CONF-801068--13

MASTER

REGULAR AND ASYMMETRIC NEGATIVE ION MAGNETRON SOURCES WITH GROOVED CATHODES*

J. Alessi and Th. Sluyters
Brookhaven National Laboratory
Upton, New York 11973

Abstract

The performance of the BNL Mk III magnetron source has been improved by geometrically focusing H^- ions produced at the cathode into the anode emission slit. In addition, an asymmetric configuration, with a large anode to cathode spacing in the back of the source, has allowed operation of the source at lower pressures. The result of these two changes is a gas efficiency of approximately 6% and a power efficiency of 8 kW/A. No isotope effect has been observed. Measurement of the energy of H^- ions shows that one extracts both slow ions and ions with an energy equal to the cathode voltage. The ratio of electrons to H^- ions can be as low as 0.5.

I. Introduction

The use of geometrical focusing in magnetron sources had been proposed by Green¹ and Sternberg², who suggested curving the cathode in order to focus H^- ions into the anode emission slit. It was not clear that geometrical focusing would work because of the relatively high pressure in the source, which resulted in the extraction of primarily "slow" H^- ions, some formed between the cathode and anode by symmetric charge exchange collisions between "fast", surface produced H^- ions and H atoms, and others possibly coming from volume production of H^- ions. Subsequently, Belchenko, et. al. applied the principle successfully in a semiplanotron surface plasma source.³ They observed sputtering on the anode from ions focused by a groove in the cathode.

A cylindrical groove was added to the cathode in the BNL Mk III magnetron source. This has allowed us to reach desired H^- current densities ($0.5 - 2.0 \text{ A/cm}^2$) with almost an order of magnitude lower arc currents than required without the groove.

To further enhance performance, an asymmetric magnetron source was tested, having a relatively wide gap in the back of the cathode, as suggested by Prelec⁴ and Wiesemann⁵. The idea of such a source is that this wider gap allows ignition of the discharge at lower gas pressures.

In addition to a discussion of source performance with the above mentioned modifications, results of measurements of the energy of H^- ions extracted under various operating conditions will be given. Finally, some experimental observations related to the ratio of extracted

electrons to H^- ions will be discussed.

II. Grooved Cathode and Asymmetric Configuration

The cathode-anode region of the magnetron, as well as the detail of the grooved region, is shown in Figure 1.

Fig. 1: The placement and dimensions of the groove put in the cathode of the Mk III magnetron.

The groove was directed perpendicular to the magnetic field, along the full front of the cathode (5 cm). The radius of curvature of the groove was 3.75 mm, and the width was 4.5 mm. In general, the emission slit was $0.6 \times 45 \text{ mm}^2$. Figure 2 shows H^- current density versus arc current for the magnetron with the groove, as well as the previous performance with a flat cathode. Within

*Work done under the auspices of the U.S. Dept. of Energy.

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the range of arc currents shown in Figure 2, we could typically operate the source with 10 to 25 ms pulse lengths, and a repetition rate of 15 to 20 pulses per minute. Beam currents were measured on a Faraday cup approximately 8 cm from the source. The extraction voltage was always high enough to insure that the H^- output current was emission limited (typically 12 kV or 80 kV/cm). In general, after running one could observe a line 0.5 - 0.7 mm wide on the inside of the anode (opposite to the groove) which had been sputtered clean by the focused H^- ions. Therefore, with the groove one could extract H^- ions coming from an area of the cathode which was 7.5 times larger than the anode emission slit.

Fig. 2: H^- current versus arc current for the normal magnetron with flat cathode, normal magnetron with grooved cathode, and asymmetric magnetron with grooved cathode.

The H^- output was quite sensitive to the source pressure and Cs coverage. One obtained maximum H^- output when operating at the lowest pressure possible without losing the discharge. An increase from this pressure by a factor of two would result in a 50% reduction in H^- current, due to the increased destruction of ions between the cathode and anode. For a given H^- current density, we observed a reduction in the source pressure by at least a factor of three over that required with the flat cathode. This is primarily due to the fact that the lower arc currents can be sustained at lower pressures.

