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## Perspective on the role of negative ions and ion–ion plasmas in heavy ion fusion science, magnetic fusion energy, and related fields

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## ABSTRACT

Some years ago it was suggested that halogen negative ions [L.R. Grisham, Nuclear Instruments and Methods in Physics Research A 464 (2001) 315] could offer a feasible alternative path to positive ions as a heavy ion fusion driver beam, which would not suffer degradation due to electron accumulation in the accelerator and beam transport system, and which could be converted to a neutral beam by photodetachment near the chamber entrance if desired. Since then, experiments have demonstrated that negative halogen beams can be extracted and accelerated away from the gas plume near the source with a surviving current density close to what could be achieved with a positive ion of similar mass, and with comparable optical quality. In demonstrating the feasibility of halogen negative ions as heavy ion driver beams, ion–ion plasmas, an interesting and somewhat novel state of matter, were produced. These plasmas, produced near the extractor plane of the sources, appear, based upon many lines of experimental evidence, to consist of almost equal densities of positive and negative chlorine ions, with only a small component of free electrons. Serendipitously, the need to extract beams from this plasma for driver development provides a unique diagnostic tool to investigate the plasma, since each component – positive ions, negative ions, and electrons – can be extracted and measured separately. We discuss the relevance of these observations to understanding negative ion beam extraction from electronegative plasmas such as halogens, or the more familiar hydrogen of magnetic fusion ion sources. We suggest a concept that might improve negative hydrogen extraction by the addition of a halogen. The possibility and challenges of producing ion–ion plasmas with thin targets of halogens or, perhaps, salt is briefly addressed.

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### 1. Introduction

Some years ago [1] it was suggested that halogens, with their very large electron affinities, might allow the production of beams of high-enough current density to make negative ions feasible as a driver for heavy ion fusion. Negative ions would have the advantage that, unlike positive ions, they would not accumulate electrons that might cause emittance growth, and they presented the appealing option of being suitable for energy-efficient photodetachment [2] to neutrals, which would result in lower average beam self-perveance during propagation across a fusion target chamber, even with subsequent reionization by target-emitted X-rays and collisions with flibe vapor. These advantages were, however, only worth pursuing if negative heavy ion beams of roughly comparable quality to corresponding positive ion beams could be easily produced.

All of the stable halogens have quite similar electron affinities, ranging from 3.06 to 3.62 eV, and they all, in the vapor phase, form diatomic molecules, rendering any of them suitable as a representative test case. We chose chlorine because, unlike iodine or bromine, it is a gas at ambient temperature, and because it is easier to handle than fluorine. Two sets of experiments with chlorine using different RF ion sources and different test facilities were subsequently carried out over the next several years through collaborations Princeton Plasma Physics Laboratory with Lawrence Berkeley National Laboratory and with Lawrence Livermore National Laboratory.

These experiments, which we have discussed in earlier papers [3], found that chlorine, and by implication the other stable halogens, was well-suited to producing beams at current densities, emittances, and survivability against charge-changing collisions in gas, which were quite similar to what could be obtained with positive ions of similar mass and electron number. The experiments at Berkeley [4] were able to extract and transmit  $\text{Cl}^-$  through the ion source gas effluent at a current density in the analyzer, which was 79% of the combined  $\text{Cl}^+$  and  $\text{Cl}_2^+$  reaching the same analyzer. The  $\text{Cl}^-$  was 99.5% atomic, while only 82% of

