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Experimental evaluation of a negative-ion source for a heavy-ion fusion negative-ion driver

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Abstract

Negative halogen ions have recently been proposed as a possible alternative to positive ions for heavy-ion fusion drivers because electron accumulation would not be a problem in the accelerator, and if desired, the beams could be photodetached to neutrals (Nucl. Instr. and Meth. A 464 (2001) 315; Fusion Sci. Technol. 43 (2003) 191; Laser Part. Beams 21 (2003) 545). To test the ability to make suitable quality beams, an experiment was conducted at Lawrence Berkeley National Laboratory using chlorine in an RF-driven ion source. Without introducing any cesium (which is required to enhance negative ion production in hydrogen ion sources) a negative chlorine current density of 45 mA/cm^2 was obtained under the same conditions that gave 57 mA/cm^2 of positive chlorine, suggesting the presence of nearly as many negative ions as positive ions in the plasma near the extraction plane. The negative-ion spectrum was 99.5% atomic chlorine ions, with only 0.5% molecular chlorine, and essentially no impurities. Although this experiment did not incorporate the type of electron suppression technology that is used in negative hydrogen beam extraction, the ratio of co-extracted electrons to Cl^- was as low as 7 to 1, many times lower than the ratio of their mobilities, suggesting that few electrons are present in the near-extractor plasma. This, along with the near-equivalence of the positive- and negative-ion currents, suggests that the plasma in this region was mostly an ion–ion plasma. The negative chlorine current density was relatively insensitive to pressure, and scaled linearly with RF power. If this linear scaling continues to hold at higher RF powers, it should permit current densities of 100 mA/cm^2, sufficient for present heavy-ion fusion injector concepts. The effective ion temperatures of the positive and negative ions appeared to be similar and relatively low for a plasma source.

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1. Introduction

The primary driver concept for heavy-ion fusion (HIF) has traditionally relied upon positive ions, although Koskarev suggested charge-symmetric drivers using alternating bunches of positive and negative ions in an RF accelerator [4]. More recently, it has been suggested that negative halogen ions could be used as heavy-ion fusion driver beams. Relative to positive ions, negative ions would have the advantage that they would not accumulate electrons in the deep potential wells that will characterize HIF beams [5], and positive ion accumulation by negative ion bunches is likely to be less of a problem, since positive ions formed in the beam path will accelerate much more slowly than electrons, and thus will be less likely to be trapped, and positive ions, unlike electrons, will not be pulled from nearby surfaces. Moreover, because the primary formation process for negative halogen ions is dissociative attachment to molecules, the extracted beams will not have the lower energy charge exchange tails that degrade the longitudinal emittance of positive ions extracted from plasma sources.

Further, if desired, because of the high power density and short pulse length of HIF driver beams, the negative ions could be efficiently converted to atomic neutrals by laser photodetachment cells just before entering the HIF target chamber. For scenarios involving hard vacuum in the target chamber, the beam could travel as an atomically neutral beam until it was ionized by X-rays from the target. For higher chamber pressures more typical of present liquid-wall concepts, the beam would be progressively ionized along the whole of the flight path, but, by starting with atomic neutrals, the average beam self-perveance would still be lower than the case with a positive-ion beam, which should result in a smaller beam spot [1–3]. Recent simulations [6] have shown such a reduction in spot size.

At energies characteristic of an HIF accelerator, the collisional total charge-changing cross-sections for heavy negative ions should be only modestly greater (a factor of 2 or less) than for similar mass singly charged positive ions [7]; a pressure of about 2.5×10^{-8} Torr should keep beam loss below 5% along a 1 km flight path [2]. Because halogen negative ions are tightly bound, Lorentz ionization should result in negligible losses [2]; recent estimates suggest a lifetime of greater than 10^{100} s for Cl^- in a 1 MV/cm electric field or a 2 T magnetic field [8].

