Effects of a Transverse Magnetic Field on an RF-Driven H− Ion Source

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(Received 23 December 2005)

We investigated the effects of a transverse magnetic field on a volume H− ion source driven by a radio frequency (RF) or a DC filament. We observed an electron cooling and an enhancement of the H− ion extraction efficiency when a transverse magnetic field was applied. The floating potential in the plasma in front of the extractor was found to increase with the magnetic field intensity, implying that a higher voltage on the plasma electrode would be required to extract the H− ions. In addition, the effect of the transverse magnetic field on the filament arc discharge was investigated.

PACS numbers: 42.30.R, 42.40.Ht, 42.30.Kq

Keywords: Ion source, Potential, Filtering magnet

I. INTRODUCTION

Magnetic multipole ion sources have been widely used as high-current proton sources or negative hydrogen-ion sources and have been adopted as injectors for high-power proton linacs or cyclotrons [1,2]. We have developed a plasma driver as an alternative instrument to an external spiral RF antenna. A negative-ion source, based on a transformer-coupled plasma source with a spiral RF antenna outside of the plasma vacuum chamber and with a high-current continuous power has been developed [3].

The production of the negative hydrogen ions in a confined volume requires contradicting conditions in controlling the electron temperature. The transverse magnetic field in an H− ion source may play a key role in controlling the electron temperature in that the axial magnetic field generated by the solenoids in the electron cyclotron source play important roles in confining the hot electrons [4].

Leung et al. developed a rod-type magnetic filter to control the electron temperature and demonstrated that the extraction efficiency of negative hydrogen from their filament are H− ion source could be optimized by adjusting the location of the filters [5]. Holmes also studied the relations between the H− ion extraction efficiency and the plasma parameters by using a magnetic filter. He found that the magnetic field could separate the plasma volume into hot and cold regions in the electron temperature distribution [6]. The diffusion of low-energy electrons through the transverse magnetic field could result from either elastic scattering of the electrons with the neutrals and other electrons [7], or some turbulence generated by the ExB force [8], or a combination of the two.

Magnetic filters are well known to help reduce the electron temperature near the extraction hole by facilitating H− ion formation and reducing H− ion destruction. However, the presence of the magnetic field affects the potential in the extraction region, which can interfere with a H− ion extraction. Because of these positive and negative effects of the transverse magnetic field on extracting H− ions, understanding the physics behind the magnetic filter, such as the potential distribution in the plasma, is essential for developing an efficient ion source. In this paper, we discuss the effects of the transverse magnetic field on the extracted ions by investigating the evolution of the electron temperature, the plasma potential, and extracted electron current under the influence of a magnetic field.

II. EXPERIMENTAL APPARATUS

A schematic drawing of the RF-driven negative-ion source is depicted in Fig. 1. The plasma generation chamber, located at the top of the ion source, is fabricated with stainless steel in a double-wall configuration to provide sufficient cooling water for high-power-density plasma operations. An RF antenna is installed opposite the extraction system and is isolated by either quartz or alumina plates. The RF supplier and the matching unit are grounded rather than maintained at a high voltage, so the ion source operates under much simpler and safer conditions.

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Fig. 1. Schematic diagram of the RF-driven H$^-$ ion source using an external antenna.

A multicusp magnetic configuration is implemented around the plasma generation chamber to confine the high-density plasma which is generated by an RF wave of 13.56 MHz with 2 kW of power. In DC arc plasma operations, we can replace the RF system, such as the RF antenna and window, with a filament and a DC electrical power system.

A set of filtering magnets is installed, in front of the extraction electrode, as shown in Fig. 2, to filter out the fast electrons which reduce the H$^-$ ion flux by stripping off the electrons from them. The field strength of the filtering magnet is adjustable up to 150 G, and the effective magnetic field profile was calculated using Superfish code [9] and is shown in Fig. 2.

