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Wave frequency dependence of H$^-$ ion production and extraction in a transformer coupled plasma H$^-$ ion source at SNU[a)]

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The effect of rf wave frequencies on the production of H$^-$ ion is investigated in a transformer coupled plasma H$^-$ ion source at Seoul National University. A Langmuir probe is installed to measure the plasma density and temperature, and these plasma parameters are correlated to the extracted H$^-$ beam currents at various frequencies. The Langmuir probe is also used to measure the density of H$^-$ ions at the ion source by generating photodetachment with an Nd:YAG laser. The extracted H$^-$ currents decrease to a minimum value until 13 MHz and then, increase as the driving frequency increases from 13 MHz while the relative H$^-$ population measured by photodetachment monotonically decreases as the driving rf frequency increases from 11 MHz to 15 MHz. A potential well formed at the extraction region at high frequencies of more than 13 MHz is considered responsible for the increased H$^-$ beam extraction even with a lower photodetachment signal. The variation in the driving rf frequency not only affects the density and temperature of the plasma but also modifies the plasma potential with the existence of a filtering magnetic field and consequently, influences the extracted H$^-$ current through the extraction as well as formation of H$^-$ ions. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.3678659]

I. INTRODUCTION

An rf wave of 13.56 MHz has been used to generate plasma in a transformer coupled plasma (TCP) H$^-$ ion source at Seoul National University (SNU), which uses an external planar spiral RF antenna.[1] However, it is well known that for various rf frequencies, the power coupling can change, and consequently, plasma parameters such as the electron density and electron energy distribution can vary. A change in the plasma parameters may result in modifying the population of H$^-$ ions since the production of H$^-$ ions is dependent on the density and energy distribution of the electrons.[2–4]

In volume negative ion sources, the H$^-$ ions are generated by dissociative attachment of low energy electrons to ro-vibrationally excited molecules. Ro-vibrationally excited molecules are known to be generated in plasma through collisions with fast electrons whose electron energy exceeds ~20 eV.[5,6] By noting that at a lower rf frequency the population of high-energy electrons increases relatively, H$^-$ production is expected to increase due to more effective production of ro-vibrationally excited hydrogen molecules by the energetic electrons. On the other hand, at higher rf frequencies, the production of H$^-$ ions can be enhanced by a higher electron density or temperature since rf power coupling is enhanced.[2–4] The rf frequency dependence of the H$^-$ current has been investigated in a DESY RF volume negative ion source;[7] however, no detailed measurements on the plasma parameters under various rf frequencies have been carried out, and especially, no investigation has been done on the rf frequency around 13.56 MHz or above.

In this study, the effect of the rf frequency on the production and extraction of H$^-$ ions is investigated by extracting the H$^-$ ion beam as well as by measuring the plasma parameters and H$^-$ population with Langmuir probe diagnostics and photodetachment diagnostics with various rf frequencies around 13.56 MHz.

II. EXPERIMENTAL SETUP

A planar spiral rf antenna isolated by a quartz window from the source chamber is used for plasma generation with rf frequencies of 11, 12, 12.5, 13, 13.5, 14, and 15 MHz, in which the existing matching network designed for 13.56 MHz can be used to generate plasma. An rf power of 550 W and a pressure of 18 mTorr is used in this study as the typical experimental conditions.

Multi-cusp magnets are installed to enhance the confinement of the plasma and a set of filtering magnets is implemented in the cusp magnets, which provides ~200 G filtering magnetic field at the center of extraction hole.[1] A schematic description of the experimental setup is shown in Fig. 1. A detailed description of the TCP H$^-$ ion source is shown in Ref. 1. Since the sheath potential is not suitable for the extraction of negative ions, a positively biased electrode, called the plasma electrode (PE), is used for the optimized extraction. A stainless steel PE 8 cm in diameter with an extraction hole 8 mm in diameter biased to 5 V is used in this study.

The H$^-$ beam current is measured with a Faraday cup and the plasma parameters such as the electron density and electron temperature are measured with the Langmuir probe.

