Development of a 27.12 MHz radio frequency driven ion source with 3 mTorr operation pressure for neutron generators

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An inductively coupled rf plasma ion source has been developed for neutron generators. The ion source configuration has been optimized for low pressure operation. Both 13.56 and 27.12 MHz rf powers have been used to generate hydrogen plasma. Experimental results show that 27.12 MHz operation is more efficient than 13.56 MHz in a low pressure region. The ion source can also be operated in pulsed mode. Current density higher than 30 mA/cm^2 can be extracted from a 2-mm-diam aperture at 2 kW rf input power and 3 mTorr operation pressure. [DOI: 10.1063/1.2113782]

I. INTRODUCTION

Various compact neutron generators based on rf-driven plasma ion sources have been developed at the Lawrence Berkeley National Laboratory.[1–3] These compact neutron generators can be used in the detection of explosives and fissile material in cargo or luggage, as well as in finding land mines and in structural evaluation. In order to produce neutrons by fussion reactions, deuterium or tritium ions need to be accelerated to over 100 keV. In order to obtain high ion current, extraction apertures of the ion source in neutron generators are usually relatively large. Thus the pressure in the acceleration column is high and voltage breakdown may occur. When radioactive tritium is used in neutron production, it has to be confined in the chamber. No pumping unit will be employed for this kind of sealed neutron tubes. In this arrangement, the pressure inside the ion source and the accelerating chamber will be the same. The neutral gas pressure has to be low enough so that voltage breakdown will not occur in the accelerating column. The breakdown voltage between accelerating columns is determined by many factors, such as the electrode shape, spacing, and surface smoothness. When an ion beam passes through the accelerating column, it may ionize some of the background gas. Large angle stray ions may hit on the electrode and generate secondary electrons. Usually the pressure inside the accelerating chamber is at the lower end of the Paschen curve. So the breakdown voltage can be efficiently increased by decreasing the operation pressure. But low ion source operation pressure can also decrease the plasma density. Operation pressure as low as 3 mTorr is chosen for a sealed tube neutron generator based on the tradeoff between the breakdown voltage of the accelerating column and the plasma density in the ion source. Multicusp ion sources with internal antennas, which have limited lifetime, had been used in early ion source development for neutron generators.[1] It's impossible to change an internal antenna in sealed tube neutron generators. As a result, developing a low pressure, highly efficient plasma ion source with an external antenna that can work at a pressure as low as 3 mTorr is important for compact sealed tube neutron generators.

II. ION SOURCE CONFIGURATION AND EXPERIMENTAL SETUP

The dimension of the ion source in the present work has been optimized for low-pressure operation. The final ion source configuration and the schematic experimental setup are shown in Fig. 1. The plasma chamber was made of a 5 mm thick, 11 cm long pyrex glass tube. The outer diameter is 13 cm. There are two pieces of SmCo permanent magnets embedded in the aluminum back plate, which can help to confine the plasma. The rf induction coil is made of three turns of 1.5 mm diam copper tubing. The plasma source and the antenna leads are totally shielded by a 1 mm thick copper sheet to minimize rf radiation leakage. There is a 2 mm diam tapered aperture in the plasma electrode. An extraction electrode is mounted at 2 mm behind the plasma electrode. The plasma chamber is biased at a positive high voltage, so that positive ion beams can be extracted, accelerated by the grounded extraction electrode, and eventually collected by the graphite electrode in the Faraday cup. The extraction electrode and the wall of the Faraday cup are both at the ground potential, so that the extraction field will not reach the surface of the collecting graphite core inside the Faraday cup. Two pieces of permanent magnets are installed at the entrance of the Faraday cup. The magnetic field can rotate the secondary electrons back to the collecting graphite core because of their low energy. Hydrogen is employed in the experiment. As the isotope of deuterium and tritium, hydrogen is a very good substitute to evaluate ion source performance without generating neutrons. All the experimental measurements in the present work are performed with hydrogen gas.

