Halogens for negative ion beams and ion–ion plasmas

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Abstract

Negative ions have attractive features as drivers for inertial confinement fusion, because they will avoid electron cloud effects, and could be efficiently photodetached to neutrals after the final focus, which could also be beneficial in heating warm dense matter targets. The halogens have large electron affinities, and thus should be able to produce high current densities of relatively robust negative ions. Recent experiments comparing chlorine beams to argon beams using the same source, extraction optics, and diagnostics have demonstrated that Cl^- beams can be produced with similar emittance to Ar^+ beams, and with about $\frac{3}{4}$ the current density from the same configuration. The observed effective beam temperature of about $\frac{1}{3}$ eV, and the similarity of current densities show that negative halogen beams can meet the current density and emittance requirements of heavy ion fusion. The near equivalence of the Cl^- and $Cl^+ + Cl_2^+$ current densities reaching the Faraday cup after passage through a substantial line density of effluent gas demonstrates that beam losses in the higher vacuum of a heavy ion fusion accelerator should be acceptable. A number of lines of evidence show that negative ion–positive ion plasmas (hereafter ion–ion plasmas), composed primarily of negative and positive ions with a small population of electrons, were produced in the sources near the extractor plane. Since Cl, F, I, and Br should all show similar chemistry, any of these halogens should be suitable as fusion driver beams, and heating thin iodine or bromine foils may produce ion–ion plasmas in the warm dense matter regime.
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1. Introduction

The halogens, all of which are characterized by large electron affinities, afford unique opportunities as negative ion driver beams for heavy ion fusion [1–3], as targets for warm dense matter studies of ion–ion plasmas, and as potential heating beams for warm dense matter experiments. As drivers for heavy ion fusion, negative ions have the advantages over positive ions that they do not collect electrons in the beam potential well, and they can be efficiently photodetached to neutrals after the final focus, but before entering the target chamber. Negative ion beams are much less susceptible to the lower energy tails common to positive ion beams, which can engender emittance growth downstream. These tails arise from neutrals ionized by the beam either by charge exchange or impact ionization, which are then accelerated through only a portion of the electrostatic extractor potential.

For negative ion applications, halogens have the great advantage over other elements that they have higher electron affinities, and thus form negative ions much more readily, and since the extra electron is more tightly bound, it is also more robust in surviving the initial extraction stage from the ion source, where most single-electron stripping losses occur. The large electron affinities of the halogens (in the range of 3.1–3.62 eV for fluorine, chlorine, bromine, and iodine), combined with the fact that the ease of forming negative ions is a very strong function of the electron affinity, also makes them the most natural candidates for forming ion–ion plasmas (plasmas consisting of positive and negative ions, with relatively few electrons).

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This paper first reviews recent experiments demonstrating the feasibility of halogen-negative ion beams as heavy ion fusion drivers with regards to their current density and emittance, then reports a new analysis of additional data demonstrating the survivability of negative halogen ions, and discusses the evidence that the experiments produced ion–ion plasmas (plasmas consisting primarily of negative and positive ions with a minimal electron population) in at least one region of the ion sources. It then discusses the proposal which evolved out of these experiments to extend ion–ion plasmas to the warm dense matter regime by heating bromine or iodine foils with intense ion beams.

2. Current densities and ion optics from experiments

The experiments used chlorine as a representative halogen because, unlike bromine and iodine, it is a gas at room temperature, and it is more tractable to handle than fluorine (which can, for instance, form hydrofluoric acid that etches insulators). Since the halogens all share similar chemical properties and large electron affinities, a successful demonstration with chlorine should serve as a validation of the other halogens as well. Bromine plasmas were studied decades ago by Bacal and Doucet [4], but these authors did not extract beams from their plasmas. In the vapor phase, halogens form diatomic molecules, and, like hydrogen, can form negative ions by dissociative attachment of low-energy electrons to the diatomic molecules. Because the halogens' electron affinities are large compared to the 0.75 eV of hydrogen, they form negative ions much more easily by dissociative attachment than hydrogen, and unlike hydrogen, in which the process requires highly excited vibrational or robovibrational states, the halogens can also undergo dissociative attachment in the ground state [5]. In H^- source physics, this process is referred to as volume production, to distinguish it from sources to which cesium has been added, in which surface production of negative ions is believed to be the dominant formation mechanism [6,7].

