Discharge Characteristics of Large-Area High-Power RF Ion Source for Positive and Negative Neutral Beam Injectors

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Abstract A large-area high-power radio-frequency (RF) driven ion source was developed for positive and negative neutral beam injectors at the Korea Atomic Energy Research Institute (KAERI). The RF ion source consists of a driver region, including a helical antenna and a discharge chamber, and an expansion region. RF power can be transferred at up to 10 kW with a fixed frequency of 2 MHz through an optimized RF matching system. An actively water-cooled Faraday shield is located inside the driver region of the ion source for the stable and steady-state operations of high-power RF discharge. Plasma ignition of the ion source is initiated by the injection of argon-gas without a starter-filament heating, and the argon-gas is then slowly exchanged by the injection of hydrogen-gas to produce pure hydrogen plasmas. The uniformities of the plasma parameter, such as a plasma density and an electron temperature, are measured at the lowest area of the driver region using two RF-compensated electrostatic probes along the direction of the short- and long-dimensions of the driver region. The plasma parameters will be compared with those obtained at the lowest area of the expansion bucket to analyze the plasma expansion properties from the driver region to the expansion region.

Keywords: neutral beam injector, RF ion source, plasma ignition, power loading, plasma parameters

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(Some figures may appear in colour only in the online journal)

1 Introduction

A large-area high-power RF (radio frequency)-driven negative ion source is being developed in Germany for the heating and current drive of ITER plasmas [1,2]. Negative hydrogen (deuterium) ion sources, including the high energy beam acceleration, are major components of neutral beam injection systems in future large-scale fusion experiments such as ITER and DEMO. RF ion sources for the production of positive hydrogen (deuterium) ions have been successfully developed at IPP (Max-Planck-Institute for Plasma Physics, Garching, Germany) for ASDEX-U and W7-AS neutral beam injection (NBI) systems [3,4]. The first NBI system (NBI-1) was also successfully developed and operated for the KSTAR tokamak [5,6]. Three long-pulse ion sources (LPIS-1, -2 and -3) of the NBI-1 system consist of a magnetic bucket plasma generator with multi-pole cusp fields, a filament heating structure, and a set of tetrode accelerators with circular apertures. There are development and testing plans for the large-area test-RF ion sources at KAERI to extract the positive ions, which can be used for the second NBI (NBI-2) system of KSTAR, and to extract the negative ions for future fusion devices such as a Fusion Neutron Source and Korea-DEMO (or Asia-DEMO) [7,8].

2 Experimental setup

A large-area test-RF ion source consists of a driver region, including a helical antenna (6-turn copper tube with an outer diameter of 6 mm including the inner flow of cooling water) and a discharge chamber (quartz tube with an inner diameter of 200 mm, a height of 150 mm, and a thickness of 8 mm), and an expansion region (magnetic bucket structure of prototype LPIS in KAERI) [9]. The dimensions of the magnetic bucket are a cross section of $64 \times 26$ cm$^2$ and a 32 cm depth. RF power can be transferred to the antenna at up to 10 kW with a fixed frequency of 2 MHz through a matching circuit (auto- and manual-matching apparatus), as shown in Fig. 1. The helical antenna was designed with...
an inductance of about 10 $\mu$H±20%. The outside of the driver region was shielded by a metal housing to prevent the leakage of RF energy. Permanent magnets were arranged linearly inside the upper flange of the driver region with a four-group array of the N-S-N-S surface poles. This magnet array may support the improvement of plasma uniformity in the driver region. Three air-cooling fans were installed in the plates of the metal housing.

A slanted slot-type Faraday shield (a thickness of 4 mm including a total of 24 slots with a slot width of 1.5 mm) made by bending a copper plate (divided by 6 paths of a rectangular cooling-water channel with a width of 5 mm and a depth of 1 mm), including an actively-cooled water path, was inserted inside the quartz tube. The water-cooled Faraday shield was installed to minimize the plasma heat load on the inner wall of the quartz tube during the high-power long-pulse RF discharges, even though a large amount of RF power could be lost to the Faraday shield structure [9]. The beam boundary of extracted negative ions was designated for the negative beam accelerator (Hole arrangement of 5×5 with 25 circular apertures of diameter 14 mm) under the expansion region of the test-RF ion source. The high vacuum of the test-RF ion source was sustained by a TMP (520 L/s) and a backup pump of a dry scroll type. The typical base pressure was 0.001–0.01 Pa, and the nominal operating pressure was 0.3–0.6 Pa with hydrogen gas. Argon gas was injected initially for the ignition of RF discharge, and then pure hydrogen gas instead of argon gas was injected finally for the hydrogen RF plasma sustainment. The argon gas ignition method of RF-driven ion source may be a candidate for generation of the RF-driven hydrogen plasmas without a typical starter filament operation. It was found that the argon component disappeared by using the measurement of the spectrometer during a few minutes after the stop of argon gas injection, even though the argon injection for the plasma ignition could increase the sputtering effect on the discharge wall.

The uniformities of the plasma parameter, such as a plasma density and an electron temperature, are measured at the lowest area (a distance of about 5 cm from the bottom of the driver chamber) of the driver region using two typical RF-uncompensated electrostatic probes, supported by two movable probe driving systems, along the radial direction of the driver region. This effort was the first diagnostics of the driver region for the test RF ion source. The plasma parameters are compared with those obtained at the lowest area (a distance of about 35 cm from the bottom of the driver chamber) of the expansion bucket region along the direction of the short- and long-dimensions using two RF-compensated electrostatic probes to understand the plasma expansion properties from the driver region to the expansion region [10].

