Beam emittance measurements of transformer coupled plasma ion source for focused ion beam

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(Received 12 September 2003; published 17 May 2004)

A transformer coupled plasma (TCP) ion source has been tested in order to test its feasibility as a high brightness ion source for focused ion beam. When operating the TCP ion source with filter magnets in front of plasma electrode for a negative ion source, lower emittances are expected. Extracted beam emittances are measured with an Allison-type scanning device for various plasma parameters and extraction conditions. The normalized emittance has been measured to be around 0.2 (π mm mrad) with beam currents of up to 0.55 mA. In particular, noting that multicusp magnets have a role in decreasing the emittance as well as increasing plasma discharge efficiency, transverse magnetic field has been confirmed to be a useful tool for decreasing emittance via electron energy control. © 2004 American Institute of Physics. [DOI: 10.1063/1.1702124]

I. INTRODUCTION

A focused ion beam (FIB) system, which can produce a nanoscaled ion beam, is becoming important as interest in nanofabrications increases.1 It has become the method of choice for a variety of applications, including circuit inspections, mask repair, micromachining, and direct lithography.2 Recently, attempts to use FIB as a microprobe of medium energy ion scattering (MEIS) spectroscopy are being undertaken. The MEIS spectroscopy equipped with FIB, so called “nano-MEIS,” promises a large improvement of the lateral resolution for nanoscale measurements. It is well known that most commercial FIB systems have adopted the liquid metal ion source (LMIS) in order to use its superiority on high brightness.3 However, FIB with conventional LMIS is not an adequate solution for the microprobe of the MEIS because it can produce only limited species such as gallium, and gallium ions can cause contamination or damage to the structure of objects.4,5 Therefore, a high brightness ion source for light ions (H+ , He+) is considered to be a crucial element in the successful development of FIB systems for nano-MEIS. As alternatives of LMIS, gas field ionization sources and plasma ion sources have attracted attentions in recent years.6 Gas field ionization sources, however, are not a favorable candidate for FIB due to its features of low current density and inconvenience of cryogenic systems. Plasma ion sources such as filament or rf-driven multicusp ion sources have also been reported for FIB in many research groups.7,8 Contamination and lifetime problems, however, still need to be improved due to the immersed filaments or rf antenna.

The transformer coupled plasma (TCP) ion source has many advantageous characteristics for FIB systems. First of all, it provides various gaseous ion beams, such as light ions (H, He) and heavy ions (Xe, Kr), so that many improvements which are difficult with LMIS-based FIB are expected. Second, it does not require the external magnetic fields as used in other high density plasmas [helicon, electron cyclotron resonance], so that transverse magnetic field or electrostatic grid can divide the source chamber into a plasma region and an extraction region, which is essential for the control of plasma and beam qualities. It is very important that high-density, low-temperature plasmas can be provided without strong axial magnetic fields at the extraction region since actual emittance of ion sources is influenced by the axial magnetic field strength at the extraction region as well as the ion temperature.9 Finally, since rf antenna is located outside of the plasma chamber possible contamination from immersed antennas or filaments can be avoided for longer source lifetime.

In order to evaluate the feasibility of novel high brightness ion sources, we have tested the TCP ion source which was originally developed for negative ion source.10 It would be of significant value if plasma ion source showing beam qualities comparable to those of LMIS could be developed. For the successful development, the main issue would be achieving high current with low emittance, i.e., high brightness. In this study, optimum conditions for low emittance are pursued at various operating conditions, especially by utilizing transverse magnetic field as a possible control knob.

II. EXPERIMENTAL SETUP

A schematic diagram of the TCP ion source is shown in Fig. 1. The source chamber was made of stainless steel (85 mm inner diameter by 75 mm height). The quartz disk was used for the dielectric windows through which rf field generated by external antenna can penetrate. The thickness of the disk is chosen to be 10 mm, and high-voltage isolation of up to 40 kV has been successfully tested. In the presence of sufficient insulation between the rf antenna and plasmas, the rf power supply and matching unit are maintained at the ground level instead of the high-voltage level, which makes ion source operation much easier. The 13.56 MHz, 1.3 kW rf power has been used to generate high-density plasmas with an L-type impedance matching network, and discharge is operated in cw mode. A single-hole extraction system was constructed to extract the ion beam. Extraction geometry was

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arranged in a simple two-electrode system with the extraction hole diameter of 5.0 mm and the extraction gap distance of 7.5 mm between plasma and extraction electrodes, respectively.

Between main plasma and the extraction system, a set of permanent magnets generating transverse magnetic field of 65 G are located to filter out fast electrons in front of the plasma electrode. Although this magnetic filter was originally introduced to modify electron energy distributions for efficient H-production, it can be used to get lower beam emittance by providing lower ion temperature with fast electrons eliminated. The source chamber was surrounded by 16 columns of Nd–Fe–B permanent magnets (10 mm width by 30 mm length each) in order to generate the multicusp field configuration for a good plasma confinement. It is noticeable that fringe field (radial component) of the multicusp magnet due to the space between multicusp magnets and filter magnet could also have a role to filter out the high-energy electrons. As a result, filtering effects could be observed by changing the strength of the multicusp field. A separate water-cooling path is provided to make sure the magnets are sufficiently cooled even in high-density plasma operations.

In order to measure the transverse component of an ion beam trajectory precisely, a two-slit electric-sweeping type emittance scanner known as the Allison-type scanner has been used. The scanner consists of a water-cooled beam dump at the entrance, two apertures at the beginning and the end of the scanner, two electrostatic deflection plates, and a Faraday cup at the end with electrode for suppressing the secondary electrons. Applied sweep voltage across the two parallel plates analyzes ions entering the front slit. Ions passing through the rear slit are then collected and measured by a Faraday cup, and the corresponding divergence angle is identified by the value of the instantaneous sweep voltage. This type of scanner is more favorable than other types of scanner such as the multislit method due to its simplicity and high resolution. The design parameters of the scanner are listed in Table I.