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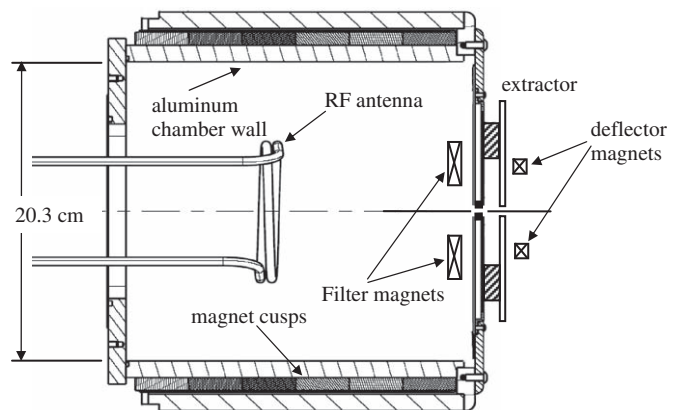
the positive chlorine current was atomic ions. Under these optimum conditions, the co-extracted electrons were only 7 times the  $\text{Cl}^-$  current, much less than the ratio of 240 based on the velocity difference, which would be expected if there were equal numbers of electrons and  $\text{Cl}^-$  ions near the extraction plane and at the same temperature (in fact, the electrons were likely hotter than the ions, which would have made the mobility ratio even greater than 240). Subsequent experiments at Livermore [5] obtained  $\text{Cl}^-$  current densities at the Faraday cup that were 85%–90% of the positive ion current at the same operating conditions, and again very low  $e/\text{Cl}^-$  ratios of just 6–7. With the same discharge RF drive power, nearly the same pressure, and the same source, beam extractor, and diagnostic devices, the Livermore experiments found that the  $\text{Cl}^-$  current density was 76% of the  $\text{Ar}^+$  current density, which could be extracted from an argon discharge, which would be a conventional ion–electron plasma, and is typical of the sorts of ions that have been considered as candidates for heavy ion fusion driver beams.

Emitance measurements on the beams in the Livermore experiments found an effective transverse beam temperature of 0.3 eV for the  $\text{Cl}^-$ , the  $\text{Cl}^+ + \text{Cl}_2^+$ , and the  $\text{Ar}^+$  beams. However, it was surmised that since, for all three beams, the normalized emittance increased with beam perveance, the beam extraction optics was probably contributing to the apparent beam temperature. Thus, 0.3 eV was taken to be an upper limit on the ion temperature in the extraction plane of the source plasma, and it was not possible to determine which of the beams started out colder.

The overall outcome of the experiments at both Berkeley and Livermore was to demonstrate that the halogens are entirely suitable for producing negative ion beams with current densities and emittances similar to those of similar mass positive ions, and with a low-enough co-extracted electron component to allow easy dumping at low energy in the beam extraction and pre-acceleration stage. Thus, the initial goal of these experiments, to show the feasibility of negative halogen beams as heavy ion drivers for inertial confinement fusion, was achieved. However, in considering the results obtained in these experiments, it has become apparent that the plasma state achieved in the extractor region of the ion sources may be of as much or more interest as the beam results themselves.

## 2. Ion–ion plasmas

Both the Berkeley and the Livermore experiments used a type of ion source that has been called, in the magnetic fusion energy community, a tandem ion source. This type of source has been used extensively for more than 2 decades to produce  $\text{H}^-$  and  $\text{D}^-$  as precursors of high-energy neutral beams to inject into tokamaks and stellarators, and at the front end of high-energy accelerators such as the Spallation Neutron Source at Oak Ridge. Most of the source volume is taken up by the driver plasma, where either cathode filaments or an RF antenna produce primary electrons to ionize gas. A magnetic filter, produced by external magnets, internal magnets, or a large current flowing along the plasma grid from which the beam is extracted, typically separates the driver plasma from the extractor plasma. The purpose of the magnetic filter has traditionally been viewed as keeping the high-energy primary electrons out of the extractor plasma region, where they would have a large cross-section for destroying negative ions. Fig. 1 shows a particular version of a tandem ion source used in the Livermore chlorine experiments. Although there are many different versions of this genre of source, most of which do not use internal magnets to produce the filter, they all have in common a driver plasma at the rear of the source and a (usually shorter)



**Fig. 1.** Schematic of the ion source built for the Livermore experiments of Ref. [5]. As in other tandem  $\text{H}^-$  sources, the filter magnets shield the extractor region plasma from high-energy electrons in the driver plasma where the RF antenna resides. The deflector magnets separate the electrons from the negative ion beam. Used with permission from L.R. Grisham, Review of Scientific Instruments 77 03A501 (2006). Copyright 2006, American Institute of Physics.

region of plasma between the magnetic filter and the extraction electrode.