![Fig.1 Photos and matching network circuit of the test RF ion source system](image-url)
3 Analyses

The surface temperature of the quartz tube in the driver region was monitored usually by using an IR camera during the discharge of the test RF ion source. The flow rate (2.0 LPM at a nominal water pressure of 6 bar) and the temperature of the cooling water in the Faraday shield were monitored typically during the operation of the test RF ion source. Conventional electrostatic Langmuir probes (RF-uncompensated probes) including a Mo-tip (a diameter of 1 mm and a length of 3 mm) were used for the diagnostics of the RF-driven plasmas under the lowest position of the driver region. The uniformities of the plasma density and electron temperature were measured using two electrostatic probes in the directions of radial dimension for the variation of RF power and discharge (hydrogen) gas pressure.

Two RF-compensated probes, including a tungsten tip (a diameter of 0.1 mm and a length of 2.0 mm) and supported by two movable probe driving systems, were used for the diagnostics of the test RF ion source under the lowest position of the expansion region [11−13]. The RF-compensated probes were moved inside the strong magnetic field of about 185 Gauss. The permanent magnets were installed as a filter field for negative ion production. The uniformities and profiles of the plasma density and electron temperature were measured along the directions of the short and the long dimensions for various RF powers and discharge (hydrogen) gas pressures. The electrostatic probes were scanned by using a sweep voltage of −40 V to +40 V at a fixed frequency of 5 Hz. Fig. 2 shows an example of a typical probe I-V curve obtained with an RF power of 2 kW by using the RF-compensated Langmuir probes under the expansion region.

4 Experimental results and discussion

Fig. 3 shows the uniformity of the plasma (ion) density along the long dimension under the lowest position of the driver region and expansion bucket region at an RF power of 8 kW, a (hydrogen) gas pressure of 0.68 Pa and 0.32 Pa, respectively. Higher gas pressure of the driver region was caused by the molecular out-gassing from the surface heating of the probe holding structure, during the sustainment of high power RF plasma. The plasma uniformity along the short dimension was a meaningless result under the lowest position of the expansion region because of the parallel scanning direction along the strong magnetic filter-field for negative ion production. Furthermore, the plasma uniformity along the short dimension was a similar shape under the lowest position of the driver region. The density uniformities (i.e., \((\text{maximum value−minimum value)/maximum value})\times 100\%\) from the central position to a driver inner boundary (an inner radius of 9.3 cm) under the driver region and those of negative beam boundary (a negative beam area of 9.4 × 9.4 cm²) along the long dimension under the bucket region are 22% and 37%, respectively. These non-uniform plasma densities may affect the ion and electron uniformities near the beam accelerator and may induce the higher non-uniformity near the beam accelerator than the typical requirement of <10% for the large-area ion source. Thus, it may be necessary to modify the structure and configuration of the driver region and expansion region to reach the required plasma uniformity near the beam accelerator. The plasma densities under the lowest position of the driver region are 20 times higher than those under the expansion region, and the low density distribution was caused by the strong magnetic field near the plasma grid surface for the negative ion beam production. The plasma density with a strong magnetic field was about 2 times lower than the previous measurement without the effect of the magnetic field [14]. Therefore, the strong magnetic field may affect the reduction of plasma ion and electron particles, even though the electron temperature was reduced from ∼3.0 eV to ∼1.0 eV, which may increase the population of negative ion particles.
Plasma densities versus RF power loads with a (hydrogen) gas pressure of 0.32 Pa are shown in Fig. 4. The position of the electrostatic probe in the long dimensions was fixed at the central position of the driver and expansion regions. The plasma density increased with increasing RF power up to 10 kW. However, the slope of the plasma density decreased gradually with increasing loaded RF power. Thus, it is necessary to define clearly for the characteristics of high power RF plasma generation such as the plasma density variation with the loaded RF power. The cooling water temperature of the Faraday shield increased gradually with the increase of loaded RF power. These results imply that the production of a high-density plasma (a plasma density of \( \sim 10^{12} \) cm\(^{-3} \)) and the minimization of power loss through the Faraday shield structure may be difficult in the development of a high-power RF ion source. Therefore, the effective design structure of the RF ion source is very important if uniform and high-density plasmas are to be generated.

![Fig.4](image-url)  
**Fig.4** Plasma (ion) density versus RF power loads at the central position of the driver and expansion regions (gas pressure of 0.32 Pa)

The distribution of electron temperatures measured using an RF-compensated probe was about 0.7–1.2 eV under the lowest position of the expansion region, including the effect of the strong magnetic filter-field for the negative ion production. The uniformity of electron temperatures inside the beam extraction dimension, scanned by the perpendicular direction to the magnetic filter-field, under the lowest position of the expansion region was 41.7%. The distribution of electron temperatures measured using an RF-uncompensated probe was about 8–11 eV under the lowest position of the driver region. The distortion \( I-V \) curves for the analysis of electron temperature caused by the effect of RF oscillation on the electrostatic probe signal was increased clearly with the increase of RF power loads. Therefore, an RF compensated Langmuir probe is essential to obtain the plasma parameters for diagnostics of the RF-driven plasmas.

5 Conclusions

There are the development and testing plans for positive and negative RF ion sources at KAERI to extract positive and negative ions, which can be used for the neutral beam injectors of KSTAR, Fusion Neutron Source, Korea-DEMO (or Asia-DEMO), and future fusion devices. A test-RF ion source was developed with an RF power of 10 kW at KAERI, and the plasma characteristics of the test RF ion source were investigated with the distribution of plasma densities and electron temperatures. A prototype RF ion source including a maximum RF power of 50 kW is being developed at KAERI for investigation of high-power discharge characteristics and steady-state operation properties.

References


Chen F F. 2003, Langmuir Probe Diagnostics. Mini-Course on Plasma Diagnostics in IEEE-ICOPS meeting, June 05, Korea


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