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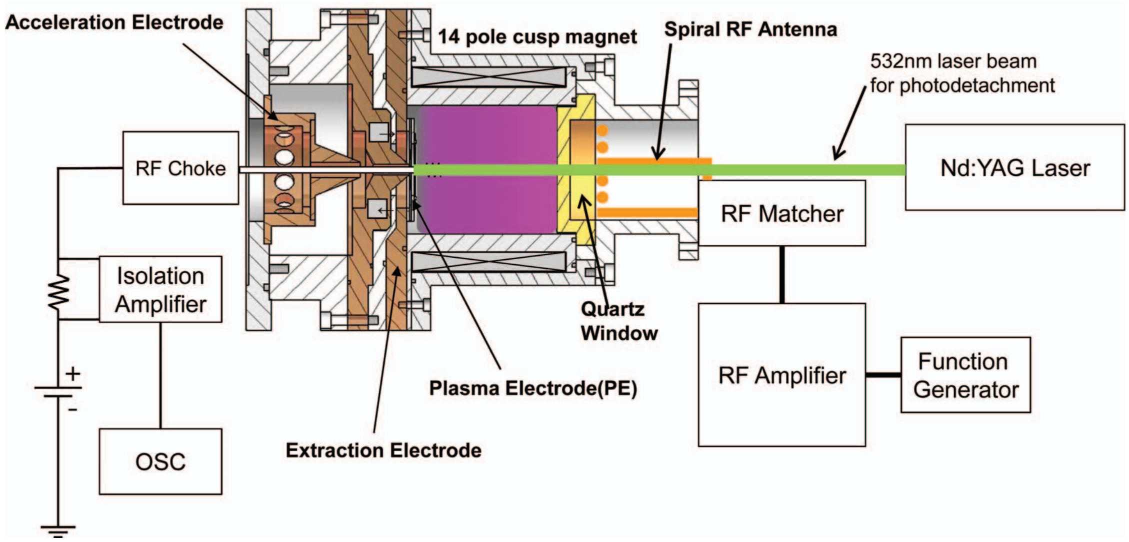

FIG. 1. (Color online) Schematic of the experimental setup.

RF-compensated probes with rf chokes and compensation rings are used to suppress the distortion of the probe signal due to rf fluctuations. Since the rf chokes should be carefully optimized for each rf frequency with heavy efforts, the measurements with the rf compensated Langmuir probe are done only with rf frequencies of 11, 13, and 15 MHz. The Langmuir probe is installed through the extraction hole and moved in an axial direction so that the plasma parameters are measured at various axial positions. In addition, an Nd:YAG laser, which can generate up to a 0.5 J laser beam with a 532 nm wavelength and a 10 ns pulse duration, is used for the photodetachment diagnostics.[8] The detachment of extra electrons from the negative ions by the laser beam results in an increase in the electron density without an immediate increase in the positive ion density.[8,9] The change in the electron density, which represents the H^- density, is measured with a Langmuir probe at a position 1 cm away from the extraction hole in the axial direction. For the photodetachment measurements, a simple Langmuir probe without rf compensation is used to minimize the perturbations from the probe. All parameters are collected at least three times and the mean value is presented with the standard deviation as an error bar.

III. EXTRACTED H^- BEAM CURRENT WITH VARIOUS RF FREQUENCIES

Extracted H^- currents as a function of the driving rf frequency are shown in Fig. 2. Extracted H^- currents are minimal at 13 MHz and increase as the driving rf frequency deviates from 13 MHz. On the other hand, the PE bias current shows an inverted dependency compared to that of the H^- current shown in Fig. 2. Since the PE is positively biased to provide an optimized potential structure for the extraction of negative ions, electron currents are collected by the PE in the same manner as the planar Langmuir probe. Thus, the PE current can be interpreted as the relative electron density in front of the PE. The PE bias currents are highest at 13 MHz and decrease as the driving rf frequency deviates from 13 MHz.

To correlate the extracted H^- current with the actual H^- density, the change in the electron saturation current due to the photodetachment, which represents the relative H^- density, is measured by Langmuir probe and a 532 nm Nd:YAG laser beam. The laser photodetachment signal at the extraction region (1 cm away from the extraction electrode in the axial direction) with varying rf frequencies is shown in Fig. 3. The photodetachment signal is measured with boxcar averaging due to a very low signal-to-noise ratio. The photodetachment signal decreases as the driving rf frequencies increase, and this result cannot explain the H^- beam extraction results that show an increasing H^- current with increasing rf frequencies at high rf frequencies of more than 13 MHz. The extracted H^- beam current at low frequencies such as 11 MHz is relatively higher, which can be attributed to the enhanced H^- production observed in the photodetachment measurements, but the increase in the H^- current at high frequencies cannot be explained by the increase in H^- production. Therefore, not only H^- production but also other causes are necessary to explain the increase in the H^- current at high rf frequencies.