While there are numerous elements which form negative ions, most of them do not appear to be suitable candidates for the low-emittance high-brightness beams required for heavy-ion drivers. Sputter sources, the normal way of producing negative ions of elements like gold or platinum, produce beams with large transverse energies (and thus large effective ion temperatures). Of elements which could be used in plasma sources, the halogens should offer the best chance for producing abundant negative ions, since they have the largest electron affinities (3.06–3.62 eV) of any elements [1–3].

Among the halogens, bromine and iodine have the masses most appropriate for the driver scenarios popular in recent years, but chlorine, which has a similar electron affinity and is a gas at room temperature, was chosen as a suitable candidate for a proof-of-concept experiment to demonstrate the potential for HIF-appropriate halogen negative-ion beam parameters. Most current HIF experiments are done with K^+, which has a similar mass.

2. Experimental arrangement

Negative ions are formed in pure hydrogen plasmas in volume production sources by dissociative attachment of electrons to vibrationally excited diatomic molecules [9]. Halogens form negative ions by a similar process, with the additional feature that diatomic molecules in the ground state can also take part [10,11]. Thus, these experiments utilized an RF driven (12.56 MHz) ion source previously used for H^- production [12,13], and a feedstock of Cl_2. A movable 135 Ga magnetic filter divided the plasma into a vibrational excitation region and an extractor region. A fuller explanation of the setup and the experiments is provided in Ref. [14]. Permanent magnets deflected electrons from the beam for measure-

ment. Ion currents were measured by a secondary-suppressed Faraday cup, and the ion species were analyzed with a magnetic mass spectrometer.

Hydrogen, with an electron affinity of 0.75 eV, requires the addition of cesium to produce negative useful ion current densities of greater than a few mA/cm^2 [12]. However, since the halogens have electron affinities four and more times greater than this, no cesium was required for these experiments.

3. Experimental results and discussion

3.1. Initial tests with oxygen

Oxygen, with an electron affinity of 1.46 eV, was a convenient non-toxic gas to use for testing the system before trying chlorine, and with its intermediate electron affinity, was useful as a comparison to chlorine (electron affinity 3.61 eV) to evaluate the variation of performance with the electron affinity of the feedstock. With 2 kW of RF power applied to the antenna in the ion source plasma (the amount of RF power coupled to the plasma was almost certainly less than the RF supply output amount for all these experiments), a maximum of $5.7\,mA/cm^2$ of O^- was extracted under the same discharge conditions which yielded $22\,mA/cm^2$ of positive oxygen (the sum of atomic and molecular species). The ratio of electrons to negative ions was 300 to 1. The ratio of extracted negative to positive ions of 0.25 is much greater than is achievable in uncesiated H discharges in this or similar sources, where it is typically of order 0.01–0.03. Fig. 1 depicts oxygen and electron currents extracted as a function of extraction voltage with 1.5 kW of applied RF power and a source pressure of 10 mTorr, with 40% of the positive ions O^+ and 90% of the negative ions O^- (the rest were OH^- and O_2^-).

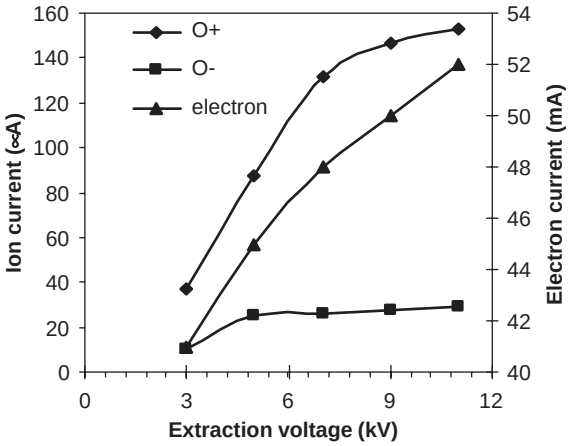

Fig. 1. O^-, O^+, and e^- currents vs. extraction voltage with 1.5 kW of applied RF power and a source pressure of 10 mTorr.