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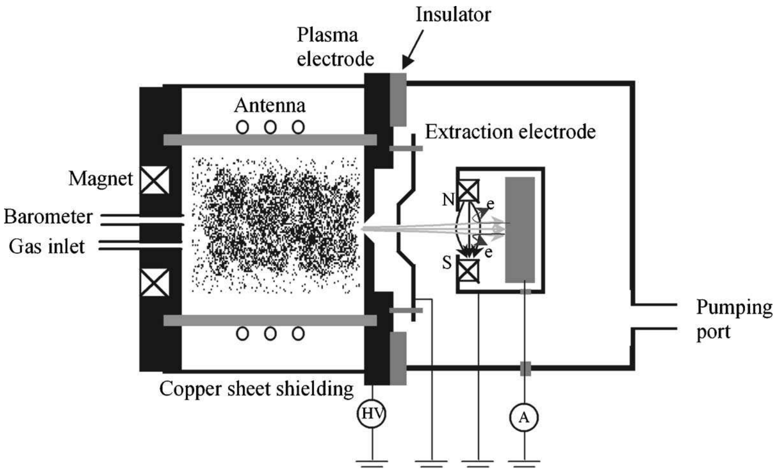

FIG. 1. Schematic diagram of the experimental setup. Ion source is on the left side. Right side is the vacuum chamber for ion beam extraction and current measurement.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Inductively coupled plasma (ICP) ion sources have been used in many applications because of their high power efficiency.[4–9] The ion source developed in the present work is also operated in inductively coupled mode. In our previous work, we developed a high brightness mini rf driven ICP ion source for focused ion beam systems.[4] The high discharging efficiency of ICP sources has already been demonstrated by the mini rf-driven ion sources. A 1.2 cm diam mini source can produce over 200 mA/cm^2 argon ion beams with only 70 W of rf power. Usually it is more difficult to ignite and sustain a hydrogen plasma compared with argon. One of the reasons could be the low mass of hydrogen ion. But for this type of source, 100 mA/cm^2 hydrogen ion current density has been obtained at 220 W rf power. Although for the same input rf power mini ion sources have high power density due to their small source volume, the operating pressure can usually reach as high as 100 mTorr. The dominating ion species in a hydrogen plasma at such a high pressure are H_2^+ and H_3^+. For neutron production application, it is more desirable to use an ion source with high H^+ ion density, which requires low neutral hydrogen pressure to enhance the atomic ion ratio.[1,10]

Mini ion sources have very high power efficiency because of their small plasma volume. However this type of ion source can only work at very high operating pressure. It is difficult to generate low pressure plasmas, especially for hydrogen. Usually large ion source volume is favored for low pressure operation, but it decreases the power density, resulting in lower plasma density. The objective of the present work is to find an optimum source dimension and configuration with external antenna, so that it can be operated with source pressure as low as 3 mTorr and produce enough ion current. Before any pressure and current measurement, the ion sources were first baked by a 250 W heat lamp for over 6 h followed by another 6 h 200 W rf plasma discharge cleaning. These processes can eliminate the outgassing impurities, which may falsely lower the operation pressure and increase the measured current density.

In order to confine electrons from losing to the back plate, two permanent magnets were placed on the back plate of the source chamber. The magnets can increase the extracted ion current by almost 30%. They can also lower the operating pressure to some extent depending on the source dimensions. Several pyrex glass tubes with different diameters and lengths have been tested when 300 W input rf power is used. At first, a 8.89 cm outer diameter tube was employed as the source chamber. The length of the tube was increased in steps from 6 to 8 cm, and then to 10 cm. A longer source body can help to lower the pressure, so that the lowest operating pressure is reduced from 11 to 7.5 mTorr, and then to 6 mTorr. But the lowest operating pressures for these ion sources were still higher than 6 mTorr. The outer diameter of the pyrex tube was then further increased to 11.5 cm. The length of the tubes was increased from 6 to 8 cm, and then to 10 cm. The lowest operating pressures were decreased from 10 to 7 mTorr, and then around 5 mTorr. Experimental results showed that larger diameter and length favored low pressure operation. Based on this fact, the tube outer diameter was further increased to 13 cm and the length was also increased to 11 cm. The operating pressure was finally reduced to less than 3 mTorr. If the two magnets were taken out from the ion source back plate, it can only be operated at higher than 6 mTorr hydrogen pressure and the plasma density was also lower.

