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DEVELOPMENT OF INTENSE NEGATIVE HYDROGEN ION SOURCES AT BNL*

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Abstract

Early in 1973 a program was initiated at BNL to develop a pulsed source of negative hydrogen ions capable of yielding beam currents of several tens of milliamperes or more. Two types of sources were constructed, a hollow discharge duoplasmatron and a magnetron. Both sources were operated without and with cesium vapor injection. A substantially higher output of H^- ions was observed from a hydrogen-cesium discharge: of the order of ten milliamperes from the duoplasmatron source and of the order of hundred milliamperes from the magnetron. Current densities at the extraction aperture and beam phase space areas are comparable to those of standard proton sources.

Introduction

The program to develop negative hydrogen ion beams at BNL started with the initial goal of achieving pulsed beam currents of the order of several tens of milliamperes. Such beams of negative hydrogen ions were to be used for the charge exchange injection of protons into the AGS. It was decided at that time to concentrate the efforts on the development of sources with direct extraction of negative ions from a plasma instead of following the route then preferred, via charge exchange of intense proton beams. This decision was strongly influenced by first reports from several laboratories in the USSR describing two new types of sources, one yielding negative hydrogen ion currents of up to 5 mA (a hollow discharge duoplasmatron[1]) and the other even more, up to 22 mA (a very compact magnetron[2]). Preliminary results at BNL obtained with similar sources, as well as further developments in the USSR laboratories,[3] were so encouraging that late in 1973 a program was proposed to develop a source of H^- ions capable of delivering beam currents of up to 1 A, with pulse lengths of 10 ms. Negative hydrogen ion beams of so high intensity are intended for applications in some plasma devices, as a means of heating the plasma by injection of high energy neutral particles.

In this paper we shall present results of the BNL's research of the two types of H^- sources mentioned above. A hollow discharge duoplasmatron was developed by adapting the existing BNL proton duoplasmatron source and introducing some novel features, as e.g. replacing the originally proposed center rod with a tube and injecting cesium into the anode region of the discharge. While the H^- yield from a pure hydrogen discharge was somewhat higher than obtained by Golubev et al.,[1] a more than two-fold increase was observed when cesium was injected into the source.

The initial design of our magnetron source followed that one described by Bel'chenko et al.[2] The second model was substantially improved, much sturdier and capable of withstanding high thermal loads. Operating modes without and with cesium injection were explored, as well as the possibility of using more than one extraction slit. In a pure hydrogen mode results similar to those reported in Ref. 2 were obtained; in the mixed hydrogen-cesium mode H^- currents above 125 mA were obtained, which is still lower than the reported value of about 300 mA.[3] Inadequate control of the amount of injected cesium vapors and of the source temperature seems to be responsible for an intensity below the optimum possible.

Hollow Discharge Duoplasmatron (HDD)

The hollow discharge duoplasmatron has basically the same geometry as a standard duoplasmatron, except for a rod[1] or a tube[4] placed along the main discharge axis and penetrating into the anode region (Fig. 1). Such a design is based on the property of duoplasmatrons to yield more of H^- ions from the edge of the discharge (when scanning the extraction aperture of a standard duoplasmatron, there is a very pronounced minimum in the H^- yield around the center of the aperture). In the BNL design the new intermediate electrode has a wider aperture of 11 mm dia., so as to leave enough space for the discharge around the center molybdenum tube (4 mm dia.). The center tube is isolated from the discharge by an aluminum sleeve except at the tip. The distance between the tube tip and the anode insert can be varied. Hydrogen gas is fed via a pulsed valve into the cathode region. Four holes

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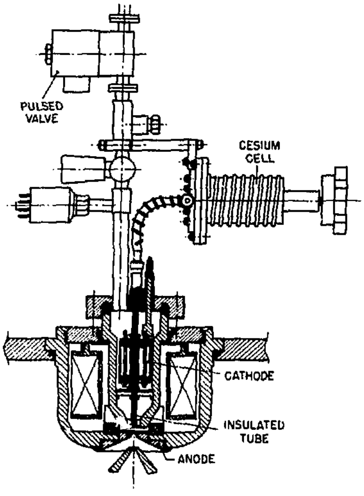

Fig. 1

situated about 12 mm from the tip of the tube served for radial injection of cesium vapors. The possibility of using the tube for hydrogen gas feed as well was not explored fully. Anode inserts (molybdenum) with different extraction apertures were used to optimize the aperture diameter.