2.1. Current densities in initial experiment

Since the halogen-negative ion formation process was expected to be a more efficient version of the process fostered in H^- volume production sources, a small RF-driven (12.56 MHz) source that had previously been used for volume production of H^- was used for the initial set of experiments. In common with other volume H^- sources, it incorporated a magnetic filter to partition the discharge chamber into a driver plasma which contained the RF antenna, and an extractor plasma with a lower electron temperature near the front of the source where the beam was extracted. An RF drive was used rather than a cathode-induced arc because of concerns that the highly electronegative chlorine would impede a traditional arc discharge.

As described in more detail in Ref. [8], extracting beam from a single on-axis aperture in this source produced a Cl^- current density that was linear in magnitude with applied RF drive power, and which reached a maximum of $45 \, mA/cm^2$ with only a 0.5% component of Cl_2^-, and no other contaminants. The maximum Cl^- current density was 79% of the total positive ion current density extracted under the same chlorine discharge conditions, but with the acceleration polarity reversed to extract positive ions. When oxygen, with an electron affinity of 1.46 eV was substituted for the chlorine (electron affinity of 3.61 eV), a maximum of $5.7 \, mA/cm^2$ of O^- was extracted, indicating a strong scaling of negative ion formation with electron affinity [8,9].

2.2. Current densities in second experiment

Although the initial Cl^- experiment demonstrated that the halogens could yield negative ion current densities adequate for heavy ion fusion driver applications, and gave some indication that the effective beam temperature was adequate (0.3 eV from a pepperpot measurement), some questions remained about the overall characteristics of negative halogen beams relative to more conventional positive ion driver candidates.

To address these issues, a new source was constructed, as illustrated in Fig. 1. This was, like the earlier source, a magnetic cusp-confined RF-driven (13.6 MHz) volume production source. In this case the driver plasma was separated from the extractor plane plasma by a pair of permanent magnets located 3.5 cm apart, and creating a filter field of 320 G cm, which had a peak strength of 179 G, declining to 68 G 1.05 cm downstream at the plasma grid. The extractor was a pair of plates separated by a gap of
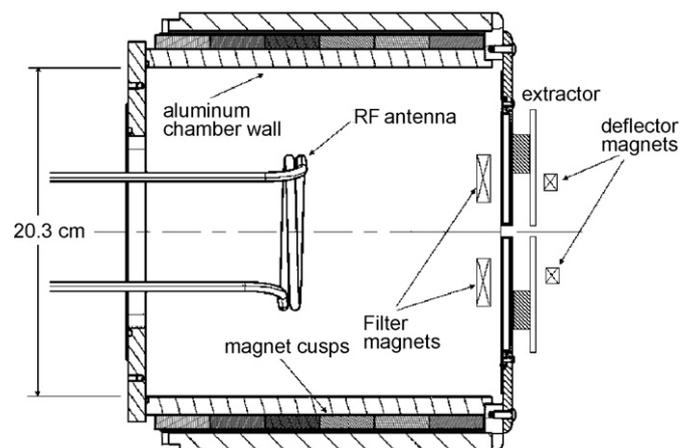

Fig. 1. Schematic of the ion source built for the second experiment comparing negative and positive chlorine with argon. As in other "volume production" H^- sources, the filter magnets shield the extractor region plasma from high-energy electrons in the driver plasma where the RF antenna resides [10]. Used with permission from L.R. Grisham, Rev. of Sci. Instrum. 77, 03A501 (2006). Copyright 2006, American Institute of Physics.

2 cm, and with a single on-axis aperture of 0.125 cm radius. In these experiments the beam pulse length was generally 20–50 μs. The co-extracted electrons were deflected from the Cl^- beam with a 275 G cm field produced by two permanent magnets located 2.9 cm downstream of the extractor ground plate [10].

Unlike the earlier source, which had copper walls, this source used aluminum, and the strength of the magnetic cusp field at the wall was about half that of the earlier source, due to thicker walls in the magnet grooves. This resulted in less efficient plasma confinement than in the earlier source and, coupled with the fact that the RF-driven power per unit volume in this larger source was lower, resulted in lower current densities being achieved than in the earlier experiment.