Although ion–ion plasmas have been the subject of a few studies in the past, they were generally either transient shells occurring on the outside of afterglow plasmas after the driving power was terminated [6], or in the few studies of equilibrium plasmas, beams were not extracted [7]. Because the initial motivation for the chlorine discharge experiments conducted at Berkeley and Livermore was to demonstrate the suitability of halogens as negative ion driver beams for inertial confinement fusion, they were designed to extract and accelerate ion beams.

By changing the polarity of the extractor/accelerator power supply connections, we could either extract a beam of positive ions or a beam comprising negative ions and electrons. The addition of a dipole magnetic field allowed the separate measurement of the negative ions and the electrons. Thus, somewhat serendipitously, measuring the parameters of the extracted beams provides a novel diagnostic for inferring some of the characteristics of the conditions in the extractor plasma near the extraction sheath. Measuring the extracted negative ion and electron currents yields a qualitative measure of the relative prevalence of electrons compared to ions in the plasma (qualitative rather than quantitative because the electrons are much lighter and therefore much more mobile than the ions, and they are usually hotter, which enhances their mobility). Measuring the normalized emittance of the ion beam gives an upper limit on the ion temperature in the extractor plasma. Changing the power supply connections so as to extract a positive ion beam, and then operating the source at the same discharge parameters (driver power and gas pressure) as were used for extraction of a negative beam, allows comparison of the relative quantities of positive and negative ions in the extractor plasma under any given set of operating conditions. Applying a momentum analyzer to the positive and negative ion beams allows the fractions of atomic and molecular ions to be assessed.

Thus, analysis of the extracted beams has emerged as a useful diagnostic of the plasma in the extractor region. An intriguing possibility is that, with further study, and with the addition of other diagnostics (such as Langmuir probes and perhaps a laser to photodetach negative ions) within the extractor plasma, it might be possible, by comparing pre-sheath densities before extraction to post-sheath densities in the beams, to infer some of the properties about sheaths in ion–ion plasmas, a topic that has had little or no experimental exploration to the best of our knowledge.

Applying the same combination of in-source and beam diagnostics to an argon beam would then allow an experimental determination of how ion–ion sheaths differ from electron–ion sheaths. Such studies, while of fundamental plasma physics interest, might also have implications for commercial applications in plasma processing.

The experiments conducted at Berkeley and Livermore with chlorine beams found five independent lines of evidence [5] supporting the inference that the extractor plasma in these two tandem ion sources was an ion–ion plasma consisting of positive ions, a nearly equal number of negative ions, and relatively few electrons. They also found that the degree to which an ion–ion plasma could be formed depended very strongly on the electron affinity of the feedstock gas. Thus, oxygen, with an electron affinity of 1.46 eV, yielded an  $O^-$  beam with about 25% of the current of the positive oxygen beam, much more than the typical  $H^-/(H^+ + H_2^+ + H_3^+)$  ratio of 2%–4% in an uncesiated volume production tandem hydrogen source, where  $H^-$  is formed through the same reaction pathways as  $O^-$ , but at much lower rates because the electron affinity of hydrogen is only 0.75 eV. Nonetheless, the oxygen discharge did not have the full characteristics of an ion–ion plasma because it contained a number of electrons, producing an  $e/H^-$  beam ratio of 300. Chlorine, with an electron affinity of 3.62 eV, yielded a  $Cl^-/(Cl^+ + Cl_2^+)$  ratio of 90% and an  $e/Cl^-$  ratio of just 6 to 7, far less than the mobility ratio of 240 to be expected if the electrons and negative ions had equal temperatures (the electrons are almost certainly hotter, which would make the expected ratio even greater) and if there were equal numbers of electrons and  $Cl^-$ . Thus, the halogens, with electron affinities ranging from 3.06 to 3.62 eV, appear to be by far the most suitable elements for the formation of ion–ion plasmas, and the phenomenon might be largely limited to them.