The source assembly was on a negative potential (up to 45 kV), with the extractor, target box and diagnostics at the ground potential. The arc voltage and current waveforms were monitored, as well as the voltage drop across 1Ω resistor in series with the center tube. Only the pressure in the gas feed line was measured. The injection rate of cesium vapors into the source was controlled by the temperature of the cesium cell, but there was no possibility of measuring this rate or determining the density of vapors in the source.

The first part of our measurements on the HDD source consisted in determining the optimum axial position of the center tube and in exploring the effect of varying the diameter of the anode aperture. The beam emittance was also measured for several combinations of source parameters. The method with two slits was used, one of them placed immediately after the extractor and the other at the exit of a small window frame magnet serving also to separate negative hydrogen ions from other heavy ions and electrons. The target was a shielded Faraday cup. Total current intensity was measured by a beam transformer, as well as by intergrating current density distribution curves obtained for different positions of the entrance slit. After optimizing the source geometry the magnetic analyzer was replaced with a unipotential lens preceded by a magnetic dipole to deflect electrons out of the beam. The beam current, passing through a 12.5 mm dia. collimator in the lens itself, was then measured by a beam transformer as well as by scanning with a retractable Faraday cup.

Experiments With the HDD Source

Experience with duoplasmatrons when used as a negative ion source has shown that it takes a day or two of running to condition a new source[6]; the same was observed with the HDD source. During this period of time the negative hydrogen ion current increases significantly and the heavy ion component reduces to less than 10%. After this initial period the source usually runs for weeks without any trouble.

The negative ion beam current was first measured as a function of the magnet current, gas flow rate and the potential of the center tube.[4] When raising the magnet current, an increase in the H^- yield was observed up to the limit of the stable operation of the source; an optimum flow rate was, however, found before reaching the limit. A very interesting behavior was observed when the potential of the center tube was varied starting from large negative values (Fig. 2). The H^- output was increasing up to an apparent optimum, beyond which the electron current drawn by the tube became prohibitive. In this par-

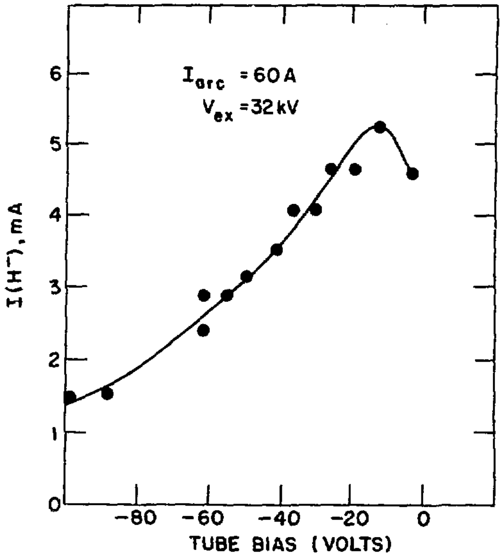

Fig. 2

ticular run the floating potential (I_{tube}≈o) was about -50 V with respect to the anode, which would indicate that the optimum potential is somewhere around the plasma potential.

Experiments have been done with only one size of the center tube. It was found that the best position of the tip is 4 mm from the anode. The extracted H^- current showed first an increase with the anode aperture and then a leveling off at around 2 mm diameter; it follows that the highest current density corresponds to the 2 mm aperture. The maximum negative hydrogen ion beam obtained without cesium was about 9 mA, with a normalized emittance (area x $\beta\gamma$) of 0.27 cm-mrad, and corresponding current density of 0.28 A/cm^2. The ion-electron beam current ratio varies between 0.01 and 0.02. Some of the source and beam parameters are shown in Table I.

TABLE I

Cesium Injection	No	Yes
Ion beam current	9 mA	18 mA
Electron beam current	400 mA	600 mA
Emittance (norm.)	0.27 cm-mrad	-
Anode aperture	3.1 mm^2	3.1 mm^2
Arc current	80 A	45 A
Arc voltage	200 V	100 V
Source magnet	5.4 a.u.	2.5 a.u.
Tube bias	- 20 V	floating
Extraction voltage	38 kV	43 kV

Before injecting cesium into the source the duoplasmatron was conditioned and its parameters optimized. The negative ion beam current as measured after the lens was 8 mA. Cesium vapors were then injected by heating the cell[6] for about one hour at 150°C (vapor pressure ≈ 10^{-2} torr). This method of controlling the rate of vapor injection has serious drawbacks because of possible over-saturation of the source with cesium; if this happens, large oscillations appear in the plasma and the beam pulse shows a large noise component. The maximum negative ion current we reached was about 18 mA, at an extraction voltage of 43 kV. It was observed that the H^- yield remains enhanced for some time after the injection of cesium vapors from the cell has been discontinued. Table I shows one set of source and beam parameters, with cesium vapors injected.

