DESIGN CONSIDERATIONS FOR HIGH-INTENSITY NEGATIVE ION SOURCES

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Abstract

The production of negative hydrogen ions (H^-) by an ion source similar to that employed in many cyclotrons has been studied. The negative ions are extracted directly from the arc plasma in a direction normal to the magnetic field without use of a charge-exchange medium. In an attempt to improve the negative-ion yield, the arc-discharge chamber has been modified to conform to assumptions made as to the probable formation mechanism of the observed negative ions. Outputs of negative hydrogen ions in excess of 5 mA have been obtained. Ion-source operating parameters are discussed, as well as considerations for the utilization of this discharge geometry by negative-ion cyclotrons.

It has been shown that the difficult problem of extracting the beam from a cyclotron, in particular the isochronous or sector-focusing type, is greatly simplified by accelerating negative ions.[1, 2] Stripping the two electrons from fully accelerated negative hydrogen ions by means of a thin foil located near the final radius of the machine causes the ions to deflect in the opposite direction and to effectively become self-extracting. By stripping but one electron from each negative ion, a beam of energetic neutrals can be had; the energy can be varied by changing the radius location of the stripping foil.

The simplicity of this method compared with other methods of extracting the beam from a cyclotron has created interest in sources of negative ions that are suitable for use in cyclotrons.

In the ion sources developed for use with Van de Graaff accelerators, positive ions are extracted from a discharge plasma with an energy of about 10 keV.[3, 4] The negative ions are then produced either by the capture of electrons by the atomic ions or by the dissociation of molecular ions as the positive ions pass through a gas-filled region. About 2% of the positive ions are converted to negative ions by this process, and beams of several hundren μA have been produced in this manner. This system, however, is not easily adapted for use in a cyclotron.[5]

A need for negative hydrogen ions for use with the Berkeley heavy-ion accelerator (Hilac) instituted an investigation of the output of negative ions from more conventional ion sources. In these experiments, an unexpectedly large output of nearly 500 μA of negative deuterons was extracted directly from the ion source normally used with the machine.[6] This source, designed to produce multiply charged heavy ions, generated negative ions directly and without the need of a charge-exchange medium or gas-filled region.[7] An ion source similar to the one used in the Berkeley 88-inch cyclotron was used to produce more than 1 mA of negative deuterons.[8] The sources used in this investigation employed the Penning-type (PIG) discharge, in which the discharge plasma column is confined by a magnetic field and the ion extraction is radial or normal to the magnetic field.[9]

A complication, however, is that to obtain these high yields of negative ions, a rather high rate of gas flow to the ion source is required. The resulting high background pressure, particularly in the immediate region of the ion source, can in turn act as a stripping medium for the weakly bound (0.755 eV) electron. Thus a good vacuum is essential if one hopes to accelerate an appreciable percentage of the available negative ions to full energy,[10] and any large increase in gas flow through the source must in turn be accompanied by additional vacuum pumping capability.

Because of the rather encouraging results of this work, however, an attempt was made to determine if the ion source geometry could be altered to favor the production of negative ions at reduced gas flow rates.

In this method of formation, the negative ions are formed within the discharge region, and are probably the result of collisions of electrons with neutral gas molecules. The cross sections for reactions of this kind have been measured by Schulz,[11] and his results are summarized in Fig. 1. The solid curve at less than 13.6 eV is associated with the reaction

$$H_2 + e \rightarrow H^- + H.$$

The formation of negative ions indicated by the dashed curve with a peak at about 6.8 eV is observed when reagent-grade hydrogen is introduced without a liquid nitrogen trap. It is interpreted as the production of H^- from water vapor present in the gas. It seems unlikely that this effect could be amplified by using a mixture of gas and water vapor, because of the extreme narrowness of the energy spectrum of electrons effective in the reaction. The sharp peak with a maximum at 14.2 eV is attributed to the reaction

$$H_2 + e \rightarrow H^- + H^*.$$

This reaction results in an excited hydrogen atom in addition to a negative ion. Above 17.2 eV the electron has sufficient energy for the production of both a positive and a negative ion, and this energy is then the threshold for the reaction

$$H_2 + e \rightarrow H^+ + H^- + e.$$

This reaction shows a rising cross section at the highest electron energies used by Schulz. Measurements at higher energies by Khvostenko and Dukel'skii show that the cross section is still rising linearly at 38 eV, the highest energy for which these measurements are available.[12] These data, which are included in Fig. 1, indicate a cross section in excess of 3.5×10^{-20} cm^2 at this point.

