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A preliminary study of a negative hydrogen PIG-type ion source for the compact cyclotron*

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Abstract: A Penning ion gauge (PIG)-type ion source has been used for the generation of negative hydrogen ions (H^-) as the internal ion source of the compact cyclotron. The discharge characteristics of the ion source are systematically studied for hydrogen operation at different discharge currents and gas flow rates on the prototype cyclotron. The preliminary study results for the low DC voltage H^- extraction measurements are presented in this paper. The H^- beam current is measured by the order of magnitude from several tens to hundreds of microamperes at different parameter conditions. The discussion and analysis for the experimental results are good for improving the design and working stability of the ion source.

Key words: PIG-type ion source, negative hydrogen, discharge characteristic, DC extraction

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1 Introduction

Recently, in the development of a cyclotron intended for the production of short-lived medical isotopes, some specific requirements have been imposed on the H^- ion source. A kind of PIG-type ion source has been widely used to generate H^- ions [1–3]. This type of ion source can be extremely compact, operate at small working gas flow, have a sufficiently long life-time, be easily changeable at a high ion beam current, and does not contaminate the accelerating system [4–6]. PIG-type ion sources have been used for a variety of applications, such as the sputtering and evaporation of surfaces, electromagnetic separation of isotopes, sealed-tube neutron generator and fusion applications [7–13].

In a typical ion source, electrons oscillate between two cathode electrodes inside a hollow anode to establish a high-voltage, low-pressure plasma discharge. An axial magnetic field increases the path length of ionizing electrons, making plasma production more efficient. For the internal ion source of a compact medical cyclotron, the special limitation in the central region makes the size of the plasma chamber only about a few centimeters.

The internal PIG-type H^- ion source has been widely used in compact medical cyclotrons abroad. However, the studies for the optimization of H^- formation in this kind of ion source have to be in depth because it has a few disadvantages, such as a high voltage loading spark and broken vacuum. The China Academy of Engineering Physics (CAEP) has developed an internal PIG-type H^- ion source for a compact medical cyclotron. The ion source is compact in size and has a simple internal structure. The designed components can reduce ion sputter and discharge ablation effectively, and avoid flashover and complete breakdown. The arc establishment is quick and stable. The ion source possesses a large arc current, long life-time (at present, over 20 hours) and easy maintenance. The discharge characteristics of the ion source are systematically studied on the prototype cyclotron. The vacuum can be maintained at a proper value while the internal ion source is operating. The designed H^- DC extraction structure and the method of measurement can reduce the sparks and corona discharge. The H^- beam current can be detected credibly. The studies of the internal negative

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ion source can promote the development of cyclotrons, proton accelerators and other ion generators.

2 The experimental setup

The compact PIG-type ion source consists of two main components: the cathode and the hollow anode. A couple of cylindrical cathodes are located at either end of the hollow anode. The cathode is made of tantalum because of its low sputtering coefficient and good conduction. The hollow anode with an ion exit slit (6 mm×0.4 mm, 0.51 mm thick) in the middle part (by height), is made of copper. A tantalum ring is set between the cathode and the anode to control the plasma boundary and reduce the discharge ablation of the anode. Electrons emitted from either cathode are accelerated into the hollow anode and trapped axially by an electrostatic well and radially by the magnetic field. The cathodes are heated by ion impact and there is no need for additional filament heating, so it is possible to minimize the ion source dimensions to 50 mm (high) and 13 mm (wide).

The magnetic field of about 0.7 T is excited by a 75 A coil current on the ion source test-stand. The average magnetic field at the cyclotron centre is about 1.2 T. A schematic of the electrical setup is shown in Fig. 1(a). The cathodes are powered by a −2 kV 2 A pulsed/DC power supply. The DC extraction measurements at low voltages were made on the test-stand. As an extractor, a screen box was placed about 0.3 cm downstream of the ion source to extract negative ions and an electrode for beam collection. The extractor and the collector have the same potential, but they are insulated from each other. As shown in Fig. 1(b), in order to avoid interference from other disturbing signals, the collector was screened by the extractor. The ion beams are affected only by the magnetic field after being pulled by the extractor.

All results presented in the paper are for hydrogen injection directly into the ion source. The pressure inside the vacuum chamber is from 10^{-4} Pa to 10^{-3} Pa when the hydrogen flow rate is from 0 to 20 cm^3/min at STP. Generally, the pressure of the cyclotron is of the order of magnitude 10^{-3} Pa for using an internal ion source. A theoretical calculation shows the pressure inside the ion source is approximately the order of magnitude 10 to 100 larger than the chamber pressure. A first-order calculation [10] also gives the same result. The ion source is operated in a large vacuum chamber which can maintain a lower background pressure.