### 3. Extraction of negative ion beams

A long-standing conundrum in the field of  $H^-$  ion source physics has been why one is able to extract negative ions from the plasma at all. In ordinary plasmas using feedstocks with modest to no electron affinity, the plasma should consist of positive ions, electrons, and a small component of negative ions. Thus, the characteristics of the sheath at the edge of the plasma should be determined virtually entirely by the positive ions and the electrons, with the negative ions playing almost no role compared to the much lighter, and therefore much more mobile, electrons. Under such conditions, ambipolar diffusion of the ions and electrons to the walls results in the establishment of a positive potential well in the plasma relative to the wall in order to retard the diffusion of electrons to the wall and enhance the movement of positive ions. This balances the positive and negative fluxes, and allows the plasma to maintain approximate charge neutrality. Under such conditions, the positive potential well should act as a trap for the negative ions, impeding their flow across the pre-sheath and sheath to be extracted as a beam.

#### 3.1. Extraction of negative ions from ion–ion plasmas

This was likely the reason why early attempts to extract negative ions from plasmas, which were dominantly of an electron–ion character, failed. [8] The situation should be quite different, however, in an ion–ion plasma such as appears to have been produced in the chlorine beam experiments at Berkeley and Livermore. If the dominant charge carriers are positive and negative ions, with only a small admixture of electrons, then since the mass imbalance between the positive and negative charge carriers is much less than in an electron–ion plasma, their

relative mobilities will also be much more balanced, so the retarding potential between the plasma interior and the wall needed to maintain charge-neutral fluxes should be much less than in an electron–ion plasma. In a plasma made solely of a single halogen, as is the case in the chlorine beam experiments, the dominant positive and negative charge carriers have almost exactly the same mass (because about 18% of the positive chlorine ions were  $Cl_2^+$ , whereas the negative chlorine was 99.5% atomic, the average mass of the positive chlorine ions in these experiments was slightly greater than the average mass of the negative chlorine ions). Thus, the retarding potential required to maintain charge-neutral wall fluxes should be small, but still non-zero, due to the influence of the small minority of electrons. As a result, the potential well trapping the negative ions within the plasma should be shallow, and it should be almost as easy to extract negative ions as it is to pull out positive ions.

In practice, there does not seem to have ever existed a clear definition of the delineation between an electron–ion plasma and an ion–ion plasma, but it would seem appropriate to call a plasma an electron–ion plasma if its edge dynamics, and therefore the edge potential gradient, are dominated by the mobilities of its positive ion and electron components, and, conversely, to call a plasma an ion–ion plasma if its edge dynamics and the resulting potential gradient are dominated by its positive and negative ion components. Such a definition would seem to be in harmony with past practices, in which transient ion–ion plasma conditions were deemed to have been produced in afterglow plasmas after the termination of the power driving the discharge [9]. After the driving power was stopped, the rapid diffusion of the remaining light electrons to the wall left behind the heavier positive and negative ions. This in turn led to a sudden rush of the negative ions to the wall after the collapse of the positive potential well that had arisen from the dominant effect of electrons upon the ambipolar diffusion retarding potential. This sort of very-short-lived transient ion–ion plasma condition could arise in the afterglow of discharges even if their component feedstocks were not strongly electronegative (such as oxygen), or were only partly composed of strongly electronegative halogens. This was because the supply of new electrons had been terminated in these afterglow plasmas, so the evolution of the decaying plasma was driven by the relative velocities of the species, along with the fact that low-energy electrons could also be captured by diatomic molecules, in turn forming negative ions by dissociative attachment.

In the case of the chlorine beam experiments conducted at Berkeley and Livermore, the beams were extracted during the powered phase of the discharge, and the multiple lines of evidence supporting the existence of ion–ion plasma conditions were characteristic of the steady phase of the discharge. While these discharges were, for reasons of cooling and power supply capabilities, limited in duration to milliseconds, the power flow through them was in equilibrium during the beam extraction periods. In these discharges, the quasi-neutrality condition would imply that the negative ion density could not, on average, exceed the positive ion density, and moreover, since some electrons must always be present to produce negative ions through dissociative attachment, the negative ion density can never quite equal that of the positive ions.