In an attempt to further reduce the source pressure (and therefore the destruction of H^- ions), the anode to cathode spacing on the back side of the magnetron was increased from 1 mm to 5 mm, while leaving the front side unchanged (see Fig. 3). The idea is that ignition of the

discharge may occur at lower pressures with the increased gap. The results with this asymmetric configuration (and grooved cathode) are shown in Figure 2. The H^- output was increased by 70% over that with the normal grooved magnetron. The source seemed to operate with a more stable discharge at somewhat lower pressures than the normal grooved magnetron. We now estimate the gas efficiency of the source (H^- ions/neutral atoms) to be at least 6%. Experiments with a 10 mm gap in the back of the source are now under way.

Fig. 3: The asymmetric magnetron configuration.

In the Cs mode, the source operates with an arc voltage of 120 - 180 volts, the lower voltage being obtained when a larger amount of Cs is supplied. A decrease in arc current is often accompanied by some increase in arc voltage. One must then increase the Cs supply rate to reduce the arc voltage at this lower current. Also, as one reduces the source pressure one reaches a point where the arc voltage begins to rise (and arc current drops). Again, additional Cs will get one back to lower arc voltages.

Emitance measurements, taken with an on-line minicomputer, gave an emitance perpendicular to the emission slit which was a factor of three lower than the emitance with the flat cathode at the same H^- current density.⁶ Presumably, this is due to the lower arc current required with the groove. The normalized emitance perpendicular to the slit is approximately 0.1π cm-mrad for a 0.5 to 1.0 A/cm² beam (135 - 270 mA). The current distribution was uniform in the direction of the slit.

An asymmetric magnetron with a series of grooves in the cathode parallel to the source magnetic field was tried. The anode emission

slits were offset slightly with respect to the grooves to compensate for the deflection of ions between the cathode and anode by the source magnetic field. While we did observe sputter marks indicating that the H^- ions were again being focused, the output with this configuration was less than 50% of that obtained with the groove and slit perpendicular to the magnetic field. The most likely explanation seems to be a spreading out of the ions at the slit by the magnetic field, preventing one from focusing the H^- ions as well into the slits.

It has been suggested that since the curvature of the groove provides an electric field component directed toward the center of the groove, this may tend to increase the concentration of electrons in the groove when its orientation is perpendicular to the magnetic field. This could result in a higher discharge current density in the groove. In an attempt to enhance this effect, if it exists, a groove was put all around the cathode. This gave no noticeable difference in source performance.

With two grooves and emission slits (approximately 10% anode transparency), we have been able to extract 380 mA of H^- with a 25A, 120 V discharge. This corresponds to a power efficiency of 8 kW/A, an improvement by about a factor of four over that with a flat cathode (with four emission slits and 50% anode transparency).

III. Operation with Deuterium

With the asymmetric magnetron operating in the Cs mode, the pulsed gas was changed from hydrogen to deuterium. A residual gas analyzer was monitored and confirmed the change in gas, but no change was observed in the operation of the source. One had the same arc current, arc voltage, and negative ion current as had been obtained with hydrogen. D^- output versus arc current fell along the same line as that obtained for H^- ions, while operating with arc current densities up to 4 A/cm². Semiplanotron results³ indicated maximum D^- currents which were only 50-70% of maximum H^- currents. In that case, however, the source was operating at arc current densities in excess of 20 A/cm². The results in Ref. 3 seem to indicate a reduction in the isotope effect at lower densities, so our failure to observe an isotope effect may not be in conflict with their results. This might suggest that in magnetron sources the isotope effect is related to the destruction of ions between the cathode and anode rather than being a surface production effect.

