A compact helicon ion source has been designed for a neutron generator. Energetic deuterium beams of 120 keV from this ion source will be directed onto a Ti-coated copper target where D–D nuclear fusion reactions take place and generate $10^8$ n/s of neutrons. High-density radio frequency (rf) plasma sources such as a helicon plasma source, known for its highest efficiency of generating high-density plasmas, are chosen for the development of a high-current density compact ion source. Highest plasma densities for hydrogen plasmas are obtained at relatively low magnetic fields of 100–300 G although plasma densities of helicon plasmas are well known to be almost linearly dependent on magnetic field strength. With Nagoya type III antenna, plasma densities of up to $2 \times 10^{11}$ cm$^{-3}$ are obtained with 1.1 kW rf power at the frequency of 13.56 MHz. With the prototype helicon ion source, hydrogen beam currents of up to 44 mA at 23 kV have been extracted in continuous wave operations with the beam current density of 28.5 mA/cm$^2$. With helical antenna instead of Nagoya type III antenna, higher plasma densities of up to $10^{12}$ cm$^{-3}$ are obtained and open up a new possibility of much higher beam current densities. © 2004 American Institute of Physics. [DOI: 10.1063/1.1699509]
axial magnetic field strength should be supplied with either electromagnet or permanent magnet. Low magnetic fields of up to 1 kG are provided with the electromagnet and higher magnetic fields are generated with the permanent magnet system. Langmuir probes are installed to measure plasma characteristics.

Plasma densities in helicon plasmas are generally known to be proportional to axial magnetic field strengths. With light gases such as hydrogen, however, the plasma density shows a peak in low magnetic field.

Wide range of axial magnetic field strength beyond 1 kG has been tested to find optimum field strength. High-density plasmas are observed in hydrogen discharge at low magnetic fields in the range of 100–300 G as shown in Fig. 3. Although permanent magnet systems are favored in ion source because of their simplicitie, an electromagnet system is equipped for a prototype helicon plasma source to provide such an appropriate magnetic field configuration.

III. COMPACT HELICON ION SOURCE

A helicon ion source was designed and constructed with the prototype helicon plasma source. Two-electrode extraction system is installed to the one side of the discharge tube, and rf power will be transmitted through two blocking capacitors, which is located between matching box and rf power supply and providing high voltage isolation. Turbo molecular pump of 850 l/s and rotary pump of 1000 l/m are equipped as a vacuum system to provide sufficient differential pumping for the ion source. In the case of 6 mm single aperture, it is possible to get lower downstream pressures by factor of about 20 than those of plasma generation region. Two-electrode extraction system for the helicon ion source has been designed with IGUN code. In the simulation, the required plasma density of \(2.1 \times 10^{11} \text{ cm}^{-3}\) is required in order to get a hydrogen beam of 50 mA with extraction voltage of 50 kV and extraction aperture diameter of 10 mm. Beam optics becomes most suitable at the electrode gap of 12 mm as shown in Fig. 4.

Hydrogen beam extraction has been performed with the prototype ion source. In the experiment using single-aperture electrode of diameter 6 mm and gap distance 6.6 mm, hydrogen beam currents of 6.6 mA with beam current density...
of 23.3 mA/cm² are extracted with 1 kW rf power at the extraction voltage of 30 kV. The Faraday cup with the diameter of 45 mm located at 12 cm from the extraction electrode has measured collected beam currents. Collected beam currents are compared with total beam currents measured by the extraction power supply currents as shown in Fig. 5, showing clear transition from underfocused diverging beam to well-focused parallel beam near 13 kV.

Beam dynamics has been simulated with IGUN code, providing valuable information. An appropriate plasma density for parallel beam extraction has been identified to be about $1.5 \times 10^{11}$ cm⁻³ with the given extraction electric field configuration, which is confirmed to be similar to the plasma density measured by Langmuir probes. However, simulation shows much higher beam current of 17 mA instead of measured beam current of 5.3 mA.

With the given plasma density, higher beam currents of 50 mA can be reached either by increasing extraction area with the fixed beam current density or by increasing extraction voltage with appropriate gap distance provided. Increasing single hole diameter generates hydrogen beam current of only 10.8 mA since the single-aperture electrode diameter has been limited up to 10 mm because of escaping plasmas with large single aperture. To overcome this problem, beam extraction with wider area has been performed with multi-aperture electrode. At about 800 W–1 kW of rf power, seven-hole electrode with different diameters of 4 mm, 5.3 mm, and 6 mm are used. In this configuration, hydrogen beam currents of up to 44 mA with the current density of 28.5 mA/cm² are extracted as shown in Fig. 6. Maximum beam currents are limited due to the limited power supply capacity since beam optics without optimization have a large amount of beam current losses outside of the Faraday cup.

Another way of increasing beam currents is to increase beam current density via improvement of plasma density. Replacing Nagoya type III antenna with helical type antenna as shown in Fig. 7, 10 times higher plasma densities of $10^{12}$ cm⁻³ are obtained as shown in Fig. 8. With this high density plasmas, 10 times higher extracted beam current densities are expected. Beam extraction experiments with this new high-density plasma source will be performed.

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