The stripping losses of  $Cl^-$  in the relatively dense column of gas flowing out of the ion source through the extractor/accelerator would be greater than or be the same order of magnitude as [10] the losses of  $Cl^+$  by charge exchange reactions. Accordingly, the fact that the  $Cl^-$  current measured at a Faraday cup was nearly as much as the positive chlorine current at the same discharge conditions (90% in the case of the Livermore experiments) suggests that these plasmas offered little if any impediment to

extraction of negative ions, and thus that there was little if any positive potential well to trap the negative ions within the extraction region plasma. The lack of an impeding electric potential in the extraction region is further evidenced by the behavior of the extracted  $\text{Cl}^-$  current when the plasma grid was biased positive relative to the plasma. Applying a positive bias of up to 40 V (the limit of the supply) did not increase the extracted  $\text{Cl}^-$  appreciably. By contrast, applying a 15 V positive bias in the same ion source when operating with an oxygen discharge produced a 20% increase in the extracted  $\text{O}^-$  current, and applying a positive bias of a few volts to the extraction grids of conceptually similar tandem  $\text{H}^-$  sources can augment the extracted  $\text{H}^-$  current by a factor of two. This trend strongly suggests that the retarding potential inhibiting negative ion extraction was less in the discharges made from oxygen, with an electron affinity of 1.46 eV, than in discharges made from hydrogen, with an electron affinity of 0.75 eV, and that the retarding potential was more or less absent in the discharges made from chlorine, with an electron affinity of 3.62 eV.

### 3.2. Negative ion extraction from electron–ion plasmas

Thus, it appears that the absence, or near-absence, of an ambipolar-diffusion-driven positive potential well to trap negative ions can explain the ease of extraction of negative ions from ion–ion plasmas. However, most driven plasmas (ones that are not in the afterglow phase) are not ion–ion plasmas, particularly the hydrogen isotope discharges from which  $\text{H}^-$  or  $\text{D}^-$  are commonly extracted to form beams that are subsequently neutralized and used to heat and drive current in magnetically confined nuclear fusion experiments. How is it that some portion of the negative ions in these dominantly electron–ion plasmas formed from a relatively weakly electronegative gas can be extracted from what should be a confining positive electrostatic potential well?

It is likely that the answer is probably due to at least two mechanisms. The first is perhaps yet another example of serendipity in the pursuit of negative ion beams. All of the high current  $\text{H}^-$  and  $\text{D}^-$  ion sources in use for magnetic fusion incorporate some form of magnetic filter field to protect the plasma near the extraction plane from the destructive effects of the high-energy primary electrons in the driver plasma, since these high-energy electrons destroy negative hydrogen ions. However, because these magnetic filters are located near the extraction region, and indeed, in one configuration arise from an electric current flowing along the extraction grid, the filter field actually pervades the entire region of plasma near the extraction grid. The dominant component of these filter fields is parallel to the plasma grid from which the beam is extracted, so that charged particles moving towards the extraction plane have to cross the magnetic field. The line averaged magnetic thickness of these filter fields across their spatial extent of several centimeter is typically a few hundred gauss-centimeter or less, so the Larmor radii of the thermal electrons in the plasma will be appreciably smaller than the distance across the filter, while the Larmor radii of the much more massive ions will be larger than the filter width. Thus, the electrons will be magnetized, while the ions are, to a large extent, not. Because crossing the magnetic field lines impedes the flow of the electrons much more than it impedes the dominant positive ions and the minority negative ions, it has much the same effect as if it were increasing their mass to the extent that they drift towards the extraction plane. The magnetic filter field parallel to the extraction plane also adds a net drift of the thermal electrons along the direction parallel to the extraction plane, rather than towards it. Thus, the magnetic filter field partly makes up for the mobility imbalance between ions and electrons,

taking the place, to some extent, of the ambipolar diffusion retarding potential that normally impedes negative ion extraction from electron–ion plasmas.

The second mechanism that facilitates negative ion extraction from plasmas with dominantly electron–ion characteristics is the positive bias that is usually applied in negative hydrogen ion sources between the plasma grid from which the beam is extracted and the plasma. Biasing the grid positive relative to the plasma can counteract the effects of the ambipolar-diffusion-driven retarding potential, increasing the fraction of the negative hydrogen ions, which can be extracted from the discharge.