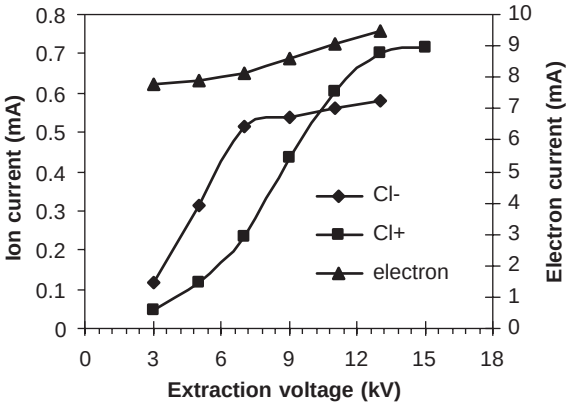

Fig. 2. Cl^-, Cl^+, and e^- currents vs. extraction voltage with 1.5 kW of applied RF power and a source pressure of 25 mTorr.

3.2. Chlorine results

With chlorine, the positive-ion spectrum was 82% Cl^+, with the remainder being Cl_2^+ and positive-ions of impurities such as nitrogen and oxygen. At the same RF output power of 1.5 kW, the negative-ion spectrum was 99.5% atomic Cl^-, 0.5% Cl_2^-, and no detectable impurities. The low level of the molecular negative-ion component is probably at least in part due to the dominant negative ion formation mechanism being dissociative attachment.

Fig. 2 shows the Cl^-, Cl^+, and electron currents as a function of extraction voltage for arc conditions with 1 kW of applied RF and a source pressure of 25 mTorr. Because chlorine's electron affinity is much greater than that of oxygen (3.62 eV vs. 1.46 eV), the ratios of negative to

positive ions and of negative ions to co-extracted electrons are much more favorable in the chlorine discharge than with oxygen.

The Cl^- current density was only weakly dependent upon the source pressure across the measured range of 20–35 mTorr, but began to decline below 20 mTorr. Similar to the case with O^-, the Cl^- current density scaled linearly with RF power. It is probably the case that a larger source would allow lower operating pressures, due to reduced wall losses, as has been the case with Ar^+.

At an RF supply output power of 2.2 kW (the maximum capability of the supply during these experiments) and a source pressure of 28 mTorr, the Cl^- current density was 45 mA/cm^2. Under the same discharge conditions, the current density of positive ions (the sum of atomic and molecular ions and positive impurity ions) was 57 mA/cm^2, so the ratio of Cl^- to total positive-ion current was about 0.79. At low energies of a few keV, such as those used for this experiment, the loss rates for negative ions due to stripping is generally appreciably larger than the loss rate of positive ions due to charge exchange. Thus the initial ratio of negative to positive ions was probably even somewhat higher than 0.79. The fact that the negative and positive ions were so comparable suggests that the plasma in the extractor plane was mostly an ion–ion plasma of positive and negative ions. Because of their large electron affinities, halogens can form ion–ion plasmas which leave very little room for electrons in charge phase space, as has been observed in iodine plasmas [15].

3.2.1. Co-extracted electrons

The scarcity of electrons in the extraction plane plasma is further substantiated by the low e^-/Cl^- ratio that was obtained without the extractor plane magnets normally employed in H^- sources used for applications on magnetic confinement fusion devices. Based simply upon the difference in mobilities (square root of the mass), one would expect an e^-/Cl^- ratio of about 240 instead of the value of 7 which was observed, if the electrons and ions had the same temperature. In fact, the electron temperature was probably higher than that of the ions, which would make the expected ratio even larger. In the case of oxygen, the e^-/O^- ratio of 300 exceeded the mobility ratio of about 160 to be expected for the same temperatures, implying that the electron temperature was probably higher than the ion temperature. The fact that the e^-/O^- ratio exceeded the mobility ratio, suggests that any suppression of electrons due to weak magnetic fields from the filter magnets partitioning the source into two plasma regions was probably not large, and not the primary reason for the very low e^-/Cl^- ratio. This best e^-/Cl^- ratio of 7:1 was obtained with a slightly different RF antenna (which broke) than the one used for the scan in Fig. 2, and the source pressure was 40 mTorr.