Both the 13.56 and 27.12 MHz rf have been used to generate the plasma. The effect of rf frequency on low pressure inductive discharge has been experimentally investigated. There are two challenges to operate the ion source at 27.12 MHz. One is the higher radiation leakage generated by 27.12 MHz rf compared with 13.56 MHz. Radio frequency radiation leakage tends to be more severe at higher frequency. At the same input power, 27.12 MHz generates higher rf voltage across the antenna. When the operation pressure reaches the threshold value, the plasma resistance is usually low and very sensitive to the neutral pressure variation. Low plasma resistance increases the induction current, which generates even higher rf voltage across the two external antenna leads, creating rf radiation leakage and high voltage sparking problems. The shields to the antenna leads and the whole ion source play an important role in the success of developing the low-pressure ICP ion sources. In order to minimize the rf leakage, the antenna leads were totally enclosed by a high conductance copper sheet in the experimental setup. The ion source chamber was totally shielded by a copper sheet with a small observation window covered by copper mesh. The copper sheet covering the source chamber can also reduce the capacitive discharge between the two ends of the antenna. The other challenge in employing 27.12 MHz rf is the matching network design. Because of the large ion source diameter, the inductance of the antenna used in this work approaches 2.2 μH. Considering the additional conductance of the plasma, the lower end of the tuning capacitor should be a couple of pF in order to match 27.12 MHz rf. The stray capacitance can exceed this value if the matching box is not properly designed. A large matching box chamber was used in the experiment to lower the stray capacitance and a small induction coil was placed in parallel with the tuning capacitor to further reduce the capacitance. The small induction coil should be carefully designed, so that the total tuning capacitance is within the desired range.

Hydrogen gas was used to test the ion source performance. The plasma ignition pressure is not very sensitive to starting rf power higher than 200 W in continuous work (CW) mode. The matching network was tuned to match the plasma-on condition in the experiment. The matching resistance changed from less than 3 Ω (no plasma) to over 30 Ω after the plasma was switched on. It is very difficult to match both conditions very rapidly. Consequently, the amount of the net rf power delivered into the ion source is limited during plasma ignition. This explains why the ignition pressure is not as sensitive to input rf power higher than 200 W. However, the rf frequency has considerable influence on the plasma ignition. The ignition pressure for 13.56 MHz rf is about 5 mTorr, while 27.12 MHz rf can ignite the plasma at 3 mTorr. Low ignition pressure is especially important for sealed neutron tubes where the source pressure cannot be adjusted during ignition.

Oh and co-workers have investigated the effect of rf frequency on inductively coupled plasma in the collision-dominated region.[11] Their particle-in-cell/Monte Carlo simulation shows that low frequency rf generates higher density plasma at neutral pressure of several hundred mTorr. But the difference decreases when the pressure was changed from 300 to 100 mTorr. Their result at high pressure shows the trend that high frequency rf might be better than the low frequency rf at the low pressure regime. Our experimental result in the collisionless region agrees with this trend very well. The comparison of the ion source performance at 13.56 and 27.12 MHz is shown in Figs. 2 and 3. A 2.0 kV extraction voltage was applied to the ion source in all the ion beam current measurements. The extracted current should be proportional to the plasma density if not saturated. Figure 2 shows the extracted current at different pressures. The input rf powers for both frequencies were maintained at 400 W. The extracted current is considerably higher when 27.12 MHz rf power was used. The difference increases from 5% at 35 mTorr to around 25% at pressure lower than 10 mTorr. This trend coincides with Oh's simulation result at the high-pressure regime. Figure 3 compares the extracted current at different rf power when the source pressure was maintained at 3 mTorr. About 17%–25% more current can be extracted from the 27.12 MHz plasma. All these results

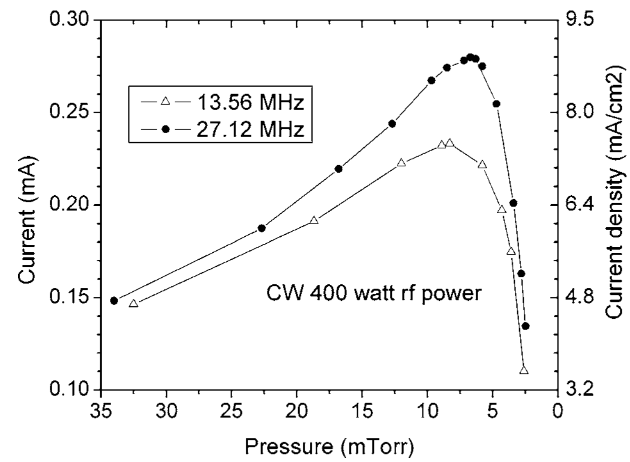

FIG. 2. Extracted current and current density at different pressure for 13.56 and 27.12 MHz rf discharge. Extraction aperture is 2 mm in diameter. rf input power was maintained at 400 W.