### 3.3. Reduced role of magnetic filters in negative ion extraction from ion–ion plasmas

Since the ion sources used in the chlorine beam experiments at Berkeley and Livermore [5] incorporated magnetic filters, one might ask whether the low  $e/\text{Cl}^-$  ratios observed in these experiments might simply have been a manifestation of an ion–ion plasma. That this was not the case is apparent from two observations in the ion source used at Berkeley. An oxygen discharge was run in this source with the same magnetic filter configuration as was used for the chlorine discharge. If the low  $e/\text{Cl}^-$  ratio of 7 were due primarily to the effects of the magnetic filter, then the  $e/\text{O}^-$  should have been even lower, since oxygen is lighter than chlorine. In fact, the  $e/\text{O}^-$  ratio at optimum conditions was much larger, 300, because  $\text{O}^-$  was less prominent in the oxygen plasma than was  $\text{Cl}^-$  in the chlorine plasma, leaving room in charge space for electrons. The second salient observation was that, when the position of the magnetic filter was varied relative to the extraction plane in the chlorine discharge, the minimum  $e/\text{Cl}^-$  ratio did not occur when the filter was closest to the extraction plane (1.1 cm), which would have maximized the magnetic field strength, and the suppression of electrons, at the extractor, it also did not occur when the filter was farthest away (2.1 cm), which would have maximized the integrated magnetic filter thickness, but it instead occurred when the filter was at an intermediate distance (1.6 cm). Thus, while the magnetic filter is probably a fundamental factor in the extraction of substantial current densities of negative ions from a dominant electron–ion plasma, it seems to be of substantially less significance to the extraction of negative ions from ion–ion plasmas.

## 4. Halogen-assisted $\text{D}^-$ extraction from deuterium ion sources

Since it appears that it is easier to extract negative ion beams from ion–ion plasmas than from dominantly electron–ion plasmas such as occur in the hydrogen ion sources used for heating and current drive in some present-day magnetic fusion devices [11] and planned for the ITER tokamak [12], it is natural to ask whether the knowledge gained from the chlorine beam extraction experiments might perhaps have some application to improving the performance of negative hydrogen sources for the magnetic fusion energy program. These ion sources, although much larger than the sources used in the Berkeley and Livermore negative chlorine beam experiments, are similar in principle; they are tandem ion sources, with a magnetic filter separating the driver region from the extractor plasma region.

If only pure hydrogen or deuterium is fed into these sources, the amount of  $\text{H}^-$  or  $\text{D}^-$ , which can be extracted, is too low (about 2–3 mA/cm<sup>2</sup>) to be useful for magnetic confinement fusion. The low yield is a consequence of the low (0.75 eV) electron affinity of hydrogen. As a result, the negative hydrogen ion sources used for magnetic fusion all feed cesium vapor into the discharge



chambers. Cesium lowers the electron work function of surfaces, and substantially increases the yield of negative hydrogen ions, so that, for instance, 10–13 mA/cm<sup>2</sup> of D<sup>-</sup> can be reliably extracted and accelerated.

There are, however, disadvantages to using cesium in these ion sources. Cesium, which drifts into the accelerator, lowers the electron work function of the high-voltage grids, with the result that they emit more secondary electrons when hit by beam ions, reducing the voltage-holding capability of the accelerator. Metallic cesium is also easily inactivated within the source by conversion to an oxide or hydroxide through contact with oxygen or water vapor, both of which are very difficult to eliminate from large vacuum systems. This is especially true in a hydrogen ion source and accelerator, because almost all high-voltage insulators that can be used in the accelerator column contain large amounts of oxygen. Atomic hydrogen, which is produced in copious amounts in these ion sources, and to a lesser extent molecular hydrogen, can remove oxygen from the metal oxides that are the basis of many insulators, and this reduction reaction results in a perpetual supply of hydroxyl and water molecules. The severity of this problem is reduced, but probably not eliminated, by the fact that most of the hydrogen that reaches the high-voltage insulators should be molecular rather than atomic by the time it contacts them.

