CHARACTERISTICS OF A SELF-EXTRACTION NEGATIVE ION SOURCE

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ABSTRACT

A multi-cusp, self-extraction, negative hydrogen ion source has been designed and constructed. Several diagnostic techniques have been applied to study the operating characteristics of this type of source. Negative H⁻ and D⁻ ions are produced on a negatively biased converter surface, and are self-extracted from the system. With the addition of cesium, the source has been operated at a neutral pressure of 1 x 10⁻³ Torr to generate a steady-state H⁻ ion current greater than 400 mA. The generation of impurity negative ions has been investigated, as have methods for reducing the presence of background electrons in the ion exit region. Plans for a larger, next-generation device will be discussed.

INTRODUCTION

Subsequent to the first meeting of this Symposium, we began the development of a concept for a negative ion source geometry which was conceived to produce continuous beams of self-extracted, surface produced, modest current density, negative hydrogen or deuterium ions. Because the self-extracted ion current density is not meant to be high (≤50 mA/cm²) large ion exit apertures are required in order to obtain the multi-Ampere beams of negative ions that will eventually be required for neutral beam injection. This in turn, means that the plasma source must be capable of operating at a low pressure. With this requirement in mind, the multi-line cusp geometry, which is known to operate with good gas efficiency, was chosen as the basic plasma generating system. The self-extraction feature was desired as it meant that no external electric fields would be required to extract the negative ions from the source plasma. The absence of such fields should greatly reduce the contamination of the beam with the unwanted electrons which are also extracted from the plasma when electric fields are applied.

APPARATUS

Fig. 1 is a drawing of the initial test geometry. The device is a cylindrical multi-line cusp arrangement (20-cm diameter and 23-cm long) with rows of samarium-cobalt magnets (B max=4 kG) placed externally around the chamber wall on all sides. In the region of the exit aperture, where the negative ions are to self-extract from the source, the spacing of the magnets has been increased. The magnetic field in this region is adjusted to be strong enough to contain all energetic electrons, which may have energies as high as 300 eV, yet weak enough to not seriously perturb the trajectories of the energetic negative ions, which are produced at the surface of the converter. The resulting cusp magnetic field pattern, mapped by iron filings is illustrated in Fig. 2 (A). A plot of the level of magnetic field, which shows the effect of the increased spacing of the magnets in the ion exit region, is shown in Fig. 2 (B).

A steady state hydrogen or deuterium plasma is generated by 60 to 70 eV primary electrons emitted from two 0.15-cm dia. tungsten filaments. The filaments are mounted on feed-throughs mounted on each of the two end plates. The entire chamber wall, which is at ground potential, serves as the anode for the discharge. The source pressure is maintained at 1 milli-Torr or less as measured by a Barocel. With an arc current of 45 A, plasma densities higher than a few x 10¹² can be generated. To produce negative ions, the converter shown in Fig. 1 (6 cm high and 10 cm long) is biased negative with respect to the...
potential of the plasma by several hundred volts. Positive ions from the plasma strike the surface of the converter with this potential. Any negative ions that are produced at the surface of the converter are then accelerated back through the sheath by this same bias potential, and are directed through the plasma to the ion exit aperture. The bias potential on the converter thus becomes the ion extraction potential. In order to increase the number of negative ions produced, the area of the converter is increased by making the height of the converter larger than the height of the extraction aperture, and the converter is curved to geometrically direct the ions to a focus at the position of the extraction aperture.

In a preliminary study, the source was operated with a clean copper converter and negative ions which were generated by reflection from the unconsolated copper surface were monitored by a compact mass spectrometer. These results have been discussed by Leung at this symposium, and a photograph of the source, and the spectrometer is shown in Fig. 3. The converter was operated with potential as high as -500 volts, but the spectrometer indicated that no energetic electrons, including secondaries from the converter electrode which would have energies equal to the converter potential, were escaping from the source.