However, the principal purpose of this second experiment was to compare the current densities and emittances of Cl^-, Cl^+, and Ar^+ beams using the same source, extraction optics, Faraday cup, and emittance scanner, in order to eliminate the significance of any systematic errors in comparing the characteristics of a negative halogen beam to a conventional positive ion beam. Argon was selected as the comparison beam because it is quite similar in mass to chlorine, and thus could use the same extractor optics as chlorine. Since it forms few if any negative ions [11], the argon plasma would be a conventional electron–ion plasma, with extractor sheath characteristics representative of many candidate-positive ion driver beams. The beam could either strike a biased Faraday cup located 12.8 cm downstream for current measurements, or a dual-slit emittance scanner (slits at 10.7 and 33.7 cm downstream).

The principal result of this second set of experiments was that the beam current density and emittance of Cl^-, Cl^+, and Ar^+ were all quite similar under similar conditions. Although the absolute current density (13 mA/cm² of Cl^-) was lower than in the earlier experiment, due to the reduced confinement and lower RF power density, the relative current densities of the three beams differed only modestly. Under similar discharge and gas conditions, the Cl^- current was typically 85–90% of the positive chlorine current (consisting of Cl^+ and Cl_2^+), and the Cl^- current was as much as 76% of the Ar^+ current from a discharge with the same RF drive and nearly identical pressure. Fig. 2 shows the Cl^- current density as a function of RF drive power and extraction voltage.

The 70% normalized emittance (terminating the emittance plot where the beam intensity had fallen by 70% from the peak) gave the most well-behaved comparison of the emittance values, and it is characteristic of the beam core. Extending the emittance integrating areas to the point where the intensity had fallen by 90% gave sometimes erratic behavior due to noise, so the 70% cutoff was adopted for comparing beams. The Cl^-, $Cl^+ + Cl_2^+$, and Ar^+ emittances all behaved in a similar manner with similar values, and increasing with beam perveance, which is usually a sign that the ion extraction optics are
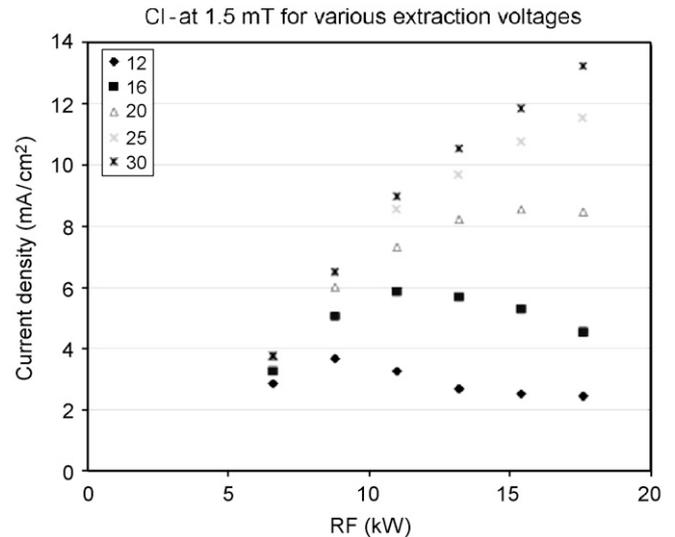

Fig. 2. Faraday cup measurement of the Cl^- beam density extracted at various voltages (in kV) as a function of RF plasma drive, at a source pressure of 1.5 mTorr [10]. Used with permission from L.R. Grisham, Rev. of Sci. Instrum. 77, 03A501 (2006). Copyright 2006, American Institute of Physics.

contributing significantly to the emittance. The only difference in behavior was that the Ar^+ emittance was insensitive to source pressure over the operating range of 2–5 mTorr, whereas the Cl^- and Cl^+ emittances tended to be modestly lower at higher pressures. The lowest normalized emittance at a given perveance was about the same for all three beams. As an example, at 0.09 nanopervs (A/V$^{3/2}$ × 10^{-9}), the 70% normalized emittance (four times the rms emittance times v/c) was 0.0049 pi-mm-mrad for Cl^- and $Cl^+ + Cl_2^+$, and was 0.0055 pi-mm-mrad for Ar^+, which was considered to be about the same as the chlorine emittance within the experimental uncertainty. Fig. 3 shows the 70% normalized emittance of the Cl^- as a function of perveance and source pressure.