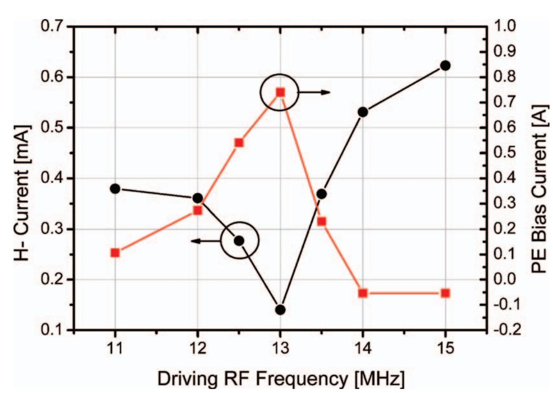

FIG. 2. (Color online) H^- current and plasma electrode (PE) bias current with various rf frequencies.

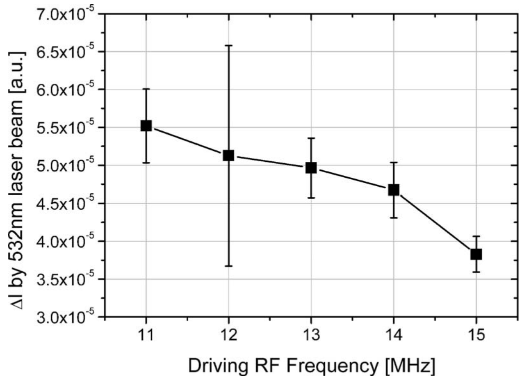

FIG. 3. Measured change in the electron saturation current by photodetachment with various rf frequencies at the extraction region, 1 cm away from the extraction hole in the axial direction.

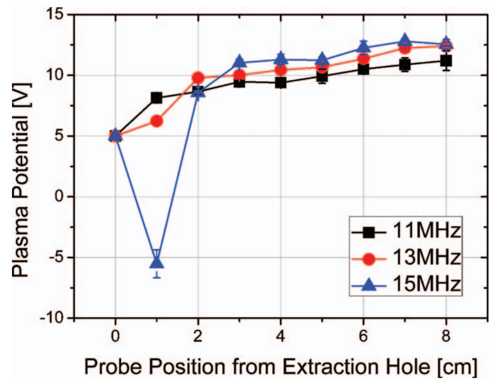

FIG. 5. (Color online) Plasma potential as a function of the axial position from the extraction hole with various rf frequencies.

IV. LANGMUIR PROBE DIAGNOSTIC RESULT WITH VARIOUS RF FREQUENCIES

The measured electron density and temperature are shown in Fig. 4. Both the electron density and temperature decrease as the measuring position moves closer to the extraction hole as a natural consequence of the filtering magnetic field near the extraction hole, indicating that the filtering magnetic field is working well for electron temperature control in all frequencies. Note that the overall electron density increases with increasing rf frequencies confirming that the power coupling increases with increasing rf frequencies. The rf power is fixed at 550 W for all frequencies. The electron density and temperature as a function of the driving rf frequency measured at the heating region (8 cm away from the extraction hole in the axial direction) clearly show that the electron temperature decreases and the electron density increases with increasing driving rf frequencies. Lower electron temperatures in the heating region with higher rf frequencies may explain the reduction of H^- production with increasing rf frequencies since a higher electron temperature is favorable for the generation of ro-vibrationally excited molecules, the precursors of H^- ions.