With the spectrometer removed, a probe was installed in the ion exit region, and to our surprise, it indicated that there was a plasma present in this region. Although the plasma density was nearly 2 orders less than that of the discharge region, its presence was indeed a disappointment as it meant that should an electric field be applied to accelerate the negative ion beam, electrons too would become a part of the beam. The probe study further indicated that the electrons in the exit region were very cold (−1 eV), and that their numbers were a function of the potential of the plasma in the discharge region. This is illustrated in Fig. 4, where probe traces taken at the center of the discharge are compared to probe traces taken just outside the ion exit aperture for two slightly different levels of plasma potential. For the probe traces marked A, the plasma potential is -6 volts positive in respect to the grounded chamber anode wall, and a plasma with a density of about two orders less exists in the ion exit region. When the potential of the source plasma was made just slightly positive in respect to the chamber wall, the density of the plasma in the ion exit region reduced by an additional two orders of magnitude, and this is shown in the probe traces marked B. These results point out the fact that while the confining magnetic field at the exit region is ample to return energetic electrons to the discharge, it is too low to
Fig. 4. Langmuir probe traces obtained at (a) the center and (b) the exit of the source for two different plasma potentials (A & B).

prevent the leakage of low energy ions from the discharge. Ion confinement by this magnetic field is not only a function of the charge, mass, and energy of the ion, but also a function of the magnitude and polarity of the electric field that exists between the volume of the plasma and the exit structure. The cold electrons found in this region could either diffuse across the magnetic field with the positive ions, or they might possibly be produced by photons that illuminate surfaces near the exit region. In either case, the electrons can be suppressed by a potential which would be expected to extract them from the discharge. In reality, the electrons are suppressed by preventing the entrance into the exit region of low energy positive ions from the discharge.

We did not wish to add to our list of operating requirements that the plasma potential be maintained negative to the chamber wall at all times. The results shown in Fig. 4 suggested that the same effect could be obtained by installing an exit aperture that could be biased slightly positive in respect to the potential of the plasma. Aperture plates were installed and the arrangement is shown schematically in Fig. 5. Probe traces, taken in the exit region as the bias of the exit aperture is changed, are shown in Fig. 6. The plasma density is only weakly affected as the aperture bias is changed from 0 to -10 volts, but with a +10 V bias, the plasma in this exit region is essentially eliminated.

Fig. 5. Source geometry with the biased aperture electrodes added.

Fig. 6. Plasma density as indicated by probe traces with -10, 0, and +10 volts applied to the aperture electrode.

The data shown in Figures 4 and 6, were taken with the source operating with an uncesed copper converter and with hydrogen gas. High mass ions can more easily penetrate the weak exit magnetic field and when cesium is added to the discharge, positive cesium ions (mass = 133) will be present. To determine whether the biased exit aperture would be effective in returning such large mass ions to the plasma, xenon gas (mass = 131) was added to the discharge. The results are shown in Fig. 7 where once again, no plasma exists in the exit aperture region when a positive bias of about +10 volts is applied to the exit aperture. When cesium is added and negative ions are produced, the potential in the exit region may become negative due to the space charge of the beam.
The mass spectrometer was also used to measure the $\text{H}^-$ ion yield for several other alkali metals. It was found that the addition of lithium to the discharge increased the $\text{H}^-$ ion yield by a factor of ten over the yield obtained from a clean copper surface, and for sodium, the yield increased by nearly a factor of fifty.

The change in the ion energy spectrum which is evident in Fig. 8, will be discussed by Leung at this Symposium (4).

**Impurities**

Negative ions other than $\text{H}^-$ and $\text{D}^-$ can also be generated at the converter surface. While using the mass spectrometer and a copper converter, the impurities were found to be largely $\text{O}^-$, $\text{OH}^-$, and a mass 25, which is believed to be $\text{C}_2\text{H}^+$. The impurity level is directly related to the system cleanliness, and can be very high (typically 75%) when a new uncesiated converter is first employed. Higher impurity levels are also observed when the source has been inoperable for a period of time. We normally operate the source without cesium until the impurity level has decreased. When cesium is introduced into the discharge, the $\text{H}^-$ ion current increases markedly, but there is generally no large increase in the impurity level. The electron binding energies of the main impurities observed are considerably higher than that of $\text{H}^-$. Thus these impurities can be formed more easily than $\text{H}^-$ with an uncesiated converter. In addition, it is possible that impurities in the system may be pumped by cesium that is trapped on the walls of the source. Because impurities can represent a sizable fraction of the total negative ion beam, total beam current readings are taken in a manner in which the impurity level can be discerned. Fig. 9 is a drawing of the grid Faraday cup that is used to read the total negative ion current. A 72% transparent fine mesh tungsten screen is biased approximately 15 volts negative to collect any low energy positive ions, and the collector plate is biased positive by 18 volts to collect any secondary electrons. These potentials were determined by varying the two bias potentials to obtain a zero reading on the cup in the presence of a plasma that contained no energetic negative ions. In addition, a portion of the beam is sampled by a small mass spectograph constructed from a pair of iron shielded permanent magnets. The magnet is designed to bend both $\text{H}^-$ and $\text{D}^-$ ions so as to be received by one collector, and all other impurity ions from mass $\approx 12$ are received by a second collector. Figure 10 is a read out of the three currents taken as the source is started up and adjusted for maximum $\text{H}^-$ output. As can be seen, the impurity level, which started out at about 40%, of the total negative ion current dropped to 1% or so in about 10 minutes when the reading was terminated. The total negative ion current,
which is now mostly $H^-$ continued up to ~450 mA as source adjustments were continued.