If one assumes that at the minimum normalized emittance observed, all of the emittance is due to the beam ion temperature, and extends the emittance diagram to near 100%, then the inferred beam ion temperatures would be about one-third of an electron volt for all the beams, with the Cl^- and $Cl^+ + Cl_2^+$ temperature slightly lower than the Ar^+. However, within the measurement accuracy, the inferred temperatures were the same, since even at the minimum emittance the extractor optics is probably making a contribution, and that contribution may not be precisely the same for the chlorine and argon beams. A comprehensive display of the data obtained in this experiment can be found in Grisham et al. [10].

3. Beam attenuation

Within the heavy ion fusion community, there has always been some concern that negative ions would prove too fragile to transport over long distances without
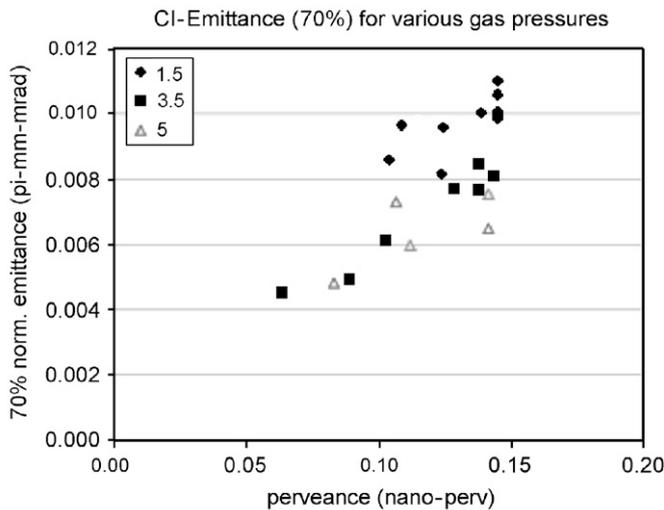
Fig. 3. Normalized Cl^- emittance at different source pressures (in mTorr) as a function of perveance [10]. Used with permission from L.R. Grisham, Rev. Sci. Instrum. 77, 03A501 (2006). Copyright 2006, American Institute of Physics.

unacceptably large beam stripping losses due to impact ionization of the additional electron, which is considerably less strongly bound than the next electron. This concern arises primarily from the experience within the magnetic confinement fusion energy neutral beam program. The magnetic confinement program is constrained to use beams composed of hydrogen isotopes for heating and current drive. Because hydrogen has an electron affinity of only 0.75 eV, and because neutral hydrogen has only a single electron, the cross-section for removing the extra loosely bound electron is substantially larger than either the cross-section for removing both electrons or for an H^+ ion picking up an electron through charge exchange. As a result, stripping losses due to impact ionization on source effluent gas are much larger in the accelerators used to produce H^- beams for magnetic fusion applications than are the charge exchange losses in H^+ accelerators for similar applications.

However, the heavy ion fusion program, unlike the magnetic fusion program, is not constrained to choose hydrogen beams. Thus, the beam attenuation advantage of positive relative to negative ion beams can be appreciably reduced through two avenues. One is by choosing negative ions which are more tightly bound than hydrogen. The high electron affinities of the halogens, the highest in the periodic table, which make F, Cl, Br, and I the best candidates for producing high negative ion current densities within the source, should also give them the best chance of surviving extraction from the source through the co-streaming source effluent gas. Single-electron stripping cross-sections typically decline with increasing velocity, and a difference in binding energy of a factor of 4–4.8 (for negative halogens vs. H^-) should make the largest difference in collisional stripping rates at the low beam energies of the extractor.

The other factor which reduces the beam attenuation advantage of positive relative to negative ion beams in heavy ion fusion is that heavy ion fusion beams are heavy, and even the lightest ions considered as drivers for inertial confinement have many more electrons than does hydrogen. At the low energies used for initial beam extraction, this large number of more tightly bound electrons is not very likely to suffer ionization, however, at the much higher energies in the main accelerator and compression region of a heavy ion fusion driver, this large electron cloud provides many targets for impact ionization, regardless of whether the ion is positive or negative, and multiple-electron loss collisions are in fact common [1,12,13]. Since any change in charge state during acceleration will result in beam loss, heavy negative ions have been estimated to undergo a factor of at most two to three times more loss in the main accelerator than heavy positive ions [14].