Four electrical probes are installed around the extraction electrode, filtering magnets, and inside the plasma chamber at the locations (A)-(D) as marked in Fig. 2, and accurately measure the plasma density, temperature, and potential. A Faraday cup is installed to measure the extracted H$^-$ ion current at 30 cm downstream of the extractor.

III. EXPERIMENTS AND RESULTS

We have investigated the effects of the transverse magnetic field on the plasma and extracted ions for various configurations of the transverse magnetic field and different operating conditions of the ion source. In a series of experiments, we measured the electron temperature, the current of extracted H$^-$ ions, the potential distribution in the plasma, and so on, to understand the effects of the transverse magnetic field.

1. Electron Temperature and Currents of the Electron and the extracted H$^-$ Ion

We measured the electron temperature at the extraction region by using an RF-compensated single probe. We operated the ion source at an RF power of 1.3 kW and a plasma flow rate of 2.3 sccm while varying the transverse magnetic field. The measured electron temperature is plotted as a function of the transverse magnetic field strength of the filtering magnet in Fig. 3. As clearly seen, the electron temperature decreases with increasing magnetic field intensity.

The similar electron cooling effects have also been observed in other volume sources with a multicusp magnetic configuration [5, 6]. The electron cooling effects
can be explained by the different diffusion rates between the hot and the cold electrons or by ambipolar diffusion in the transverse direction to the magnetic field. The transverse magnetic field effectively filters the hot electrons, which can strips off the electrons of \( \text{H}^- \) ions, and may eventually enhance the relative flux of the \( \text{H}^- \) ions.

The currents of the electrons and the extracted \( \text{H}^- \) ions were measured by using a Faraday cup under similar to those operating conditions for the electron temperature measurement with an extraction voltage of 5 kV. We show the measured currents as a function of the magnetic field intensity in Fig. 4. The extracted \( \text{H}^- \) ion current shows an interesting feature. The \( \text{H}^- \) ion current increases sharply as the intensity of the magnetic field increases up to 60 G. From 60 G to 100 G, the \( \text{H}^- \) ion current increases gradually, and then slowly decreases with magnetic fields for stronger than 100 G. This interesting nature can be understood by the argument that up to 60 G, the magnetic field effectively reduces the loss of \( \text{H}^- \) ions by filtering out the hot electrons that can neutralize the \( \text{H}^- \) ions by stripping off the electrons. However, strong magnetic fields above 60 G start to deteriorate the plasma discharge at the RF driving region, which can reduce the density of the vibrating neutrals and electrons which are precursors of the \( \text{H}^- \) ions.

In contrast, the extracted electron current monotonically decreases with the magnetic field intensity, as shown in Fig. 4. While measuring the extracted electron currents, we simultaneously measured the bias current in the plasma electrode. The evolution of the bias current also shows a trend similar to that of the electron current, as shown in Fig. 5. These phenomena can be explained by a perturbation in the plasma induced by the magnetic field. The perturbed plasma distorts the potential distribution in the plasma, especially near the extraction region, which will be discussed in detail in the following
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From the measurements of the extracted H\(^+\) ion and electron current, we conclude that the transverse magnetic field plays a positive role in enhancing the H\(^-\) ion extraction while lowering the electron current, which effects that have been also observed in other volume ion sources.

2. Potential Distribution in the Plasma

In case of the H\(^-\) ion source, understanding the spatial potential distribution in the plasma is much more important than it is for a proton source because the potential distribution determines the diffusion and confinement of charged particles, such as electrons, positive ions, and H\(^+\) ions, in the same volume. Especially, the H\(^-\) ions may not be extracted at a relatively higher positive potential at the extraction region than that of beam extractors, such as the plasma electrode because the positive plasma potential plays the role of a barrier and prevents H\(^-\) ion extraction. Hence, detailed information on the potential distribution in the plasma is required to relieve the potential barrier by applying an appropriate voltage to the plasma electrode.