IV. Energy Analysis of H^- Ions

An energy analyzer was constructed in order to determine the relative importance of the fast and slow H^- components under typical operating conditions for the grooved, asymmetric magnetron. Figure 4 shows a schematic of the energy analyzer. The source was operated in a uniform magnetic field. H^- ions coming from a 0.75 mm diameter hole

were deflected by 180°, and detected by a monitor containing thirty small metal strips, collecting ions with Larmor radii from 3.0 to 4.5 cm. Thirty sample/hold circuits allowed one to get the complete energy spectrum at any time during the beam pulse. A 0.5 - 1.0 kV extraction voltage was applied across a 0.25 mm gap, while the magnetic field was within the range required for operation of the source (0.9 - 1.6 kG).

Fig. 4: Schematic of the H^- ion energy analyzer

Fig. 5 is a typical energy spectrum, containing two peaks - the left peak is at the extraction voltage (V_E) and the right one is at V_E plus the cathode voltage (V_C). In the hydrogen mode, one observed only the peak at V_E . As Cs was added, the second peak, at $V_E + V_C$, appeared. With increasing amounts of Cs, this second peak grew, and moved toward the first peak as the cathode voltage dropped.

By shifting the extractor voltage by an amount equal to the cathode voltage, one could clearly see that the energy difference of the two peaks was equal to V_C . We did not observe peaks at higher energies, as one might have expected if reflection of atomic and molecular ions at the cathode was occurring. The spectra differ somewhat from that measured by Belchenko, et.al.⁸. While they also observed two peaks, one at V_E and one around $V_E + V_C$, the tail on the high energy peak extended up to $V_E + 2V_C$. In the present spectra the peak at $V_E + V_C$ has no such tail.

$V_E = 1000 \text{ eV}$
 $V_C = 250 \text{ eV}$
 $B = 1.1 \text{ KG}$

1000 eV
 1250 eV

Fig. 5: H^- energy spectrum, showing a peak at the extractor voltage, and one at the extractor plus the cathode voltage.

As one went into the proper Cs mode, the fast ion peak ($V_E + V_C$) increased. With decreasing source pressure the ratio of fast ions to slow ions increased (less charge exchange), while at the same time the magnitude of both peaks increased (less destruction of ions). Figure 6 shows a series of spectra taken at various arc currents ($V_E = 1000 \text{ V}$, $V_C = 150 \text{ V}$, $B = 1.1 \text{ kG}$). The decrease in the ratio of fast to slow ions with increasing arc current could be due to more dissociation of hydrogen at the higher arc currents, resulting in an increased fraction of fast H^- ions undergoing charge exchange collisions.

It appears that, while the ratio of fast to slow ions changes with source conditions, we do not normally operate in a regime where either component is less than 20% of the total beam. Even with a large slow ion component the cathode groove enhances the source output by increasing the concentrations of slow ions around the emission slit.

V. The Electron Component

In going from the normal magnetron with the flat cathode to the asymmetric magnetron with grooves, we were able to extract a given H^- current density at approximately an order of magnitude lower arc current. Somewhat surprisingly, however, the ratio of electrons to H^- ions extracted showed no dramatic improvement. This seemed to indicate that most of the extracted electrons were not the result of diffusion from the main plasma. Subsequent experiments seem to confirm this conclusion.

Typically, the anode emission slit was 0.6 mm wide, and the anode wall was 0.5 mm thick. Electrons should diffuse much more easily parallel to the source magnetic field than perpendicular to it, and so tend to run into the slit walls rather

5 A

10 A

20 A

28 A

35 A

1000 eV
 1150 eV

Fig. 6: H^- energy spectra for various discharge currents. The discharge voltage was 150 V, extraction voltage was 1000 V, and $B = 1.1 \text{ kG}$. The pressure and Cs coverage was the same in all cases.