Nonetheless, at the low beam energies and high co-streaming gas densities characteristic of the extraction channel from a plasma ion source, stripping losses of negative ions will be at their most severe. Thus, it is interesting to ask what can be deduced from the negative halogen currents which survived extraction from the ion source and reached the biased Faraday cup ($+300\,V$ collector and $-300\,V$ suppressor).

The fact that, under the same discharge and gas conditions, the Cl^- current at the Faraday cup was 85–90% of the positive ion current (about 82% Cl^+, 18% Cl_2^+, and a few lighter contaminants, from measurements in the first set of experiments) indicates that the attenuation rate of the Cl^- could not have been very large compared to that of the positive ions. This is because the density of negative ions in the extractor plasma can never equal the positive ion density, since there must always be a minority of electrons to form negative ions by dissociative attachment. Thus, at most, only a few percent of the negative ions extracted from the source plasma could have been stripped on their way to the Faraday cup.

In order to estimate the implications of this for transmission through a high-energy accelerator environment, a 2D Monte Carlo code was used to roughly estimate the chlorine gas density profile through the 2 cm extraction gap and in the region just beyond it in the target tank. With a pressure of 1.5 mTorr of Cl_2 inside the ion source, which was the condition under which the most data was taken, the Cl^- which reached the Faraday cup had survived passage through roughly 1.2×10^{-3} Torr cm of chlorine gas. The fact that the calculation used a 2D code instead of a 3D code probably somewhat overestimated the line density, since the code included conductance parallel to the beam direction, but only a simple 1D conductance perpendicular to the beam between the extractor plates to the tank, so for purposes of this estimate we will reduce the line density to 8×10^{-4} Torr cm to allow for the extra expansion of the gas into the third dimension not included in the code. This should be fairly realistic, especially since the beam had to also survive passage through an additional

8 cm at the target tank pressure of a few times 10^{-5} Torr. At these low energies of tens of kilovolts, stripping cross-sections are approximately proportional to the geometric cross-section of the target gas, and Cl_2 is about twice the cross-section of N_2. However, some fraction of the chlorine gas flowing from the source is atomic chlorine, although much of this recombines to Cl_2 when it scatters off the extraction electrodes. If we assume that the average geometric cross-section of the chlorine along the beam trajectory is about 1.5 times that of N_2, then transporting the Cl^- beam through 8×10^{-4} Torr cm of chlorine gas with, at most, only slightly more loss than the positive chlorine ions, would be equivalent to transporting it at low energy through about 1.2 km of an accelerator with a residual background pressure of 1×10^{-8} Torr.

Since the average beam energy in the main accelerator of a heavy ion fusion driver would be many times higher than the 12–30 kV that was used in these experiments, the single-electron stripping cross-section would be much less than was the case here. This is because single-electron stripping cross-sections typically peak at low energies, and then rapidly decline at higher energies. In the case of H^-, for which the cross-sections are well known, the stripping cross-section is largest and slowly varying at energies up to about 300 eV, after which it declines steeply with beam energy, having fallen by two orders of magnitude at a beam energy of 4 MeV. The behavior should be fairly similar for Cl^-, except that the peak of the cross-section should occur at a higher energy because chlorine is heavier (11 keV Cl_{37}^- would have the same velocity as 300 keV H^-). Since Cl^- is almost five times as strongly bound as H^-, this would shift the peak of the cross-section somewhat higher still. Thus, the 12–30 kV Cl^- beam in this experiment was exposed to much higher single-electron stripping cross-sections than would be the case in the main accelerator of an inertial confinement driver beam. Accordingly, the Cl^- beam survived with little more loss than the positive chlorine beam experienced through the equivalent of high-energy passage along many kilometers of an accelerator with 1×10^{-8} Torr of residual N_2.

At the much higher energies in the main accelerator, multi-electron loss collisions [1,12,13], which are not a significant factor in the extractor, will contribute to the total cross-section for beam loss, but this component should be roughly 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 the electron cloud of a Cl^- is about the same as the electron cloud of an Ar^+. This becomes even more the case with heavier ions. Accordingly, the vacuum requirements for transmission of negative halogen beams with an acceptable loss rate in the accelerator and beyond should be only modestly more stringent than for positive ions of similar mass. This is in agreement with the results of a cruder line density estimate from the earlier set of Cl^- beam extraction experiments [8].