Each of the reactions discussed in connection with Fig. 1 can contribute to the H^- production; however, it is the simultaneous production of H^- and H^+ above 17.2 eV that would seem by far the most important. Here the cross section remains high over the broad spectrum of electron energies that are available in the ion source. It is perhaps more important, however, to recognize that each reaction requires the presence of hydrogen in molecular form. Any of the many competing processes within a discharge which results in either the ionization or dissociation of the required molecular state will be detrimental to negative ion production.

If the reactions described are important for production of the negative ions observed, it would seem that special attention should be given to maintaining an abundance of molecular gas in the immediate region of the arc, from where the negative ions are to be extracted. In the previous investigation using hot cathode sources, the gas was fed into the arc chamber near the cathodes, and -- as with most ion sources designed for high current output -- the arc plasma column was located immediately behind the ion exit slit. In line with the above reasoning, neither condition would seem to be ideal.

The attempt to incorporate these considerations into an ion source geometry is illustrated in Fig. 2. Gas is fed into the arc chamber directly in the region of the ion-exit slit. In addition, the plasma column has been defined so as to be recessed from the ion-exit slit. This allows the incoming molecular gas to completely surround the discharge column in the region where any negative ions formed can be immediately extracted from the discharge chamber. The arc-defining hole, located directly below the heated filament, is 3/32 in. in diameter. The remainder of the arc chamber is 3/16 in. in diameter, and thus the edge of the arc column is recessed from the metal wall by 3/64 in. in the region of ion extraction. These, then, are the major changes in the basic arc structure, and both are designed to enhance the content of molecular hydrogen near the slit region.

Among the parameters that remained unchanged was the filament. The filament, cut from 0.150-in. tantalum sheet, is much larger than would appear necessary. However, a large filament is essential for arc operation at the higher gas flow rates. Under these conditions the majority of the filament heat is supplied by ion bombardment of the cathode surface, and the added filament mass serves as a heat sink which allows the arc to be run in a controlled manner.

The water-cooled tantalum reflector cathode is electrically insulated from the source structure and can be connected externally to either the anode or cathode potential, or electrically isolated so as to allow this electrode to assume its own electron reflecting potential. All three styles of operation were tried.

Figure 3 shows the ion source installed in operating position. It was operated in a mass spectrometer arrangement with the extractor electrode at ground potential and the source structure biased negatively in order to extract the ions. With these polarities and dc extraction voltages, a sizable electron current is also removed from the arc plasma. These electrons migrate in small trochoids along equipotential lines normal to the magnetic field. Unless intercepted, they migrate to the high-voltage insulator on which the source is supported, thereby causing breakdown. They are removed by providing a component of electric field that is in line with the magnetic field. This component, provided by the carbon block F in Fig. 2, causes the electrons to be dumped into the water-cooled copper cup shown in Fig. 3. With rf extracting potentials such as employed in a cyclotron, these electrons present no severe problem, but with the dc potentials used for these tests, considerable power can be expended, as the electrons are dumped with full potential. The water-cooled cup eliminated the gas bursts caused by local heating, and the source could be operated for long periods of time with no difficulty, even at the higher system pressures.

Two ion-beam-monitoring Faraday cups were employed. One was located at the 180-deg focal plane of the mass spectrometer and was used for mass analysis. The cup could be moved, its position being determined by a lead screw which was controlled from outside the vacuum system. The other cup, which could be positioned closer to the extracting electrode, was used when higher magnetic field operation would not allow the extracted ions to reach the minimum position of the analysis Faraday cup. The size of this cup was such as to allow changes in the ion Larmor radius without the necessity of changing the cup's location. Faraday cup bias, although available, was not required to obtain reliable readings, and both cups repeatedly gave identical ion-current readings. Both Faraday cups are shown in Fig. 3.

Initial operation was with deuterium gas so that the performance could be compared with that obtained with unmodified geometry. It was immediately apparent that the output of the modified arc, under similar operating conditions, had improved.[6] The diode and PIG type of source operation were compared, and the results for one gas flow rate are shown in Fig. 4.