Accordingly, it would be of substantial practical interest to investigate whether there might be an alternative way to increase the extractable negative ion current density from an H<sup>-</sup> or D<sup>-</sup> ion source. The negative hydrogen current density that can be extracted from an uncesiated tandem ion source is much smaller (two orders of magnitude) than the positive ion current density that can be extracted. While it is possible that this represents all the negative ions available to extract, it might also be the case that the ambipolar-diffusion-driven positive potential well that traps the negative ions is not very well compensated by the drag on the electrons from the filter field and the applied bias of the plasma grid. Since it appears, as discussed above, that in ion–ion plasmas it is possible to easily extract essentially all of the available negative ion current density, it would be appropriate to try to alter the negative charge carrier composition in a hydrogen ion source to give it more of an ion–ion plasma character.

Changing the characteristics of a hydrogen discharge from those of an electron–ion plasma to those of an ion–ion plasma might be attempted by adding a halogen to the discharge. With electron affinities of 3.06–3.62 eV, halogens will form negative ions much more readily than does hydrogen with an electron affinity of 0.75 eV. Thus, in order to minimize the negative halogen current that will be co-extracted with the H<sup>-</sup> or D<sup>-</sup>, one should minimize the mobility of the halogen ion relative to a hydrogen ion by picking a heavy halogen. Iodine would appear the most appropriate. If I<sup>-</sup> and D<sup>-</sup> have about the same temperature in the discharge, then the extracted D<sup>-</sup>/I<sup>-</sup> current density ratio should be roughly the inverse of the square root of their masses if the I<sup>-</sup> and D<sup>-</sup> are at equal densities in the plasma. Since the mass of iodine is 131, while D is 2, this ratio would be about 7.8 under conditions of equal temperature and density. However, achieving any benefit from this technique requires that a large fraction of the electrons within the extractor plasma be displaced by negative ions. Thus, there will probably need to be several times more I<sup>-</sup> ions in the extractor plasma than there are D<sup>-</sup> ions, resulting in a co-extracted I<sup>-</sup> current that is comparable to or larger than the D<sup>-</sup> current.

This would clearly be wildly impractical if the combined beam were sent through the whole accelerator, as it would decrease the electrical efficiency by the I<sup>-</sup>/D<sup>-</sup> ratio, which no practical system could tolerate, and it would result in a heavily contaminated beam. However, it should be practical to use magnetic fields to

dump the I<sup>-</sup> ion on the extractor grid, much as the co-extracted electrons are dumped on the extractor grid by permanent magnets implanted in the extractor grids of the large H<sup>-</sup> and D<sup>-</sup> ion sources presently used in magnetic fusion experiments. The accelerator would need to be inclined at a slight angle relative to the extraction plane of the plasma so that the D<sup>-</sup> ion would continue while the I<sup>-</sup> ion would be stopped. Since the extraction stage energy is usually low compared to the total acceleration energy (5–6 keV for the extractor, compared to 370–1000 keV for the full acceleration potential), the decrease in the accelerator electrical efficiency would be small (0.5%–1.6%), and the effect on the overall beam system efficiency would be even smaller, since there are other power inputs besides the accelerator supply.

While it might be possible that this approach, if it should turn out to be useful, could be employed in cesiated negative hydrogen sources, it would be easier to try initially in an uncesiated source. This is because a halogen and an alkali can combine to form a salt, such as cesium iodide, so they might inactivate each other. If the rate of salt formation within the discharge chamber environment were slow enough, then the cesium and the iodide might co-exist, allowing the possibility of enhanced D<sup>-</sup> beam extraction from the higher D<sup>-</sup> densities possible in a cesiated ion source.

However, it would be fairly easy to try adding iodine vapor to an uncesiated hydrogen discharge (using the same sort of oven system that is presently used to inject cesium vapor), and then measure whether there is a large increase in the H<sup>-</sup> current density, which can be extracted. If there is even a moderate increase in the extracted H<sup>-</sup> current density, this would be of basic sheath physics interest, but if there is a large increase, it might be exploitable in large negative hydrogen neutral beam systems for ITER and other large fusion devices.

As a practical matter, it would be even easier to add chlorine to an uncesiated hydrogen discharge, since chlorine is a gas at room temperature. Thus, a good first experiment would be adding chlorine to an H<sup>-</sup> ion source to see whether the extracted current density of H<sup>-</sup> is significantly enhanced. If it is, then an oven for iodine vapor injection could be added.