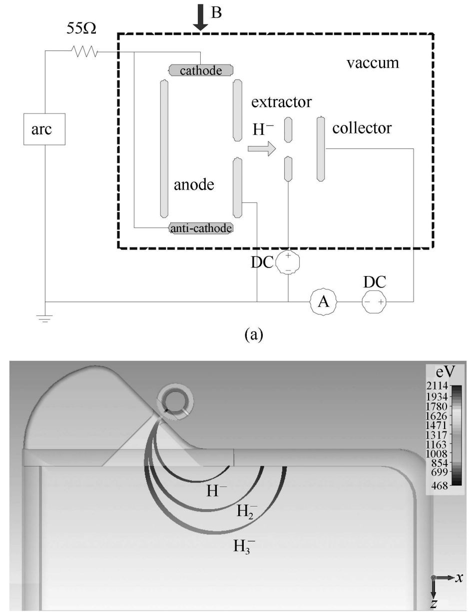

Fig. 1. (a) Schematic of the electrical setup of the ion source and (b) the trajectories of the negative hydrogen ions in the measurement area.

3 Results and analysis

The discharge characteristics of the ion source were studied in terms of arc current, gas flow rate and magnetic field on the prototype cyclotron. For each continuous discharge, the gas flow rate, the arc current and voltage were recorded. The arc voltage-current characteristics are shown in Fig. 2. A bright pink plasma inside the ion source can be seen at the beginning and then becomes visually brighter as the arc current increases. The current of the arc discharge is supplied by the thermionic emission. The ion source is under a self-heating cathode condition. As shown in the figure, the voltage-current relationship has a negative slope (as the current increases, the voltage decreases) at the whole arc currents. As the discharge current increases, large numbers of high-energy ions bombard the cathode, which make the temperature increase. The experimental voltage-current curve is in accord with the arc discharge characteristics. Actually, the ion source has another cold-cathode working mode, which has 1.7–1.8 kV discharge voltages and 0.03–0.04 A discharge currents. Different working modes of the ion source should be chosen based on the ion beam requirements of the cyclotron.

Figure 3 shows the arc voltage versus the gas flow rate of the hydrogen. At low gas flow rate (1–5 cm^3/min), the arc voltage drops rapidly. From 6 to 20 cm^3/min, the arc voltage changes slightly with increasing gas flow rate at a fixed arc current. Visual observation also shows the brighter pink plasma inside the ion source as the gas flow rate increases. For a constant current power supply, the arc voltage changes as the load changes. In general, the result is as what has been expected. As the gas flow rate increases, more gas becomes available for plasma production and the resistance of the ion source decreases, which makes the arc voltage decrease.

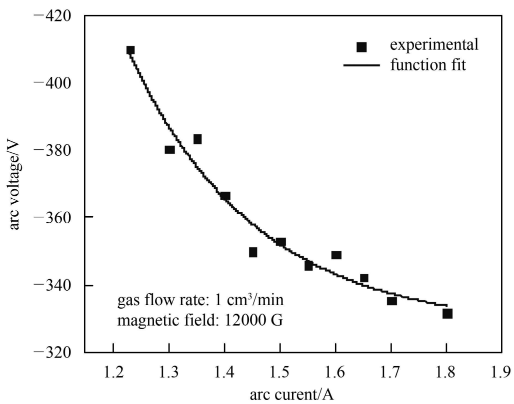

Fig. 2. The arc voltage of ion source with respect to the arc current.

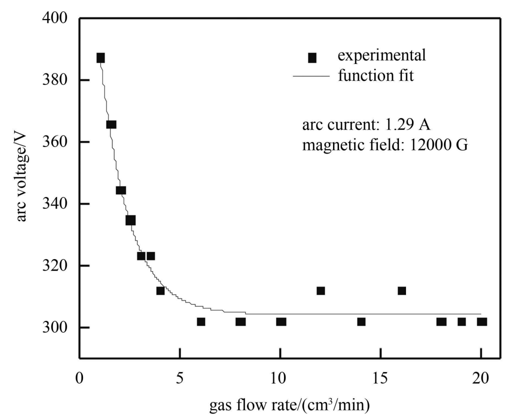

Fig. 3. The arc voltage of ion source with respect to the gas flow rate.

The design study on the magnet of the cyclotron is important. The proper magnetic field is related to the operation and the stability of the internal ion source. Fig. 4 shows the arc power of the ion source versus the magnetic field. The arc power is almost constant as the magnetic field changes at a fixed arc current and gas flow rate. Actually, the relationship between the magnetic field and the ion source plasma is rather complex [14]. The axial magnetic field restricts the radial movement of the electrons, which reduces them hitting the wall of the hollow anode and makes the discharge plasma uniform. The magnetic field and electric field make the electrons move as $E\times B$ track, which prolongs their moving distance and increases the collision probability. The changing of the magnetic field will affect the H^- formation and extraction. More detailed experiments for the relationship between the ion source structures and the H^- yields should be carried out with different magnetic fields.

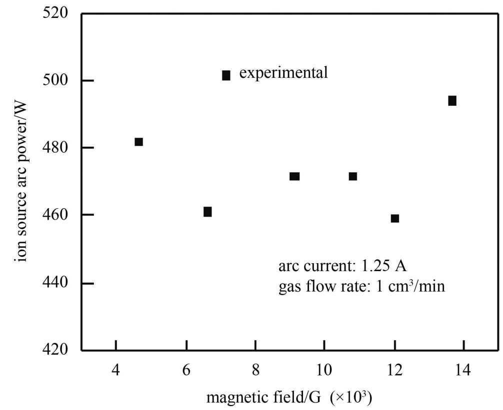

Fig. 4. The arc power of the ion source with respect to the magnetic field.