Several explanations have been proposed for the efficient extraction of H^- ions from the edge of a discharge.[7] In a hydrogen discharge the polar dissociation $e + H_2 \rightarrow e + H^- + H^+$ is probably the process most responsible for creation of H^- ions, although some authors do not rule out the possibility of the dissociative recombination ($e + H_2^+ \rightarrow H^- + H^+$) taking place as well. Surface conversion of ions and atoms into negative ions seems to be negligible because the conversion coefficients for clean surfaces with high work function are very small.[8] This is in agreement with the observed variation of the H^- yield with the center tube bias: where the surface conversion the dominant process, the H^- yield should not depend so much on the bias. On the other hand, an exponentially increasing number of electrons arriving at the center tube as its potential is changing from the floating toward less negative values certainly does enhance the creation of H^- ions via polar dissociation; a higher density of hydrogen molecules in the vicinity of the center tube due to a very high recombination probability for atoms hitting the metal surface would help as well.

The situation, however, changes when cesium is injected into the source. The fact that the enhancement of the H^- yields lasts much longer than the injection of Cs itself, points out to surface effects as the explanation of a higher H^- yield. Unfortunately, the possible dependence of the H^- yield on the center tube bias was not explored in detail, although there are indications that it is less pronounced than for a pure hydrogen discharge. A much less dramatic effect of cesium in a HDD source than in a magnetron may be explained by a less favorable position of the emitting surface with respect to the extraction aperture.

Magnetron

Although it is possible to envisage further developments of a HDD source resulting in higher currents of H^- ions, improvements by two or more orders of magnitude cannot be expected. The magnetron[2,3,7] is certainly a more promising source of H^- ions for CTR applications and currents of 0.88 A have already been reported[9] from a larger version and helped by cesium injection. It consists of two electrodes, cathode and anode, with a racetrack discharge chamber between them. In the normal operating mode the discharge is established in that part of the chamber where the electric and magnetic fields are mutually perpendicular; it is sustained probably by secondary electron emission from the cold cathode under bombardment by positive ions. There is an expansion slot in the anode, next to the extraction slit, which serves to enhance the motion of H^- ions toward the slit,[3] slowing down at the same time the diffusion of electrons toward it.

Our first model of the magnetron source suffered from several weak points in the design itself, resulting in appreciably lower arc currents and extraction voltages than expected and operating rather unreliably. The second model, although having basically the same dimensions, was of a much sturdier design and it is with this model that most measurements have been done (Fig. 3, 4). Anode block parts were machined out of stainless steel, the cathode with its side shields is of molybdenum as suggested in Ref. 2 and 3 for the lowest contamination by heavy negative ions. The magnetic field can be varied up to 3 kG; an interesting feature of the magnet is that the coil is outside the vacuum box. The source is enclosed in a stainless steel can, except for one or more extraction slits adjacent to the plasma expansion chamber in the source. Extractor blades are stainless steel as well; in one mode of operation they were mounted on the grounded pole pieces with only the source on a high negative potential, in the second mode the source and the magnet were on high potential with only the extractor grounded. In either case the gap between the extractor and the source was 1 mm. Same system of gas and cesium injection was used as described earlier, except that the feed line to the source itself was common for both hydrogen and cesium. Pressure in the source was not measured.

The pulsed power for the arc was supplied by a delay line pulser with 3Ω internal impedance and 2 ms pulse length. The arc voltage and current waveforms were monitored. Same diagnostic equipment as for the HDD source was used for beam current and emittance measurements.

Experiments With the Magnetron Source

First experiments have been done with hydrogen as the operating gas. In the normal mode of operation which is achieved after several hours of conditioning, the necessary arc voltage ranges between 500 V and 700 V, depending more on the arc current and less on the magnetic field and gas pressure. However, at lower pressures and/or magnetic fields we have observed another mode of operation characterized with a voltage of a few tens of volts only and current limited by the external circuit. Output of negative ions in this mode was practically zero, and this phenomenon determined the limit of the useful values of the arc current. For certain combinations of the pressure and the magnetic field this limit was as low as 20-30 A, but when the parameters were properly adjusted currents up to 100 A were obtained in the high voltage mode.