In the diode type of operation, the lower electrode (B in Fig. 2) is returned to anode potential. Electrons from the cathode thus make only a single transit through the arc chamber before striking the lower electrode. The electrons are therefore not efficiently used and a higher arc current is required. In this style of operation, the arc voltage is quite critical, with a definite peak occurring for the gas flow rate shown for Fig. 4 of about 100 volts. This seems to indicate that the cross section for the simultaneous production of H^+ and H^-, as shown in Fig. 1, is not high at this value of electron energy. With this geometry, the electron energy in the region of ion extraction can be effectively tuned by changing the arc voltage, and thus some indication of the upper limit of electron energies favorable to the negative ion production can be had.

The modifications improve the diode style of operation by about a factor of two. Electrons are left with considerable energy when they strike the lower electrode, however, and cooling of this electrode becomes difficult. In these tests, it was not uncommon to melt the lower tantalum electrode at the arc currents required to maximize the negative ion outputs at the higher gas flow rates, and therefore work was concentrated on the use of the more efficient PIG style of operation.

When the lower electrode becomes an electron reflector by being returned to the same potential as the heated cathode (PIG), the comparative improvement is greater. Where a peak negative ion output of 0.2 mA was available at 1 A of arc current from the unmodified geometry, an output of nearly 1 mA is available after modification, or an improvement by a factor of 5.[6] It is interesting to note the decrease in negative ion output at the higher arc currents. If the electron density, for a given gas density, becomes too high, the competing processes that reduce the molecular gas content can increase. The result is an increase in dissociation and ionization of the required molecules, removing them from the state from which they can be converted to negative ions. This process would not be detrimental for the production of positive ions, and indeed, when the source is operated to produce protons, no similar fall-off with increasing arc current is seen. With the arc recessed from the ion exit slit, a higher arc current can be tolerated before these competing processes become dominant.

The H^- output of the source at a number of arc currents and gas flow rates is shown in Fig. 5. It can be seen that the optimum arc current is a function of the gas flow rate. As the gas flow is increased, the optimum arc current also increases, and at the higher gas flow rates this optimum has not been fully attained. The optimum arc voltage also increases with the gas flow rate. At the lower gas flow rates an arc voltage of approximately 250 V is best, and at the higher gas flow rates an arc voltage of at least 350 V is required. The ions bombarding the heated filament at this energy provide considerable heat, and it is at this point that the use of a large filament becomes important.

The maximum current obtained at each of the various gas flow rates in Fig. 5 is replotted in Fig. 6 along with the corresponding vacuum system pressure. It is rather interesting to note that the points fall on a line with a slope indicating that the negative ion current available is directly proportional to the gas flow rate. From the slope of this curve one could expect to determine the magnitude of gas flow rates required to obtain higher negative ion currents than the 5.3 mA obtained with a gas flow rate of 30 cm^3/min (STP). At this flow rate in the test system, which had a pumping speed for hydrogen of about 5000 liters/sec, gas pressure was 6×10^{-5} mm Hg, and nearing the pressure at which high-voltage breakdown becomes intolerable.

The ion beam outputs shown in Figs. 5 and 6 were emission-limited. Although the arc was generally operated with an extraction potential of 12.5 kV, the output was essentially emission-limited at about 8 kV, and no additional ion current was extracted as the voltage was increased above that value. That the output is effectively independent of extraction parameters means that Fig. 6 can be used to determine the number of negative hydrogen ions that are available for acceleration in any particular cyclotron. One need only determine the gas flow rate through the ion source that can be tolerated by the cyclotron's vacuum system.

Many cyclotron ion sources use a floating reflector cathode (B in Fig. 2). During these tests, this electrode, which was normally connected electrically to the heated cathode, was allowed to float. In each case there was a noticeable decrease in negative ion output. The amplitude of this decrease varied somewhat with arc conditions, but in general ranged from 20 to 30%.

