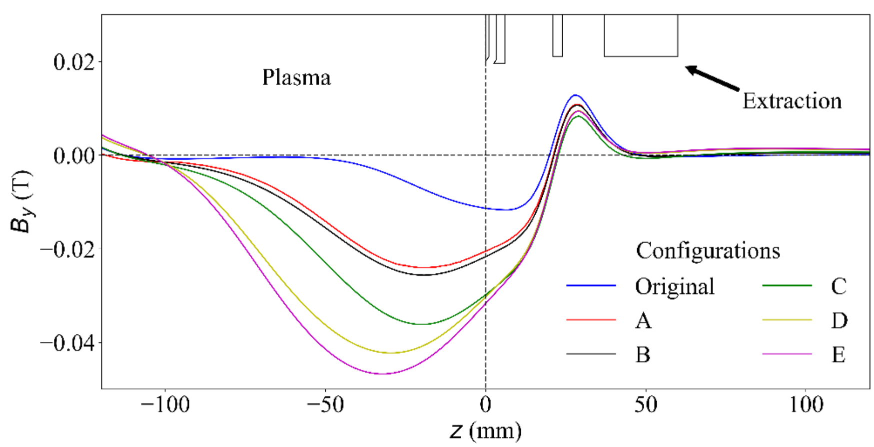

FIGURE 7. *y* component of the magnetic field along the center of the ion source for various magnetic field configurations. The plasma electrode is located at z=0, the negative z values correspond to the plasma chamber and the positive z represent the extraction region. The location of the electrodes is presented in the upper region of the plot.

The magnetic field integral along the z axis in the plasma chamber increases with each configuration. We expect that the electron density close to the plasma electrode will decrease with each increase in the magnetic field integral since the magnetic field filters the fast electrons, allowing only slow electrons to drift to the plasma electrode. The co-extracted electron current will thus be lower with the lower electron density in the plasma. Figure 8 presents the C_2^-

beam current, the co-extracted electron current and the glitch rate as a function of the RF power for the different magnetic configurations of Fig. 7.

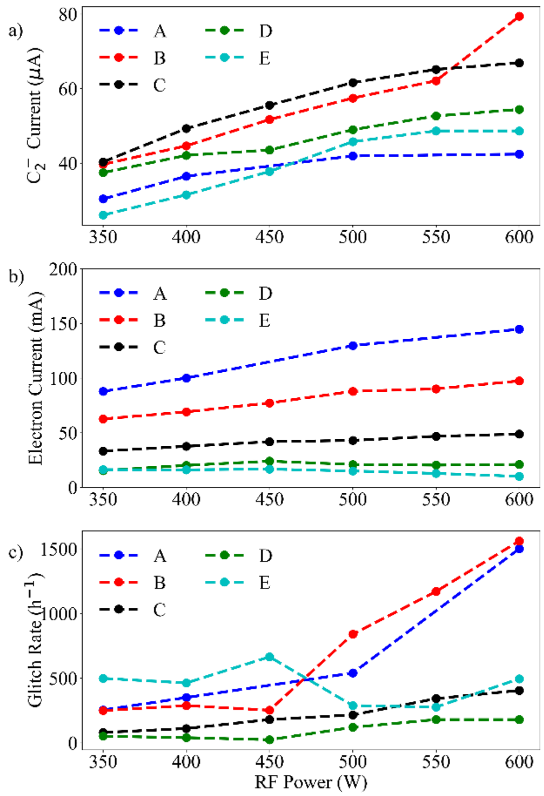

FIGURE 8. a) C_2^- beam current, b) co-extracted electron current and c) glitch rate as a function of the RF power for the magnetic configurations presented in Fig. 7. The measurements were completed at a gas flow of 20 sccm, at a bias voltage of 10 kV. A plasma electrode aperture diameter of 10.5 mm and an extraction electrode aperture diameter of 14 mm were used.

As expected, the co-extracted electron current is lower as the magnetic field integral increases. The C_2^- beam current is maximum for magnetic configuration C, which indicates that the optimum magnetic dipole field filter strength for the production of C_2^- is larger than the original configuration. The glitch rate is slightly lower for the larger magnetic fields, except for configuration E where the glitch rate was higher for most of the RF powers. This might be explained by the improper dumping of the electron due to the larger magnetic field that extends in the extraction region. Simulations of the extraction system should be done with the new magnetic configuration to determine where the electrons are dumped, and a new configuration could be proposed that properly dumps the electrons.

CONCLUSION

Our goal is to extract more than 0.5 mA of C_2^- current with a beam energy between 10 keV and 30 keV, a normalized 4 RMS emittance of less than 1 mm·mrad and a glitch rate of less than 10 per hour. The highest beam current achieved with the original ion source configuration was of 0.27 mA of C_2^- at an energy of 30 keV and an emittance of 0.92 mm·mrad, but the stability with this configuration was more than two orders of magnitude higher than our goal, at about 1500 glitches per hour. We found that increasing the aperture size of the extraction electrode and reducing the bias voltage on the ion source significantly reduces the number of glitches seen. Additionally, by modifying the magnetic field in the extraction system, we could prevent the electrons from being dumped on the front face of the extraction electrode which led to less breakdowns between the electrodes. Finally, by varying the magnetic field configuration in the plasma chamber we could reduce the co-extracted electron current and reduce the glitch rate even further. We were able to achieve about 20 glitches per hour with the modifications to the ion source. However, the extracted C_2^- was of 50 μA, the beam energy was set to 10 keV and the 4 RMS normalized emittance was of 0.71 mm·mrad. The glitch rate is still higher than our stability goal but presents a significant improvement over the initial configuration. The beam current was however, significantly lower with the modified configuration, nevertheless this may still be useful in certain applications.

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