In H^- volume sources, biasing the plasma grid positive relative to the plasma reduces the co-extracted electron current and can increase the extracted negative ion current significantly (by a factor of 2 or so) [16,17]. Using oxygen, a bias produced a smaller, but still noticeable effect, augmenting the O^- current by 20% while diminishing the e^- current by 25% as the bias rose from 0 to 15 V; higher voltages reduced both species. In chlorine plasmas, varying the bias from 0 to 40 V had essentially no effect upon the Cl^- current, while reducing the e^- current by about 10%. The sharp reduction in the effect of the bias voltage in going from hydrogen (electron affinity 0.75 eV) to oxygen (electron affinity 1.46 eV), to chlorine (electron affinity 3.62 eV), probably reflects a reduction in the electron content of the extractor plasma as more electronegative feedstocks are used.

Fig. 3 depicts Cl^- and e^- currents as functions of source pressure. The e^- current is much more sensitive to pressure than the Cl^- current, declining strongly with pressure, while the Cl^- current increases only slightly. This might be due to a decrease in the electron temperature of the extractor plasma at higher pressure, which would reduce the electron mobility.

Fig. 4 shows the Cl^- and e^- extracted currents as a function of the separation between the plasma grid and the magnetic filter which partitions the plasma into an excitation region and an extractor region. The e^- current is significantly more sensitive to the filter position than is the Cl^-

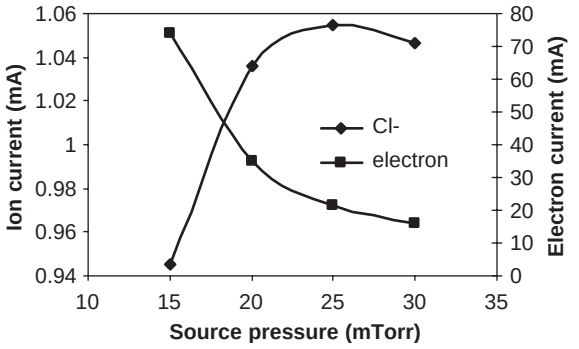

Fig. 3. Cl^- and e^- currents vs. source pressure, showing a much stronger pressure dependence for the e^- than the Cl^-.

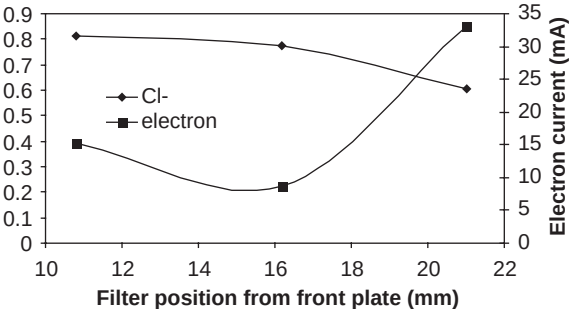

Fig. 4. Cl^- and e^- currents vs. magnetic filter distance from plasma grid showing the greater sensitivity to filter position of e^- relative to Cl^-.

current. The strong rise in e^- current at the largest distance from the extraction plane might be due in part to the fact that this movable filter may have permitted leakage around its edges of energetic electrons from the excitation region, which is closer to the RF antenna driving the discharge. With a greater separation between the filter and the plasma grid, a greater number of these more mobile energetic electrons may have reached the axis, where the extraction aperture was located. Alternatively, at the larger distances, the filter may have been too close to the RF antenna, allowing more electron heating beyond the filter, which would have increased the electron mobility.