For cyclotrons with the usual internally located ion source, the maximum gas flow rate that can be accommodated before negative ion loss by residual gas scattering becomes excessive limits the source output to small fractions of a milliampere. Should the ion source be externally located so that differential pumping can be employed, this limitation can be removed and the full output of the source can be made available. Ions have been successfully injected into the University of Birmingham's radial-ridge cyclotron. In this case, positive ions were injected axially through a hole through the center of the pole tip from an externally located ion source.[13] A similar method, using an ion source arrangement of the type employed in these tests, is illustrated in Fig. 7. Here the beam enters the machine through a hole in the magnet and is deflected into the dee structure by means of an electrostatic beam deflector. The ion source, which utilizes a separate magnet and vacuum system, is operated in the manner successfully employed in the Berkeley heavy-ion accelerator.[14] The converging ion beam enters the beam tube after traveling approximately 110 degrees in the source magnet. Because the negative ion beam emerges from a slit and is then subject to a focusing force normal to but not in line with the source magnetic field, some correction for astigmatism is required. In the diagram, this correction is provided by the box-type lens structure. With the ion source externally located, the cyclotron can operate at the system's base pressure, a condition much more favorable for the acceleration of negative ions.

The largest deterrent to beam control is usually the space-charge repelling forces within the beam itself. In the negative ion beams observed in this work, these forces are extremely weak, and problems in beam control are greatly simplified.

Acknowledgment

This work was done under auspices of the U. S. Atomic Energy Commission.

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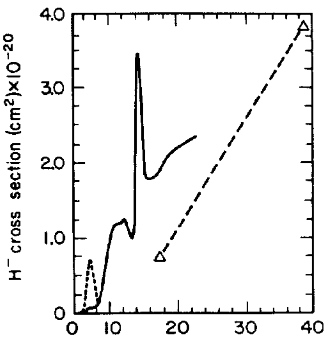

Fig. 1. H^- cross section as a function of electron energy. △: data from reference 12.

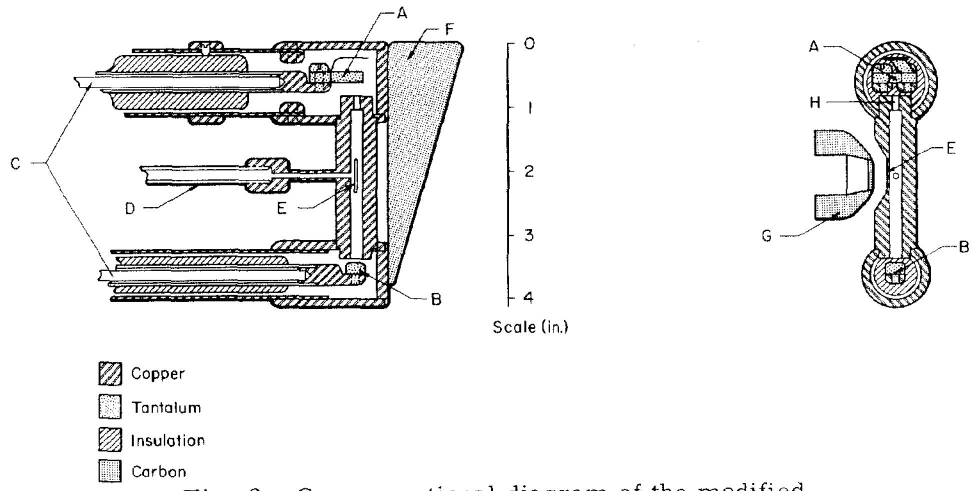

Fig. 2. Cross-sectional diagram of the modified ion source geometry.
A: heated filament
B: cold reflector cathode
C: water-cooled squirt tubes
D: gas feed line
E: ion exit slit
F: trochiodal electron dump block
G: ion-extracting electrode
H: arc-defining hole

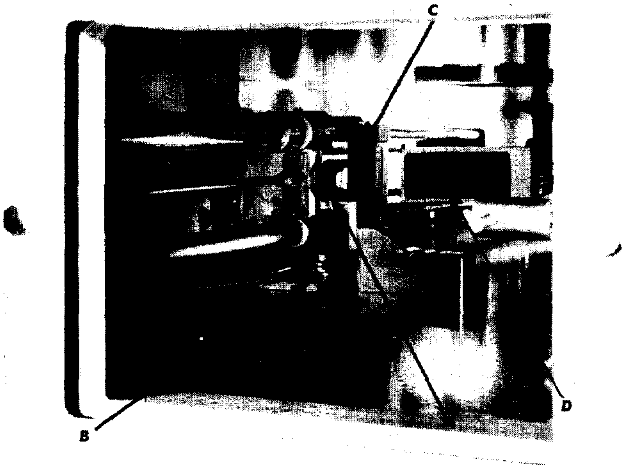

Fig. 3. Ion source in operating position.
A: ion-extracting electrode
B: water-cooled electron receiver
C: traveling Faraday cup
D: test Faraday cup