Using electrical probes, we measured the floating potentials at four points, (A)-(D) in Fig. 2. The electrical probe at (A) is located within the skin depth under the RF window to measure the floating potential in front of the cusp field, which can confine the electrons and heat the plasma efficiently. The electrical probe at (B) measures the floating potential just behind the cusp field, where the effects of the transverse magnetic field come in. The electrical probe at (C) measures the floating potential at the maximum transverse magnetic field. The floating potential at the extraction region is measured by the electrical probe at (D). Transverse magnetic field is not applied, the floating potentials at (A), (C), and (D) must be negative because the floating potential is solely determined by the electrons in the plasma, which are relatively faster than the ions. However, positive floating potential is expected at the location (B) because of the loss of the electrons caused by the radially diverging cusp fields.

We measured the floating potential at the four locations while applying a transverse magnetic field, and presented in Fig. 6. The floating potentials at (B), (C), and (D) rapidly increase with the magnetic field intensity, while monotonically decreasing at (A) where the magnetic field is less effective. The positive floating potential at the extraction region explains why the electron loss rate is higher than the H\(^-\) ion loss rate under the influence of the magnetic field. The measured floating potential is about ten times higher than that of other volume sources, which implies that a higher-plasma-electrode voltage is required to extract H\(^+\) ions.

We can measure the extracted H\(^+\) ion current is dependency on the plasma bias voltage, as shown in Fig. 7, which shows that the extracted H\(^+\) ion current increases with the bias voltage of the plasma electrode up to 20 V at a transverse magnetic field of 100 G. As discussed earlier, H\(^-\) ion extraction requires relief of the potential barrier by applying a bias voltage to the plasma electrode. We applied a higher bias voltage to the plasma electrode compared to the few volts in the other volume sources. The measured maximum bias voltage is similar to the plasma potential at the extraction region with the same filtering magnetic field.

The negative floating potential at location (A) may result from the increased electron density and temperature. When we measure the Balmer alpha line by using a PC-based compact optical spectrometer, we observe that the optical emission intensity in the driving region actually increases with the filtering magnetic field intensity. Without the filtering magnet field, the plasma generated from the RF window diffuses away from the extraction region, that is, to bottom regions of the cylindrical plasma chamber. The transverse magnetic field enhances the plasma formation in the driving region and isolates the floating potential in the plasma.

3. Filament Heating Power on the Arc Discharge

Numerous studies on the effects of transverse magnetic fields in filaments based H\(^-\) ion sources have focused on filtering the fast electrons and separating the extracted fast electrons [5, 6]; however, it may be interesting to study some positive effects on the plasma characteristics by the filtering magnetic field in the plasma driving region. To study the plasma characteristics in the plasma driving region, we replaced the RF system, including the antenna and window, with a filament. We investigated
the arc current at different heater powers and different filtering field intensities. We observed an interesting feature in the arc current as shown in Fig. 8. The arc current increases with increasing transverse magnetic field intensity at a fixed filament heater power and a fixed arc voltage. The enhancement in the arc current resulted from reducing the loss of seed electrons to the extraction region, which occurs in a similar manner in case of an RF discharge. Because the plasma ion current in the vacuum arc discharge is proportional to the arc current [10], the magnetic field is expected to reduce the filament heating load at a fixed arc power and to enhance the filament lifetime.

IV. CONCLUSIONS

We have investigated the effects of a transverse magnetic field on the electron temperature and the floating potential in an RF driven H\textsuperscript{−} ion source. Interpreting the observed effects, we found that the electron temperature could be controlled by using a transverse magnetic field and that control of the potential such as the plasma electrode bias at the extraction region is required to increase efficiency of H\textsuperscript{−} ion extraction because of the increasing potential near the extractor. In addition, we found that the transverse magnetic field enhanced the arc current by reducing the plasma loss toward the extractor without increasing the filament heater power, which could play an alternative role in adjusting the arc current.

ACKNOWLEDGMENTS

This work is supported by the 21st Century Frontier R&D Program of the Ministry Of Science and Technology, Republic of Korean.

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