show that 27.12 MHz rf is more favorable for the low pressure ICP ion source. The threshold pressures at 400 W rf power are about 2.5 mTorr for 27.12 MHz rf and 2.7 mTorr for 13.56 MHz rf (as shown in Fig. 2). The ion sources developed in the current work can operate very stably at a pressure of 0.5 mTorr above the threshold. Usually high input rf power can reduce the threshold pressure. With input rf power higher than 400 W, the ion source can function reliably at 3 mTorr neutral gas pressure. It is possible to further reduce the operation pressure and increase the plasma density by increasing the input rf power. But high input rf power can cause serious heating problems on ion source body in CW mode. A multicusp ion source with internal antenna can be cooled with water flowing through the source chamber wall. Cooling the ion source with an external antenna is a challenging issue. Usually the insulator part (pyrex in the current ion source) on the chamber wall can be heated to a very high temperature. The over heating problem can be improved by using alumina as the ion source wall material because it has better heat conductivity. This can also be improved by operating the ion source in pulsed mode. The peak power can be set to a very high value. But the average power can be still as low as several hundred watts. A 27.12 MHz rf

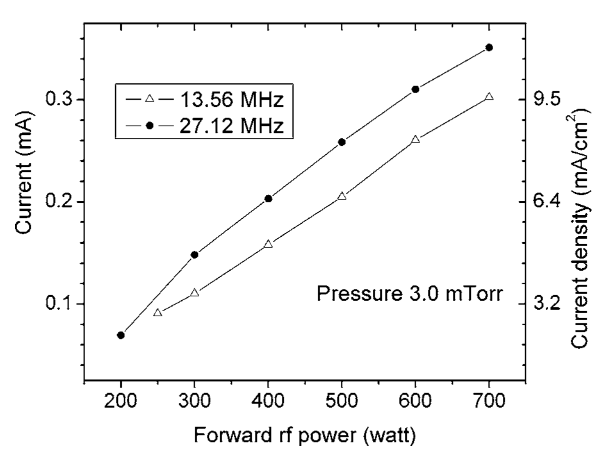

FIG. 3. Extracted current and current density at different power for 13.56 and 27.12 MHz rf discharge. Pressure was maintained at 3 mTorr.

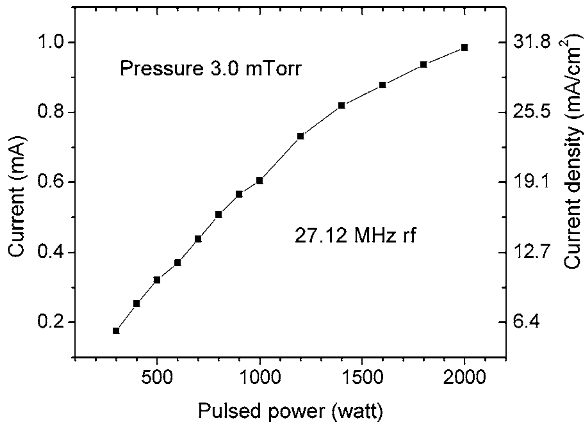

FIG. 4. Extracted current and current density at different 27.12 MHz rf power in pulsed mode. Pressure was maintained at 3 mTorr.

power supply was used to test the pulsed mode operation at 3 mTorr because of its low ignition pressure. Low ignition pressure ensures the stability of pulsed mode operation. The pulse period is set to 20 ms. The duty factor is 25%. The extracted current through a 2 mm diam aperture was measured at different pulsed rf powers, as shown in Fig. 4. Over 30 mA/cm^2 current was obtained at peak rf input power of 2 kW, which demonstrates the high power efficiency of the ion source developed in this work considering the large source volume and low operation pressure. The pulsed mode operation can be used together with a fast ion beam chopping system developed in our group for some neutron-based imaging systems. The ion beam chopping system has been proved to be able to produce ion beam pulses with 15 ns full width half maximum.[12]

Even though the working gas in neutron generators is either deuterium or a mixture of deuterium and tritium, the results obtained with hydrogen should be similar to those of deuterium or tritium. Actually, deuterium or tritium can be operated at lower pressure than hydrogen in the same ion sources due to the higher ion masses. The ion source developed in this work can work reliably at 3 mTorr with enough current for compact neutron generators.

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