than diffuse out of the source. In switching to an anode slit 0.25 mm wide and 0.75 mm thick (a configuration which should have reduced diffusing electrons) we obtained the expected reduction in H^- current, but the e^- current dropped by the same fraction, maintaining the same e^-/H^- ratio. Going to the other extreme, with the anode slits oriented parallel to the source magnetic field, one still obtained approximately the same e^-/H^- ratio. Finally, for source magnetic fields from approximately 1.0 to 1.7 kG, the e^-/H^- ratio does not change (nor do the magnitudes change). Thus, this seems to rule out the possibility of the extracted electrons coming from the main plasma. (In the hydrogen mode, where the H^- density is low, the extractor field may penetrate through the anode slit. In this case, one may be extracting plasma electrons. In the Cs mode, however, the H^- ion density inhibits the penetration of the extractor field).

Under optimum conditions of source pressure, Cs coverage, and extractor voltage, one can attain the ratio $e^-/H^- = 0.5$ (i.e., H^- /total extractor supply load = 0.67). The best ratio is obtained when the pressure is as low as possible. Figure 7 shows various currents as a function of source pressure. The increase in pressure decreases the H^- current, but the electron current (extractor supply load - H^- current), remains essentially constant. The grid and magnet pole currents (electrons) are also constant.

Fig. 7: Dependence of various currents on the source pressure. P_{min} is the minimum pressure at which the source will operate.

Therefore, one may conclude that ionization in the extractor gap is not the primary contributor to the electron load. Destruction of H^- ions in the extraction gap should be very small. A likely origin of some of the electrons is through destruction of fast and slow H^- ions in the emission slit, or by electrons released in collisions of ions with the walls of the anode slit. There is also the possibility that photoelectrons are produced in and around the anode slit (enhanced by any Cs coating). Light reflected from the front of the mirror - like cathode is focused at the anode slit by the groove, so it is not unreasonable that photoelectrons produced in the slit region were increased in going from the flat to the grooved cathode along with the increased H^- current. Extraction of photoelectrons would be consistent with the observed constant electron current versus pressure in Figure 7. A simple calculation of the rate of H^- destruction in the emission slit as a function of pressure indicates that it is also possible to explain Figure 7 by claiming that the electrons originate from H^- destruction. The pressure dependence of this rate of H^- destruction (i.e., rate of electron creation) goes as $K_1 P e^{-K_2 P}$, where K_1 and K_2 depend on H^- destruction cross sections, ratio of H to H_2 , etc., and P is the source pressure. This function can have a relatively flat region around its maximum. When one puts numbers into a more careful calculation one finds that the flat part of the curve can indeed be in the range of pressures where we are operating the source. The position of this maximum does shift depending on the H to H_2 ratio, among other things, so one can only conclude that electrons arising from H^- destruction cannot be ruled out on the basis of Fig. 7.

VI. Summary

The performance of the BNL Mk III magnetron has been improved significantly by the use of geometrical focusing of H^- ions and by increasing the anode to cathode spacing in the back of the source. We can now extract almost all H^- ions reaching the front anode plane, even with a low anode transparency. We have extracted 1.0 A/cm² of H^- ions (270 mA) with an arc current density of less than 2 A/cm² (25 A arc current). This is an order of magnitude lower arc current than what was required with the normal magnetron and flat cathode. The fact that one can operate at lower arc currents allows one to decrease the pressure in the source, which in turn reduces the destruction of H^- ions. The net result is an improvement by about a factor of three in gas efficiency (to 6%), and a factor of four in power efficiency (to 8 kW/A).

The H^- energy spectrum contains only two peaks, one corresponding to slow ions produced by charge exchange of the fast ions with neutral atoms, and one at an energy equal to the cathode voltage. Peaks at higher energies, coming from reflection of ions at the cathode, are not observed.

Under optimum conditions we can obtain a ratio of electron to H^- current equal to 0.5. The electrons are not diffusing from the main plasma, but seem to be produced in and around the anode emission slit, by either H^- destruction or photoemission.

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