4. Ion–ion plasmas in Cl^- sources

Both sets of Cl^- source experiments produced results which implied the existence of an ion–ion plasma in the portion of the ion source between the magnetic filter and the plasma grid. A convenient feature of studying ion–ion plasmas in a beam source is that each of the plasma components—negative ions, positive ions, and electrons—can be extracted as a beam for analysis.

The first piece of evidence for an ion–ion plasma is the near equality of the negative and positive ion currents extracted from discharges with similar arc power and pressure. In the first experiment, the maximum Cl^- current was 79% of the positive ion current [8], and in the second experiment the Cl^- current was 85–90% of the positive ion current over the whole range of arc conditions except at the lowest RF power. The fact that the negative ion and positive ion currents as measured at the Faraday cup were almost equal suggests that the density of positive and negative ions in the extraction plane must have also been nearly equal, especially since at these low energies the negative ions would be expected to undergo more loss due to stripping reactions in the extractor than the losses the positive ions would suffer from charge exchange. In H^- ion sources, the addition of cesium produces large increases in H^- current density [7]. Adding cesium to the chlorine plasma in the first experiment had very little effect, suggesting that the negative ion density already filled up most of the negative charge phase space in the extractor plasma without the cesium.

The second piece of evidence supporting an ion–ion extractor plasma is the very low ratio of co-extracted electrons to Cl^- in both experiments. In the first experiment the lowest e/Cl^- ratio was about 7, achieved under the same discharge conditions with maximum RF power which produced the maximum ratio of $Cl^-/Cl^+ + Cl_2^+$ in the beam at the Faraday cup [8]. Similarly, in the second experiment, an e/Cl^- ratio of 6–7 was measured across most of the range of RF powers, rising only at the lowest RF powers [10].

Since in each of these experiments a single beamlet is extracted from only a small fraction of the plasma surface, one would expect that, in the absence of any magnetic suppression fields, the e/Cl^- ratio extracted in the beam would be similar to the ratio of their relative mobilities which, if the electrons and Cl^- were at the same temperature, would be the square root of their mass ratio, which is about 240. In most sources, the electron temperature is higher than the ion temperature, and if that is the case here, then it would drive the expected mobility ratio even higher. Since the measured e/Cl^- ratio was about 35 times smaller than the mobility ratio for equal temperatures, this strongly suggests the presence of an ion–ion plasma consisting of Cl^-, Cl^+, and Cl_2^+, with little room in space charge phase space for electrons.

A third piece of evidence comes from comparison of the chlorine results to the current ratios obtained using oxygen

discharges in the small source used for the first set of experiments. Like hydrogen and the halogens, oxygen is a diatomic gas which can form negative ions by dissociative attachment of low-energy electrons. With an electron affinity of 1.46 eV, it is almost twice as electronegative as hydrogen, but nonetheless much less electronegative than chlorine's 3.61 eV electron affinity. The maximum ratio of $O^-/O^+ + O_2^+$ achieved was 0.25, much less than with chlorine, demonstrating that the ability to form an ion–ion plasma is a very strong function of the electron affinity. This was further borne out by the fact that the lowest e/O^- ratio was 300. Since this ratio exceeds the equal tempera-ture mobility ratio of 160, it suggests that, as would be expected, the electrons in the extractor plasma are indeed hotter than the negative ions.

It also demonstrates another important feature. The e/O^- ratio of 300 was obtained with the same magnetic filter configuration in the source as was used to obtain the e/Cl^- ratio of 7. This clearly shows that the low ratio of co-extracted electrons in the chlorine case is primarily due to the presence of a negative ion–positive ion plasma with relatively few electrons, and is only weakly due to suppression of electron extraction by the fringing magnetic filter field at the extraction plane.

The fact that the fringe field from the filter was not the primary cause of the low ratio of co-extracted electrons to Cl^- is further confirmed by the observation in the first experiment [8] that, when the distance between the filter magnets and the plasma grid was tried at distances of 1.1, 1.6, and 2.1 cm, the lowest e/Cl^- ratio occurred not at 1.1 cm, which would have corresponded to the strongest magnetic field in the extraction plane, but rather at 1.6 cm.