Measurements of the H^- yield from a pure hydrogen discharge were done with a single extraction slit of 0.6 x 10.5 mm^2. When measured as function of the discharge current in the range from 20 to 50 A, the extracted current showed as increase from 7 mA to 17 mA, at constant pressure, magnetic field (2 kG) and extraction voltage (10 kV). The heavy ion content was about 10%, the electron component about 5-6 times higher. Maximum current density is comparable to that one reported in Ref. 2 (270 mA/cm^2), but the electron load is higher probably due to a shallower anode slot. Beam emittance was measured at a beam current of about 7 mA of H^-, in directions parallel with the extraction slit (0.44 cm-mrad norm.) and perpendicular to the slit (0.6 cm-mrad,

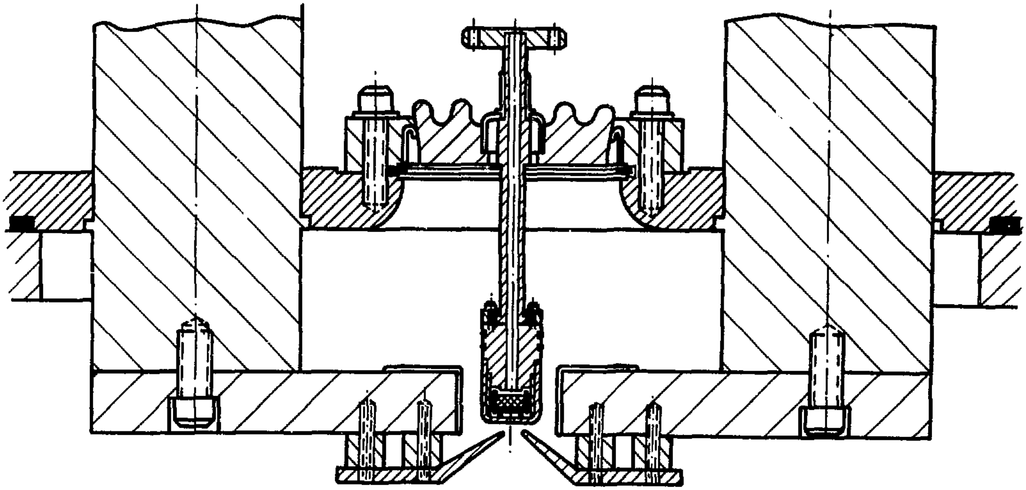

Fig. 3

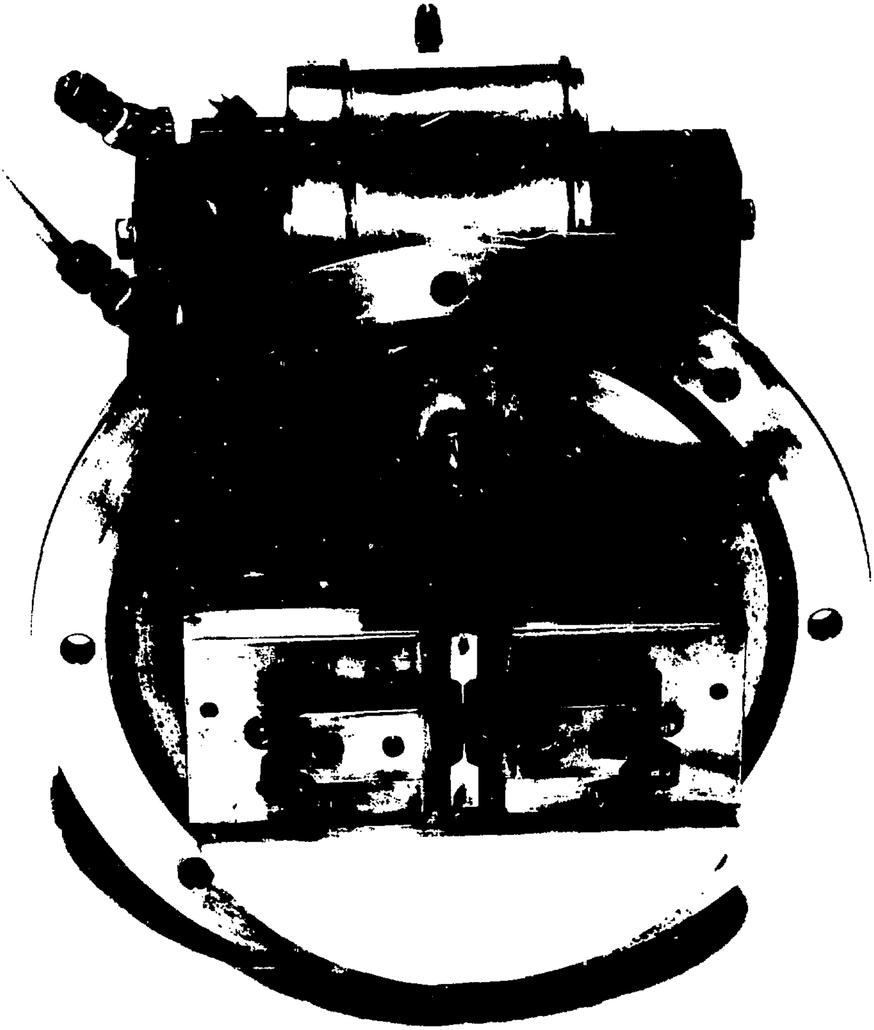

Fig. 4

norm.). Soon afterwards cesium was injected and once the source was contaminated, it was very difficult to establish a pure hydrogen mode again (to be frank, we did not try very hard, either!).

Experiments with cesium injection are still in progress and, as mentioned above, often accompanied by difficulties due to an imprecise control of the injection rate. A number of modes was observed, depending on the hydrogen gas pressure and even more on the condition of the cathode surface (degree of contamination with cesium). Arc voltages as low as 100 V were possible with arc currents up to 150 A. The arc voltage was not very sensitive to changes in the magnetic field or in the arc current. Lowest voltages were obtained during and immediately after the cesium injection. However, sometimes it was possible to run the source in a mixed mode (with cesium injection discontinued) for several weeks, but the arc voltage would slowly increase in time from a very low value to 300-400 V. The highest H^- current achieved with the slit 0.6 x 10.5 mm^2 was about 100 mA, which corresponds to a density of 1.6 A/cm^2, from an arc discharge of 100 A and at an extraction voltage of 15 kV. The electron component was not more than 200 mA. The emittance was measured under similar conditions, but at a lower extraction voltage of 10 kV only. In the direction perpendicular to the extraction slit the normalized emittance was 1.2 cm-mrad, for a net H^- current of 45 mA. The contamination by heavier negative ions was higher this time: up to 20% of the total beam. When the source was operating in the mixed mode, it was easy to keep the extracted current in the range from 50 mA to 75 mA for several days. With the slit width increased to 1 mm, the extracted current did not increase as expected. It is, however, possible that the rate of cesium injection was not properly adjusted.