## 5. Ion–ion plasmas in the warm dense matter regime

Previously, we have suggested that it should be possible to extend the halogen ion–ion plasmas studied in the recent negative chlorine beam experiments into the warm dense matter regime by heating a (cooled) iodine or bromine foil with a short high-power burst of heavy ions or laser light, producing a transient ion–ion plasma at much higher density than is obtainable in ion sources. While this should be of intrinsic scientific interest, it will, however, be harder to diagnose than the ion–ion plasmas produced in the chlorine beam experiments. This is in part because measurements on the beams of extracted positive ions, negative ions, and electrons provided insight into the plasma characteristics, and this diagnostic technique will not be available for the study of transient foil plasmas. An additional complication is that the tiny transient ion–ion plasmas produced from a foil will probably be surrounded by ordinary electron–ion plasma, which is likely to contaminate the results obtained by measurements of electrical or dielectric properties of the ion–ion plasmas.

Thus, since understanding how best to do experiments with ion–ion plasmas is likely to require some learning, it would be helpful to start with a target that is easier to fabricate and store than is an iodine or bromine foil, but which still contains large amounts of halogens. To this end, it might be good to start with a thin layer of salt deposited on a substrate of carbon or gold, two

fairly standard substrates, which also happen to be somewhat electronegative (although less so than halogens). While sodium chloride should be suitable, potassium chloride would have the advantage of constituents that have approximately the same mass during the first few nanoseconds of the expansion before the salt cloud is thoroughly mixed with the substrate cloud. A salt should be a suitable precursor for an ion–ion plasma, since half of its constituent atoms are halogens, and when used as an electrolyte in solution, a salt forms an analogue to an ion–ion plasma.

## 6. Summary

The experiments conducted so far to validate negative halogen beams as potential driver beams for inertial confinement fusion were successful in this goal. However, they also produced an interesting physical regime, ion–ion plasmas, and a novel way of inferring some of its properties by measurements upon extracted beams of the different plasma components. Further experiments could provide valuable additional insights into ion–ion plasmas, ion–ion sheaths, and whether it might be possible to extract very low-temperature beams of positive or negative ions to produce small focal spots for applications in heavy ion fusion, ion lithography, or production of warm dense matter. Adding a heavy halogen such as iodine to a tandem  $H^-$  ion source could test whether, by altering the ambipolar-diffusion-driven potential well for negative ions, more of the available  $H^-$  might be extractable. This should be fairly easy to test in an uncesiated  $H^-$  ion source,

and if successful there, it might also be possible to use halogen-enhanced extraction of  $D^-$  in a cesiated source.

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## References

- [1] L.R. Grisham, Nuclear Instruments and Methods in Physics Research A 464 (2001) 315.
- [2] L.R. Grisham, Fusion Science and Technology 43 (2003) 191.
- [3] L.R. Grisham, J.W. Kwan, S.K. Hahto, S.T. Hahto, K.N. Leung, G. Westenskow, Review of Scientific Instruments 77 (2006) 03A501.
- [4] L.R. Grisham, S.K. Hahto, S.T. Hahto, J.W. Kwan, K.N. Leung, Nuclear Instruments and Methods in Physics Research A 544 (1–2) (2005) 216.
- [5] L.R. Grisham, J.W. Kwan, G. Westenskow, Nuclear Instruments and Methods in Physics Research A 577 (1–2) (2007) 267.
- [6] I.D. Kaganovich, Physics of Plasmas 8 (2001) 2540.
- [7] M. Bacal, H.J. Doucet, IEEE Transactions on Plasma Sciences PS 1 (1973) 91.
- [8] P.D. Edgley, A. von Engel, Proceedings of the Royal Society of London A 370 (1980) 375.
- [9] I.D. Kaganovich, B.N. Ramamurthi, Demetre J. Economou, Applied Physics Letters 76 (2000) 2844.
- [10] Sant'Anna, et al., Plasma Physics and Controlled Fusion 46 (2004) 1009.
- [11] L.R. Grisham, IEEE Transactions on Plasma Science 33 (2005) 1814.
- [12] R.S. Hemsworth, J.-H. Feist, M. Hanada, B. Heinemann, T. Inoue, et al., Review of Scientific Instruments 67 (1996) 1120.