A final piece of evidence supporting the presence of an ion–ion plasma is the lack of response when the plasma grid was biased positive relative to the plasma. In volume sources of this sort producing H^-, such a bias can increase the H^- current by a factor of 2, while reducing the co-extracted electron current [15,16]. Applying a bias to the source in the first experiment while running oxygen produced a 20% increase of O^- and a 25% reduction of electrons at the maximum voltage of 15 V. With chlorine, a bias of up to 40 V did not alter the Cl^- current appreciably, and reduced the electron current by only 10%. This appears to confirm a reduction in electron content of the extraction region plasma as more electronegative gases were used.

5. Extension of halogen ion–ion plasmas to the warm dense matter regime

Since the results described in the previous section were, both individually and collectively, strongly indicative of the production of ion–ion plasmas with relatively few elec-trons, it was natural when interest in warm dense matter studies arose within the heavy ion fusion program in 2004 to propose producing halogen ion–ion plasmas by heating micron thickness bromine or iodine foils with a brief

intense ion beam. Bromine and iodine are the most plausible choices for experiments using foils because, while the physics of negative ion formation should be similar for all the halogens, bromine and iodine have the advantage that they are solids at room temperature. While the foil could be heated by a number of methods, the one that would work best with moderate cost ion beam facilities would be to use the method of dE/dX peak heating. In this technique, the beam energy and target thickness are chosen such that the beam enters the target at an energy just a little higher than the energy of the top of the dE/dX peak, and leaves at an energy just a little below it. Since, by definition, the slope of dE/dX goes to zero at the peak, this approach simultaneously ensures the maximum uniformity of heating through the target, as well as the highest rate of energy transfer from the beam to the target [17]. Evidence for the existence of high-density ion–ion plasmas has already been observed in laser-heated gold foil targets [18].

The concept of the experiment is to heat the foil hot enough to produce a weakly ionized plasma, several tenths of an electron volt, and allow processes similar to those in an ion source to take place. Since the halogens can form negative ions by dissociative attachment of low-energy electrons to ground state molecules, the lack of a separate driver plasma with high-energy electrons to excite high vibrational states in molecules should probably not be a fatal impediment. Similarly, with a foil target, the lack of a magnetic filter field to block high-energy electrons from the region of interest should not matter much, since the only high-energy electrons will be those stripped from the passing beam, and these should leave the small volume of the heated foil on a time scale much shorter than the foil expansion time. If a large fraction of the low-energy electrons dissociatively attach to molecules to produce negative ions, as appears to happen in the extractor plasmas of the chlorine experiments, then a weakly ionized plasma may form consisting of positive and negative halogens, comparatively few low-energy electrons, and a lot of neutral molecules.

In most respects, this might be a less interesting state of matter than the ion–ion chlorine plasmas we have recently produced in sources, since ion source plasmas are typically several percent ionized, more than these are likely to be, and the physics governing the negative ion production in the ion sources is much more clearcut. However, the ion source plasmas, which, although pulsed, are effectively steady state on the time scale of molecular processes, must always have a minority component of low-energy electrons to maintain the dissociative attachment process. Because the warm dense matter bromine or iodine plasma would be produced in a tiny region (a 1 or 2 mm radius area in a foil about 1 mm thick) from a beam burst only one to a few nanoseconds in duration, there may be some chance for some of the low-energy electrons, which will have velocities large compared to the much heavier halogen molecules, to move out of the central core of the expanding target, leaving a very small region in which essentially all the

charge carriers are positive and negative ions immersed in a sea of neutrals. Since overall charge neutrality must be conserved, the electrons cannot travel far from the core, so it is not clear whether any totally electron-free region might be achieved, even a tiny one.

One of the more interesting characteristics of such a region is that, like the electrolyte in a battery, it should exhibit ionic electrical conductivity. In principal, it should be interesting to measure the conductivity of this region as it evolves from an ion–ion plasma with a few electrons to an essentially electron-free plasma. In practice, it is hard to conceive how such measurements could be made with the nanosecond-scale resolution required. Moreover, the presence of any free electrons in the surrounding plasma, which would almost certainly always be the case, would completely dominate any conductivity measurement, since electrons are hundreds of times lighter than bromine or iodine.