3.2.2. *Effective beam temperature measurements*

A pepper pot measurement was done to obtain an approximate measure of the effective beam temperature (T_{eff}) transverse to the beam propagation axis. Measurements were done in the directions parallel and perpendicular to the magnetic field which was employed to deflect the co-extracted electrons for measurement. The T_{eff} was larger in the perpendicular direction due to the magnetic deflection of the ions. The T_{eff} in the perpendicular direction were 0.5 eV for both Cl^- and positive chlorine ions. In the parallel direction they were about 0.3 eV for Cl^- and about 0.2 eV for the positive chlorine ions.

The separation magnet which led to the higher T_{eff} in the perpendicular direction was only there to permit a measurement of the co-extracted electron content of the beam. With a co-extracted electron component as low as the best observed in these experiments ($e^-/Cl^- = 7$), it would probably not be necessary to include any magnets in the multi-aperture extractor array of an HIF ion source, in which case the T_{eff} in the parallel direction (about 0.3 eV for Cl^-) would probably be the relevant parameter.

All of these T_{eff} are somewhat low compared to common values for positive ions extracted from ordinary ion–electron plasmas. For instance, the effective ion temperature recently measured for Ar^+ extracted from a fairly similar RF-driven plasma source was about 2.0–2.4 eV [18]. If it is really the case that both the negative and positive ions extracted from ion–ion plasmas have lower T_{eff} than do positive ions extracted from the much more common ion–electron plasmas, then this might be explainable by the fact that the ambipolar potential should be smaller in ion–ion plasmas (especially in heavier ions) than in electron–ion plasmas, leading to lower ion energies. In addition the gradients occur over shorter distances, which might also have an ameliorating effect [19,20].

4. Implications for heavier halogens

The heavier halogens, bromine (mass 79 and 81) and iodine (mass 127), are more likely than chlorine to fit the mass requirements most commonly considered for HIF driver beams [21], although recent proposals using solenoidal trans-

port might use beams as light as chlorine. Experiments with elemental feedstocks of bromine or iodine would require ion sources at moderately elevated temperatures, since Br and I boil at 59 and 114 °C respectively. Since they should form negative ions through the same mechanism as Cl (dissociative attachment of low-energy electrons to vibrationally excited diatomic molecules, and perhaps ground state diatomic molecules as well), results with the heavier halogens should be similar to these Cl experiments.

The achievable current density with a given amount of RF power driving the ion source plasma may be somewhat lower for Br, with an electron affinity of 3.36 eV, and for I with an electron affinity of 3.06 eV, than for Cl, with its electron affinity of 3.62 eV. However, this will probably not be a problem, especially if the observed linear scaling of negative-ion current density with RF power continues to higher levels. For instance, the 45 mA/cm^{2}of Cl^- found at 2.2 kW of RF extrapolates to about 100 mA/cm^2 at 5 kW, which was the planned level for these experiments before problems were found with the intended RF supply. Either of these current densities would probably be adequate for the multi-aperture beamlet injector concept under consideration [21].

Although it could be expected that the co-extracted electron component would be greater with Br and I than with Cl, both because of their greater mass and their somewhat lower electron affinities (which might result in a larger electron component in their extractor region ion–ion plasmas), this may be compensated to an unknown extent by a competing effect: the greater mass of Br^+ and I^+ compared to Cl^+. This is because the addition of cesium to H^- sources not only raises the production of H^-; it also significantly reduces the co-extracted electron current. The electron suppression is thought to occur because the massive (133 amu) Cs^+ in plasma near the extraction plane provides a drag on the flow of low-energy electrons to the extraction meniscus [22]. If this hypothesis is correct, then the same effect could be expected to occur in halogen plasmas. Thus, the low level of electrons co-extracted with Cl^- might be partly attributable to the mass of Cl^+ (37 and 35 amu), in which case the electron suppression associated with this effect could be more favorable for Br and I. Iodine has almost the same mass as cesium (127 vs. 133), and the density of I^+ in an iodine plasma should be significantly higher than the density of Cs^+ in a dominantly hydrogen plasma.