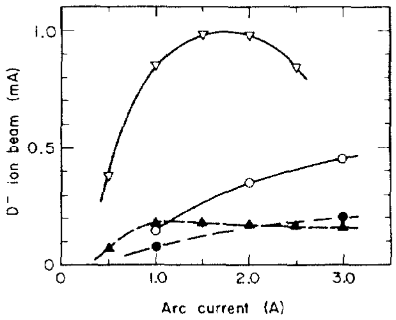

Fig. 4. Increased negative ion current as a result of modification of arc geometry. Original geometry: ● - diode, ▲ - PIG type; modified geometry: o - diode, ▽ - PIG type Gas flow rate: 8.6 cm^3 (STP) per min.

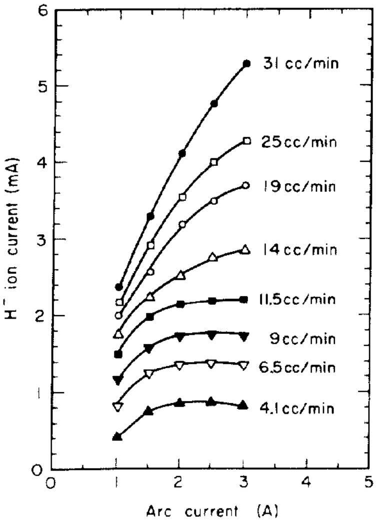

Fig. 5. Beam current of H⁻ ions obtained from the PIG-type discharge with changing arc current and gas flow rate. Extraction potential, 12.5 kV; magnetic field, 3.5 kG.

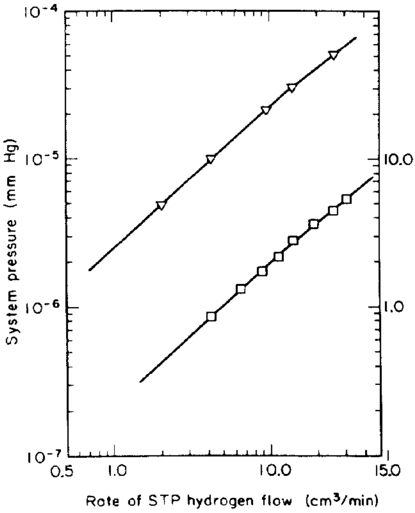

Fig. 6. Relation between negative ion current output and system pressure as a function of gas flow rate. ▽: system pressure, □: H⁻ ion current.

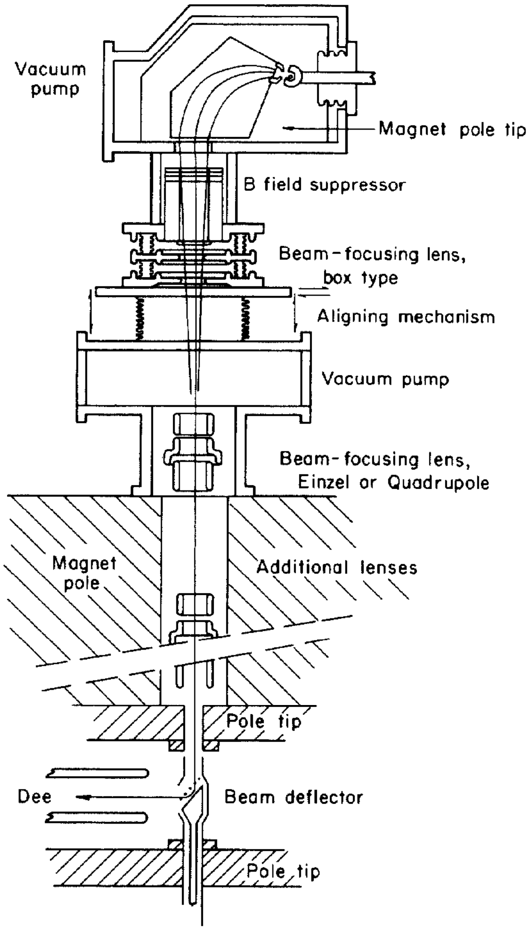

Fig. 7. Axial injection of negative ions into cyclotron from an externally located ion source.