Nonetheless, because bromine or iodine ion–ion plasmas in the warm dense matter regime would form an interesting comparison to the ion–ion chlorine plasmas produced in a much lower density regime in the sources, it is interesting to ask what sort of beam might be required using the dE/dX heating peak approach. Ref. [17] considered a number of beam scenarios for dE/dX peak heating. As an example, a 1 MeV He^+ beam extracted from a 5 cm radius multi-aperture source with operating parameters characteristic of existing tokamak heating systems, could deposit 1.5×10^{11} J/m^3 in a 1 mm radius region extending through a 1 μm foil with a longitudinal uniformity of 4%. This would require using plasma neutralized drift compression to compress a 200 ns beam pulse to 1 ns, and a very strong focusing element, such as a plasma lens, to focus it [17].

This should produce a temperature of approximately 0.3 eV in the target. The hydrodynamic transit time in a 1 μm target would be about one-third of a nanosecond [14], so the deposition would not be isochoric, but the expanding plasma, if it is an ion–ion plasma, could still be interesting. The heating could be closer to isochoric if, for instance, a 3 μm target were used with a 1.6 MeV He^+ beam. However, both the factor of 200 beam compression and the strong focus to a small point required have not been demonstrated with any beam at this time. In the nearer term, approaches using existing facilities, and which do not fully take advantage of the dE/dX heating approach, may be used.

A scenario for a warm dense matter experiment which would use halogens as both the target and the heating beam would be to use the dE/dX peak heating approach on an iodine or bromine foil with a fluorine beam. The advantage of the fluorine beam would be that, as a halogen, it could provide a high current density of F^- which could be photodetached after the final focus. If the warm dense matter target chamber were at a pressure of 10^{-5} Torr or less, the beam should be able to focus to a very small spot, since it would be free of space-charge. The drawbacks of this approach are that it would probably require pulse compression without space charge neutralization, and it would require a beam energy of about 15 MeV to access the dE/dX heating peak.

6. Conclusion

These experiments have demonstrated that the halogens can produce negative ion beams with current densities and emittances adequate for heavy ion driver applications and perhaps also as a heating beam for warm dense matter studies. Moreover, the emittance is similar to that of an argon beam produced from the same source configuration, and the current density is not greatly less.

Several lines of evidence show that the plasma in the region of the ion sources from which the beam was extracted was an ion–ion plasma composed primarily of Cl^-, Cl^+, a smaller amount of Cl_2^+, and a minority component of electrons. This is a novel state of matter, at least from the point of view of one accustomed to conventional electron–ion plasmas. A conventional plasma, with few negative ions, consists of nearly equal amounts of of bosons and fermions, with an enormous mass difference between the positive and most of the negative charge carriers. In these chlorine ion–ion plasmas, both the positive and most of the negative charge carriers are bosons, and the positive and negative charge carriers have nearly the same average mass, and thus are almost mass-symmetric.

An ion–ion plasma might be expected to have a lower effective ion temperature than would a conventional ion–electron plasma at similar discharge parameters, due to a reduced ambipolar potential [19,20] arising from the much greater average mass of the charge carriers. In the case of an ion source, this could have significant practical implications, since it might allow extraction of lower temperature negative or positive ion beams that could be more finely focused than beams from ion–electron plasmas. Such cold beams would be useful as heavy ion fusion drivers or for semiconductor fabrication using ion lithography. In these experiments, the observed effective ion temperatures of all the beams: Cl^- and Cl^+ from an ion–ion plasma, and Ar^+ from an electron–ion plasma, were low, about one-third of an electron volt, but they were also all about the same.

One explanation might be that ion–ion plasmas are not colder than analogous electron–ion plasmas, but a more likely explanation is that the emittance had a significant contribution from the extractor optics which masked the differences in intrinsic ion temperatures. These experiments were performed with circular aperture optics. It is hoped that these experiments can be repeated with a slot beam someday, in which the beamlet is much longer than it is wide. Measuring the emittance in the direction parallel to the long direction of the slot would give an emittance value which, except for slot end effects, would reflect just the beam ion temperature, and thus should have a better

chance of observing ion temperature differences between ion–ion and ion–electron plasmas.

The study of ion–ion plasmas can probably also be extended to the warm dense matter regime by heating thin foils of bromine or iodine.

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