H^- ion sources commonly remove their far more abundant co-extracted electrons by embedding permanent magnets inside the extractor grid to deflect the electrons onto the extractor aperture walls, while they are still at low energy. The effect upon the H^- optics is small because it is much more massive than an electron. Although this technique works well, the space required by the magnets reduces the maximum grid transparency achievable in a multi-aperture beamlet array.

The same technique could be applied to multi-aperture beamlet arrays for halogens. Because they are much more massive than hydrogen, the effect upon the ion optics should be much less (by the square root of the ratio of the mass) than in today's H^- sources. However, it may be unnecessary to install magnets in the extractor grid if the co-extracted electron component does not increase greatly beyond that found under the best conditions in these experiments. Applications of multi-aperture H^- ion sources must dump the electrons at the extractor stage because the beam pulses last for seconds, and if not dumped, the electrons would otherwise reach the full acceleration energy, consuming many times the total acceleration power drawn by the ions, and then depositing this energy on beam system surfaces. However, HIF ion sources will fire microsecond beam pulses with a very low duty factor, and the acceleration potential in the ion source represents only a very small fraction of the total acceleration applied to the beam, so it should be acceptable to dump the electrons after the source before they reach the main accelerator, since both the heat load and the decrease in the efficiency of the total acceleration system would be small. Magnetic focusing devices such as quadrupoles and solenoids, used in HIF drivers, can be effective in separating the electrons from ions.

5. Conclusion

Heavy negative ion beams offer appealing characteristics as HIF drivers [1], and halogens are the most natural candidates because of their large electron affinities and usability in plasma sources [2]. A proof-of-concept experiment was conducted using Cl, which can be employed in a room-temperature source, and is a good surrogate for bromine and iodine, which have masses typical of the range often considered for HIF, but require moderately elevated source and extractor temperatures.

In contrast to ion sources using hydrogen (electron affinity of 0.75 eV), it was not necessary to add cesium to obtain Cl^- current densities. To evaluate the effect of feedstock electron affinity upon yield, the source was first operated with oxygen (electron affinity of 1.46 eV), producing an O^- yield of 5.7 mA/cm^2, an O^- to positive ion ratio of 0.25, and an e^- to negative ion ratio of 300. Chlorine (electron affinity of 3.62 eV) yielded a negative ion spectrum which was 99.5% Cl^- and 0.5% Cl_2^-, with no detectable impurities. At the optimum conditions observed for negative ions, the Cl^- current was 79% of the obtainable positive-ion current, suggesting a mostly ion–ion plasma near the extraction plane. Under the most optimized conditions with respect to electrons, the ratio of co-extracted e^- to Cl^- was 7, much less than the mobility ratio of about 240 if the electrons and ions had equal temperatures, which also suggests a paucity of electrons in the extraction plane plasma. Biasing the plasma grid positive relative to an oxygen plasma modestly decreased co-extracted electrons and increased O^- (but much less than the effects observed in H^- sources), and grid biasing in chlorine had even less effect in decreasing co-extracted electrons, and essentially no effect on the Cl^-, again suggesting a scarcity of electrons in the extractor plane plasma, consistent with electron exclusion as more electronegative feedstocks were employed.

Measurements with a pepper pot diagnostic gave effective T_{eff} of about 0.2 eV for Cl^+ and 0.3 eV for Cl^- in the direction parallel to the electron analysis magnets, and 0.5 eV in the direction perpendicular to the analysis field. These values appear acceptable for HIF drivers, which would probably not need to deflect electrons in the ion source extractor. These T_{eff} are also significantly lower than is often the case for positive ions extracted from ordinary ion–electron plasmas in a similar source [18]. This might be due to the lower ambipolar potentials and shorter gradient lengths that should occur in ion–ion plasmas [19,20] compared to electron-ion plasmas. If these apparently low T_{eff} can be confirmed by further experiments, then halogen sources with ion–ion extraction plane plasmas might be the preferred choice for positive-ion beams as well as negative-ion beams in injector concepts using multi-aperture beamlets extracted from plasmas. The small spot size a low T_{eff} would permit could, if confirmed by more measurements, make these sources attractive for high energy density physics studies, but the limitation to a singly charged ion would preclude their use in schemes involving only a few MeV of acceleration.