The H^- extraction experiments have been carried out with low DC voltage up to 2 kV on the test-stand. The details of the experimental setup have been described in Section 2. The trajectories of the negative hydrogen ions in the measurement area are shown in Fig. 1(b). The extracted beams may contain various particles, such as electron, H^-, H_2^- and H_3^-. It is hard for the electron to enter the measurement area to be collected in such a strong magnetic field and low extractor voltage. The trajectories of negative hydrogen ions (H^-, H_2^- and H_3^-) are separated for different q/m. The collector was placed according to H^- trajectory in the beam current measurement. The measured DC H^- beam current versus gas flow rate is shown in Fig. 5. As shown in the figure, the H^- beam current increases as the gas flow rate increases from 1 to 5 cm^3/min. When the gas flow rate is larger than 5 cm^3/min, the extractor electrode easily produces visible sparks or corona discharge, which makes the H^- beam signal hard to measure precisely. The gas flow rate, in other words, the gas pressure, is sensitive to H^- production. The high gas flow rate is advantageous to H^- formation in the ion source, but it increases H^-destruction in the extraction region at the same time. Furthermore, the relationship between H^- beam current and the arc current are obtained. As the arc current increases, the extracted H^- beam current increases, which means more plasmas are formed and available for the extraction in the ion source.

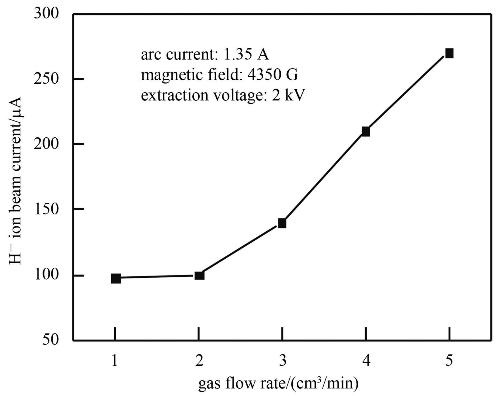

Fig. 5. The H^- beam current with respect to the gas flow rate.

The H^- beam current with respect to the DC extractor voltage is shown in Fig. 6. The solid line corresponds to the fitted curve that was calculated according to the function $BC\,(\mu A) = -50.92{+}44.51x^{3/2}$. The dependence of DC voltage on beam current can be approximately extrapolated by the above function. The dashed line corresponds to the calculated curve using the ideal planar diode space charge limited current [14] with the extraction gap 3 mm and exit slit 6 mm×0.4 mm. As shown in the figure, the H^- beam's current increases as the DC voltage increases. Actually, the beam current cannot increase all the time. There exists the emission limited current of the ion source, which is related to the plasma density and the electron temperature, for certain extracted voltage [14]. We obtained the H^- beam current of about several tens to hundreds microamperes with low DC voltage on the test-stand. The preliminary RF H^- beam current measurements were also carried out on the prototype cyclotron with 1% RF duty operation, the arc current 1.3 A, and gas flow rate of 4 cm^3/min. The beam probe was located at 50 mm to 380 mm from the cyclotron centre. The obtained peak value of the H^- beam current is about several microamperes. The optimization experiments are being carried out in order to increase the H^- formation in the ion source and decrease the H^- destruction in the extraction region and the cyclotron.

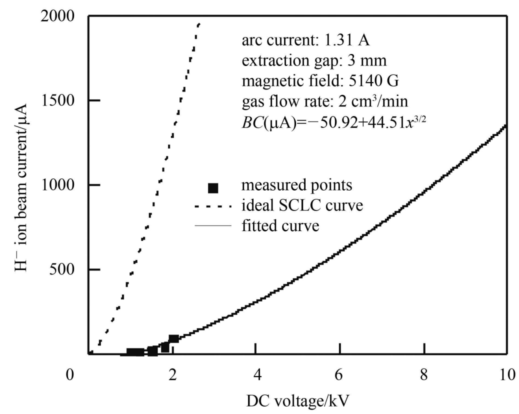

Fig. 6. The H^- beam current with respect to the DC extractor voltage.

4 Conclusion

A PIG-type ion source has been designed as an internal ion source of a compact medical cyclotron. In order to obtain relatively large H^- beam current (~1 mA), the operation of the ion source has been tested. The discharge characteristics are studied for hydrogen operation at different discharge currents and gas flow rates. The gas flow rate and arc current are sensitive to the H^- production. A large arc current could obtain a large H^- beam current. Proper gas flow rate (4 to 5 cm^3/min) is confirmed for the optimization of H^- production. The preliminary study results for the H^- DC extraction measurements are presented in this paper. At present, more detailed beam commissioning experiments are being carried out on the prototype cyclotron.

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