III. EXPERIMENTAL RESULTS AND DISCUSSION

High-density plasmas in the regime of “H mode” have been generated with at least 250 W rf power provided. Hydrogen gas has been used as a working gas, and argon gas is added only at initial breakdown to help H-mode transition by seeding electrons with high ionization efficiency.

For various gas feeding ratios, extracted beam currents are plotted as a function of extraction voltages in Fig. 2. It is clearly shown in Fig. 2 that the extracted ion currents are limited either by the space charge force (“Child–Langmuir limit”) where extraction voltages are below 3 kV, and by the emission capability (“ion saturation limit”) where extraction voltages are above 3 kV. It is also noticeable in Fig. 2 that ion currents are higher as gas flow rates are lower. Note that actual gas pressure inside the source chamber is proportional to mass flow rate, and it is approximately 10 mTorr when gas flow rate is 2 sccm. In the previous experiment, the optimum gas pressures for high density in the TCP have been observed as well as its dependency on rf power by measuring H-alpha intensity. In this operating regime, therefore, it can be explained that plasma densities decrease as operating gas pressures are increased, resulting in lower ion currents with higher gas flow rates. Further study is planned to investigate the physics of hydrogen TCP resulting in such a behavior in this gas pressure range.

Among various ion source requirements such as reliability, long lifetime, low emittance, and high brightness, high brightness with low emittance is the most important one for the ion source of FIB. High current ion beams with low divergence can be obtained with good beam optics of ion source as well as plasma parameters appropriate for low emittance. By comparing beam currents collected by the Faraday cup with total beam currents read from the extraction power supply extracted beam optics can be roughly understood. Figure 3(a) shows that ion optics has an optimum condition around 5 kV, where almost all extracted beam currents are collected at the Faraday cup. If the extraction voltage is too high, the plasma meniscus will become too concave so that this will result in an overfocussed ion beam trajectory. Optimum conditions of ion optics can be confirmed by looking at the extraction voltage where normalized

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**TABLE I. Design parameters of emittance scanner.**

<table>
<thead>
<tr>
<th>Parameters</th>
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<tbody>
<tr>
<td>Plate length $D$ (cm)</td>
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</tr>
<tr>
<td>Slit size $s$ (cm)</td>
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</tr>
<tr>
<td>Gap distance $g$ (cm)</td>
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<tr>
<td>Plate margin $d$ (cm)</td>
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<tr>
<td>Slit length $l$ (cm)</td>
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<tr>
<td>Maximum analyzable angle $\pm X m'$ (mrad)</td>
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<tr>
<td>Mechanical resolution $\pm \Delta \theta$ (mrad)</td>
<td>1.00</td>
</tr>
</tbody>
</table>

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**Figure 1.** The schematic diagram of the TCP ion source with diagnostics systems.

**Figure 2.** Extracted ion beam currents as a function of the extraction voltage for various gas feeding ratios at the fixed rf power of 1 kW.
emittance becomes minimum. Figure 3(b) shows minimal emittance at around 5 kV, indicating good beam optics at this extraction electric field. Minimum divergence can be obtained by adjusting gap distance for best matching between extraction electric fields and plasma densities with taking the extraction geometry of the aspect ratio ($s = r/d$, where $r$ is the hole radius, and $d$ the gap distance) into account.9

Neutral gas pressures are believed to influence not only plasma densities but also plasma temperatures, even ion temperatures by changing collision frequencies.13 Since ion temperatures decrease as neutral gas pressures increase, beam emittances are expected to decrease with gas pressure as shown in Fig. 4. However, emittance changes are not so significant in this case, which may come from higher emittance of overfocused beams with lower plasma densities. Since the emittances are measured in the condition of 1 kW rf power and 15 kV extraction voltage where extracted beams are already in the overfocused regime, lower plasma densities with higher gas pressures as shown in Fig. 2 make the beam further overfocused, resulting in larger emittance.

In the previous section, it has been mentioned that fringe fields (radial component) of multicusp magnets generated between a set of filter magnet and multicusp magnets can also filter out high-energy electrons. By filtering high-energy electrons, ion temperatures can be reduced and then beam emittance may be decreased as a result. To see this effect, beam emittances are measured with the field strength of multicusp magnets by varying the number of cusp magnet layers. Surface magnetic field strengths of multicusp magnet systems are 0 G for 0 layer, 3.3 kG for single layer, 4.5 kG for double layer of cusp magnets. The emittances are measured in the condition of 1 kW rf power and 15 kV extraction voltage, and results are shown in Fig. 5. It is clearly seen that beam emittance is significantly reduced by high-energy electron filtering with increased fringe fields of multicusp magnet. This effect may be pronounced by improved beam optics with increased plasma densities due to a good confinement at higher cusp field strength. This opens up a new potential of developing a low emittance, high current density ion source with the optimal design of a magnetic field configuration.

ACKNOWLEDGMENTS

The authors would like to thank Dr. Dae-Won Moon of KRISS for an invaluable support. This work was supported by Ministry of Science and Technology, Korea.

FIG. 3. (a) Comparison between total beam currents from extraction power supply and ion beam currents collected by Faraday cup. (b) Measured emittances for different extraction voltage, showing optimum emittance near 5 kV. All experiments were performed in the condition of 1 kW rf power and 2 sccm gas feeding rate.

FIG. 4. The normalized emittance as a function of neutral gas pressures.

FIG. 5. The normalized emittance as a function of the number of multicusp magnet layers (strengths of multicusp fields).