In both O and Cl plasmas, the negative-ion current density scaled linearly with RF power. At the maximum RF output of the supply used (2.2 kW), the Cl^- current density was 45 mA/cm^2, which, if the linear scaling continued to higher power, would extrapolate to 100 mA/cm^2 at 5 kW (the planned level before power supply problems). Either of these current densities should be adequate for HIF driver applications.

Since these experiments show that halogens permit negative-ion current densities close to positive-ion densities, the extractable current densities of heavier driver ions such as I^- or Cs^+ should depend upon the magnitude of the extraction voltage which can be applied. This will be a function of the extractor design, and not the polarity of the ion. Thus, achievable ion source parameters appear acceptable for halogen negative ion driver beams.

The highest Cl^- current density (45 mA/cm^2, equaling 79% of the total positive ion current) was obtained at a source operating pressure of 40 mTorr. The current was measured after the 14 keV beam had traversed a distance of about 0.1 m at a pressure estimated to be $5-10\times10^{-5}$ Torr of Cl_2. Since single electron stripping cross-sections at these low energies are

approximately proportional to the geometric cross-section of the target molecules, and since Cl_2 is about twice the cross-section of N_2, this corresponds to transporting the 14 keV Cl^- beam a distance of 1–2 kilometers at a pressure of 1×10^{-8} Torr if the bulk of the background pressure in the accelerator and drift duct were N_2.

Moreover, single-electron-stripping cross-sections typically are largest at very low energies and then start to decline rapidly at higher energies. For H^-, for instance, they are their largest and slowly varying at energies up to about 300 eV, and then begin to decline at higher energies. For Cl^- the behavior should be quite similar, except that the energy where the steep decline begins will be higher because the equivalent velocity for Cl^- would correspond to an energy (for Cl_{37}) of 11 keV, and since Cl^- is nearly 5 times as tightly bound as H^- the drop in the stripping cross-section should begin at a somewhat higher energy still. Thus, the 14 keV beam of this experiment was exposed to single electron stripping cross-sections much higher than would be the case for an actual beam traveling at high energies through an accelerator.

Accordingly, so far as single-electron-stripping was concerned, the distance through which this 14 keV beam was transmitted corresponded to many kilometers for a high-energy beam in an accelerator with a residual nitrogen pressure of 1×10^{-8} Torr. Despite this, the Cl^- evidently did not undergo much stripping, since the Cl^- current was 79% of the Cl^+ current, and the ion–ion plasma in the extractor had to be less than 50% Cl^-, since a part of the negative charge must always be free electrons to form the negative ions. The cross-section for multi-electron loss collisions, which was not a factor at these energies, will contribute to the total beam loss cross-section at higher energies, but this component should be quite similar in magnitude for negative ions or singly charged positive ions of similar mass, since, after the first one or two electrons, the rest of a Cl^- is similar to an Ar^+, and this becomes even more the case for heavier ions. Thus, while beams of negative halogens will have somewhat more stringent vacuum requirements than beams of singly charged positive ions of similar mass, the difference should be modest.

Since quite similar currents of positive or negative ions can be extracted from the same halogen plasma, sufficiently rapid bipolar switching of the extractor polarity might perhaps allow them to be useful for scenarios recently considered in Japan in which alternating bunches of positive and negative ions would be injected into an induction linac followed by storage rings [23]. If slightly different extraction voltages could be applied for the positive and negative ion bunches, then the currents could be equalized.

Future experiments are planned on a larger test stand to compare the current density and effective ion temperature (using an emittance scanner) of Cl^+, Cl^-, and Ar^+ (from an argon plasma in the same source with the same extraction optics), along with the co-extracted electrons, both with a single and multiple beamlet apertures, and at higher RF powers.

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