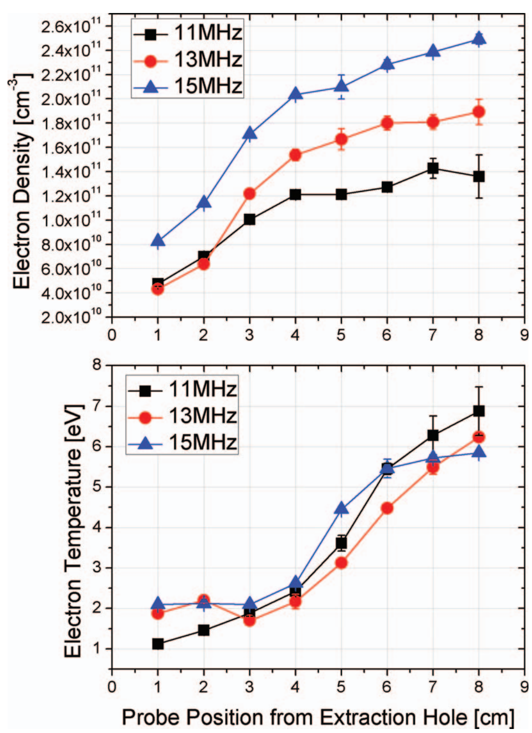

FIG. 4. (Color online) Electron density (upper panel) and temperature (lower panel) as a function of the axial position from the extraction hole with various rf frequencies.

The plasma potential profile is also measured as shown in Fig. 5, which shows that the overall plasma potential increases as the rf frequency increases. The plasma potential is determined by finding the peak of the derivative of the I–V curve data. Note that the standard deviations of the measured plasma potential values are presented as the error. However, the plasma potential at the extraction region deviates from that of the bulk plasma. At the extraction region, 1 cm away from the extraction hole, the measured plasma potential decreases as the driving rf frequency increases, contrary to that of the heating region. At 15 MHz, the plasma potential at the extraction region is even negative and forms a potential well with a ~15 V potential difference from that of the bulk plasma.

V. PRODUCTION AND EXTRACTION WITH VARIOUS RF FREQUENCIES

At low frequencies such as 11 MHz, the volume production rate of H^- negative ions is high since the electron temperature at the heating region is high enough to generate the precursor, ro-vibrationally excited molecules while the low electron temperature at the extraction region well controlled by the filtering magnetic filed is suitable for H^- production through dissociative detachment. The H^- production rate is consistent with both the photodetachment signal and the extracted H^- current at rf frequencies under 13 MHz that decreases with increasing rf frequencies. However, the increase in the extracted H^- current at high frequencies such as 15 MHz does not agree with the laser photodetachment signal, which shows a relative decrease in the H^- density as the rf frequencies increase. The increase in the H^- current at high frequencies such as 15 MHz cannot be explained solely by H^- production; therefore, there has to be another factor that affects the extracted H^- current.

However, there is one possibility that can enhance the extracted H^- current at high frequencies; the improved H^- extraction could be due to the extraction-favorable potential well formed at high frequencies. This improved H^- extraction is believed to be a result of the negative potential well formed in front of the PE.

At high frequencies, one favorable factor for improved H^- beam extraction is a suitable potential structure originating from the formation of the potential well. As seen in Fig. 5, the plasma potentials are more than 10 V for all frequencies and the PE bias voltage is fixed at 5 V. When the potential well is not formed, the PE has a lower potential than the plasma potential in the extraction region, therefore, the H^- negative ions and electrons in the extraction region will be repelled back toward the bulk plasma. However, by the formation of the potential well, the PE potential becomes higher than the plasma potential at the extraction region; therefore, the negative ions will be accelerated toward the extraction hole and can be easily extracted. Thus, with a potential well, the H^- ions can be easily extracted.

The mechanism for the formation of the potential well has not been elucidated yet; one conjecture is that it might originate from the trapping of low energy electrons since the electron temperature decreases with increasing rf frequencies. As the electron temperature decreases, high-energy electrons are lost across the filtering magnetic field and slow electrons may be trapped and accumulate to form a potential well.

VI. CONCLUSION

H^- ions are extracted by varying the rf frequency from 11 MHz to 15 MHz, and the extracted H^- beam current has a minimum value at 13 MHz. However, H^- ion production decreases monotonically with increasing rf frequencies as observed by the relative H^- ion density from the laser photodetachment diagnostics. The measured plasma density and temperature from the Langmuir probe are consistent with the H^- ion production. Although the discrepancy at high frequencies cannot be explained by the H^- production, it is possible since H^- beam extraction is favorable in the presence of a potential well observed by the Langmuir probe measurements at high frequencies.

Therefore, the variation in the driving rf frequency not only affects H^- production due to the changing density and temperature of the plasma, but the variation also changes the H^- beam extraction by modifying the plasma potential structure in the presence of a filtering magnetic field.

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