A double extraction slit (two 0.5 x 10 mm^2 slits) was tried in order to check the possibility of using multiple slits in a magnetron source. First results with the source operating in a mixed mode (arc voltage 200 V, arc current 100 A) showed that it was possible to extract up to 125 mA, corresponding to current densities of 1.25 A/cm^2, which is lower than from a single slit of similar dimensions. A few pulses were observed with even higher peaks (up to 150 mA), but again we could not find an optimum because of poor cesium injection technique. It is worthwhile mentioning that again the yield of H^- ions was rather stable for many days, and that it was possible to extract currents between 75 mA and 125 mA from a mixed mode discharge as long as the arc voltage did not increase above 200 V.

A magnetron source, operating in the pure hydrogen mode, yields several times higher H^- currents and current densities than a Penning source. Still, the same explanation may be proposed for the creation of H^- ions in both sources: polar dissociation of molecules in collisions with electrons of energies above 17 eV. Secondary emission of electrons from the cathode under bombardment by positive ions with an energy of 500-600 eV is a rather efficient process with a coefficient of about 0.1. These electrons are accelerated while passing through a very thin cathode fall region and enter the plasma with energies of several hundred eV or more. While performing spiraling trajectories in combined electric and magnetic fields they collide with neutral molecules and produce new positive ions, and occasionally a negative ion as well. A much higher plasma density and a shorter path H^- ions have to traverse before reaching the extraction slit may explain a higher yield from the magnetron source. However, an order of magnitude higher currents of negative ions from a magnetron source operating in the mixed hydrogen-cesium mode cannot be explained by processes in the plasma alone, but by surface conversion of energetic positive and neutral particles when hitting the cathode.[3] It is interesting to note that an order of magnitude increase in the H^- yield is accompanied by a much smaller increase in the electron component, which would indicate that the plasma density did not increase very much following the injection of cesium.

Conclusions

Our experiments have shown that the HDD source is capable of delivering H^- currents of up to 18 mA. A new source has been built with much more flexibility in changing the geometry of the critical region around the anode; it should make possible optimization of other source parameters as well. It is expected that improvements in the way cesium is injected into the source will further increase the yield of H^- ions.

The most important problem in the operation of the magnetron source has been the cesium injection. By mastering this technique it should be possible to reach intensities obtained in USSR by G.I. Dimov and his group. Experiments are planned with a larger version of the source, with up to 5 narrow extraction slits. Measurements of the energy spectra will shed more light on the question of the origin of negative ions.

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