![Faraday Collector Diagram](image)

**Fig. 9.** Faraday collector including impurity analyser

![Chart of total negative ion current and the change of impurity level with time](image)

**Fig. 10.** Chart of total negative ion current and the change of impurity level with time.

**CONVERTER**

The mechanism by which negative ions are produced on the surface of the converter once cesium has been added to the discharge has yet to be fully understood. Thus one is unable to state the characteristics that the converter material should possess in order to obtain the best yield of $H^-$ ions. Therefore, we conducted an empirical study, the results of which will be discussed by Leung.\(^4\) In addition to producing the maximum yield, a number of other parameters deserve close consideration. The sputtering rate of copper for example, the first converter material that we tried, is very high, and only short periods of operation were required to completely coat the entire source system with a layer of copper. To minimize sputtering, the use of high mass elements in the region of tungsten(6) is best as they exhibit the least sputtering rate for ion energies in the range of a few hundred volts. The sputtering rate for 300 volt $D^+$ ions on copper (mass=63) is more than two order of magnitude larger than the sputtering rate for tungsten (mass=184).

Cesium ions which strike the converter will have a sputtering rate that may be several orders of magnitude higher than that of deuterium, thus sputtering of the converter is an important consideration. In order to minimize sputtering, elements such as hafnium and tungsten would seem to be the best materials.

It is indeed possible that the converter material itself could appear as a contaminant negative ion. Thus one would desire the electron attachment energy of the converter to be low so as to minimize the probability of negative ion formation.

To minimize converter material as a negative ion contaminant on the basis of the electron attachment energy, hafnium or rhenium would appear to be the best choice. One would not wish to choose platinum as it has a very high electron attachment energy. Work function is important as it may relate to the ability of the material to contain cesium on the surface. Of the metals tested we have selected rhenium and molybdenum our best converter materials. Rhenium is a high mass material, with a high work function, and a low electron attachment energy. In our tests, reproducibly rhenium and molybdenum were the materials that produced the largest yield of $H^+$. Although we prefer rhenium, it is both very expensive and difficult to fabricate, thus the majority of our test data has been obtained using molybdenum converter surfaces.

**Operating Characteristics**

The arc power supply available for use with this experiment is a constant voltage type. Thus any changes in arc impedance are reflected as changes in arc current as the arc voltage is held constant at about 70 volts. Changes in arc power are therefore made by controlling the filament temperature, hence the arc current.

The converter potential, though adjustable, is generally maintained at about ~200 volts. This is the approximate bias potential that is the most productive of negative ions, regardless of the material from which the converter is constructed. The sides, rear, and entrance support of the converter are covered with a floating quartz housing. Thus, the
converter current that we monitor is made up of positive ions striking, and negative charges leaving the curved front converter surface only.

The arc current and the converter current are sensitive to the mass of the gas. For example, if cesium is added to the discharge, the arc impedance becomes less and the arc current increases. Operation with deuterium as well reduces the arc impedance and the impedance will be further reduced as cesium is added.

Operating with hydrogen only, the converter current will read approximately 15% of the arc current. When cesium is added, the converter will read about 25% or less of the arc current. For example, with an arc current of 40 A, arc voltage of 70 volts, and a converter current of 10A, we typically read 400 mA of H-. With a 3.5-cm high limiting exit aperture our best stable operation is with an H- output of about 450 mA. Without a limiting aperture, 500 mA is readily obtained. We have on occasion, produced H- outputs as high as 700 mA, but in general, these are not easily reproduced or available for long time, stable operation. Fig. 11 is a recorded output of the Faraday cup showing stable operation at the 450 mA level, despite several sparks from the converter to the plasma.

Fig. 11. Chart of Faraday output showing the effect of converter sparking.

Converter spotting will generally clean up, however one arc every few minutes is not unusual. We have a spot-detector circuit incorporated in the converter supply, which is designed to sense a spot or unipolar arc, reduce the voltage level for a few milli-seconds, and then reapply the voltage. Stable operation of the biased converter with cesium present in the discharge has not been as difficult a problem as we expected it to be.

In so far as the arc conditions change when one uses deuterium gas, it is difficult to make accurate comparisons between D- and H- yields. But if we use the converter current as a comparative parameter, we do see a definite isotope effect. In general, the production of D- is less than H- by very roughly \sqrt{2}.

BEAM SHAPE

A small movable grided Faraday cup was constructed which could scan the beam height to determine the effect of the geometric focussing. Fig. 12 is a plot of the ion beam shape taken at several distances from the converter. Fig. 13 compares the FWHM of these measured beam shapes with a geometric projection of the converter geometry.

Fig. 12. Beam shape at several distances from the converter.

As can be seen, the beam rather closely follows the design geometry. If all negative ions formed on the converter surface left the surface with zero energy, the geometry should fully control the ion trajectories, however those ions which have appreciable initial
Fig. 13. Measured beam widths (FWHM) compared to the converter geometry.

energy, such as those produced by reflection, are not confined to the geometrically determined path.

The program goals, as established by the review panel of the recently convened Negative Ion Program Review, are to accelerate an H-ion beam of \( n \) A to an energy of \( \leq 50 \) keV with pulse lengths from 5 seconds to steady state. In order to meet these goals we are constructing a larger source, accelerator, and vacuum system. A stainless steel chamber (approx. 4' x 5' x 2') will serve as the main vacuum vessel and will be pumped by two turbo-molecular pumps for source operations. Two auxiliary liquid helium cryo-pumps (\( \sim 12,000 \) L/sec ea.) will be added for beam acceleration studies.

Figure 14 is a drawing of the negative ion source. The shape of the source is designed to be scaleable in both \( x \) and \( y \) in order to obtain larger negative ion currents than from just the one converter shown. By increasing the vertical height, and maintaining the magnet spacing shown for the single exit aperture, additional ion exit apertures could be added, along with additional converter electrodes which would be placed above and below the single one shown. The magnet mounts, which also include the mechanical stiffeners needed to support the vacuum load, are sized to contain available ceramic or samarium cobalt magnets. This will allow us to adjust, by roughly a factor of two, the cusp magnetic field strength at the exit aperture. The use of the stronger magnets is detrimental only in that the ion beam is moved sideways farther in the direction of \( E \times B \). As can be seen in Fig. 2, the direction of the magnetic field changes as the ion moves through the exit aperture, and the \( E \times B \) motion given to the ion on one side of the magnet is removed on the other side. Thus after passing through the magnetic fields at the exit aperture, the beam emerges with a trajectory that is normal to the converter, but moved sideways by an amount that is proportional to the magnitude of the magnetic field and the ion energy.

Fig. 14. Side view of "next generation" source geometry.

This can be as much as several centimeters, and thus a provision has been made to position the converter sideways by a like amount. The water cooled converter is 8 cm (the dimension shown) by 25 cm.

The exit aperture, which is electrically isolated so that a bias potential can be applied, is mechanically adjustable such that the width of the defining exit aperture can be changed from 3 cm. to nearly closed. The slit will be made as narrow as possible so as to reduce the gas flow rate, yet not so narrow as to impede the exit of optically useful negative ions.

The source design incorporates feedthroughs for 8 tungsten filaments (0.15-cm dia.) with four located at the top and four at the bottom of the chamber. The filaments are distributed so as to provide a uniform plasma illumination of the converter surface. Initially, cesium will be fed from an oven through a single, resistance heated, coaxial tube located below the ion exit slit. The cesium will be sprayed into the discharge rather than directly onto the converter surface.

The beam defining electrode of the single stage accelerator has an opening of 5 cm. The accelerator geometry was computer designed.
using the WOLF code, (8) and is designed for a uniform H+ ion density of 8 mA/cm² at 40 kV. The design, which will be refined when the beam shape has been fully determined, will be discussed by Anderson (9).

The design of source and beam diagnostics, including a water-cooled calorimeter is underway.

REFERENCES

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