Status Report on the Development of a Compact Permanent Magnet Electron Cyclotron Resonance Ion Source for a D–D Neutron Generator at KAERI

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1. Introduction

Korea Atomic Energy Research Institute (KAERI) is currently developing a mobile deuterium – deuterium (D–D) neutron generator with a neutron yield rate of over 10^{10} neutrons per second for various applications. The neutron generator functions by fusion reactions between accelerated D^+ ions through accelerating electrodes and the nuclei within a stationary cold target. An ion source in the neutron generator plays an essential role in supplying the D^+ ions to the electrodes. We selected the electron cyclotron resonance (ECR) plasma source as the ion source due to its high intensity ion beams at low operating pressures ranging from sub-mTorr to a few mTorr. This ensures extraction and acceleration of the D^+ ions with minimizing energy loss by collisions with background gas molecules. For the development of the neutron generator, two compact permanent magnet ECR ion source systems have been fabricated [1~3]. These ECR ion sources with a plasma electrode aperture of 10-mm diameter will provide sufficient D^+ ions of 50 mA for acceleration electrodes of 200 kV inside the neutron generator. In this article, current status of the ECR ion source development and the first results of the ion sources are presented and discussed.

2. Status of ECR Ion Source Development for a D–D Neutron Generator

The goal of the ion source is to deliver at least 50 mA D^+ for the neutron generator. For achieving this goal, a dual-track strategy was proposed: One is using a commercial ion source (Adelphi Technology Inc.) and the other is using a self-developed ion source called KAERI ECR ion source. Since the related project was launched and the proposal was selected, we have been constructed and tested two test beds equipped with the commercial ion source (see Fig. 1 and Table I.) and with the KAERI ECR ion source, respectively. To date, the beam extraction experiments of the commercial ion source and the first plasma generation of the KAERI ECR ion source have been successfully completed. In this report, we present current status of ECR ion source systems, especially the KAERI ECR ion source, and some experimental results on the plasma and ion beam of the systems.

The KAERI ECR ion source has a plasma chamber of 10 cm in inner diameter and 10 cm in inner length. Its wave frequency and the magnetic field intensity corresponding to the ECR zone, B_{ECR}, are 2.45 GHz and 875 G, respectively.

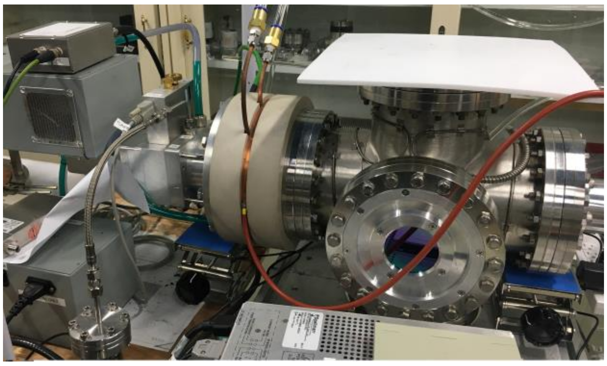

Fig. 1. Picture of the commercial ECR ion source mounted on a testbed.

Table I: Specifications of the commercial ECR ion source

Parameters	Values
Max. current density	> 100 mA/cm^2 (D^2)
Microwave max. power	600 W
Wave frequency	2.45 GHz
Standard operating mode	Continuous

For the development of the high intensity ion source, following two considerations were reflected in the design at the conceptual stage: (1) Since electron heating is effectively enhanced by ECR and right hand polarized wave (R-wave) in the region where the magnetic flux density ranges between B_{ECR} and $1.3B_{ECR}$ [3], it is favorable to put the magnetic flux densities along the chamber axis (or z-axis) within $B_{ECR} < B < 1.3B_{ECR}$ as much as possible for obtaining a high-density plasma. (2) In order to prevent the ions from being deflected by stray magnetic fields in the vicinity of the extraction/acceleration system, resulting in beam emittance growth, the magnetic field intensities near acceleration electrodes are required to be kept as low as possible. Taking these considerations into account, we have analyzed and optimized the magnetic field configuration with three neodymium iron boron (NdFeB) ring permanent magnets and two iron yokes using OPERA3D (Cobham plc) as illustrated in Fig. 2. Based on the optimum magnetic field configuration, the design and fabrication of the KAERI ECR ion source have been carried out. Fig. 3 (a) and (b) illustrate a 3D sketch and a picture of the assembled KAERI ECR ion source.

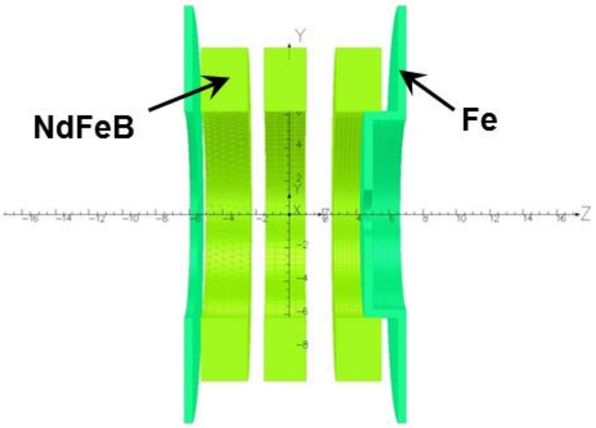

Fig. 2. The optimum magnetic field configuration with three NdFeB ring permanent magnets and two iron yokes for the ECR ion source.

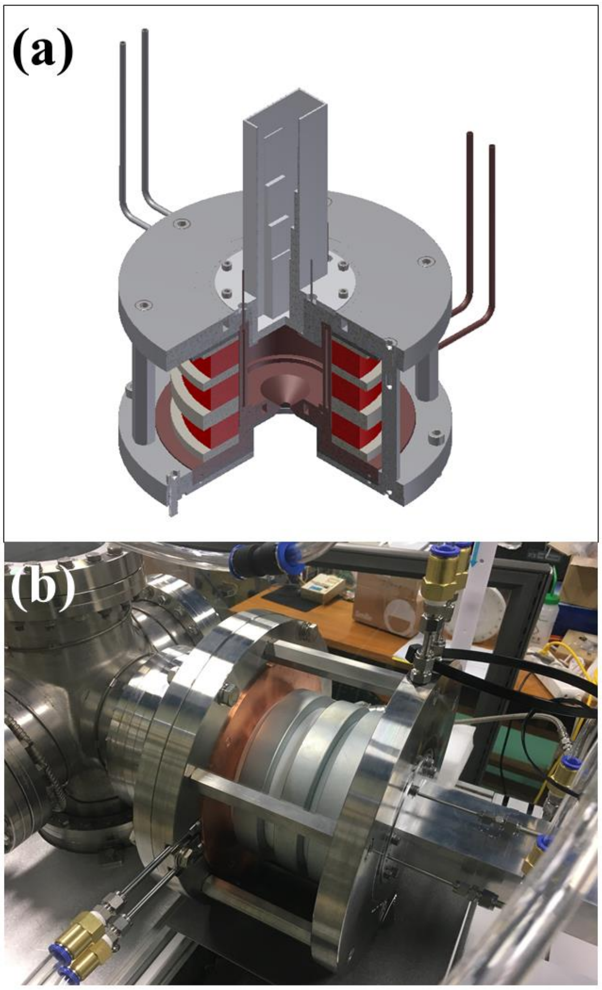

Fig. 3. (a) 3D sketch and (b) picture of the assembled KAERI ECR ion source mounted on a testbed.

Fig. 4 shows the measured magnetic flux density distribution along the z-axis in the KAERI ECR ion source using a Gauss meter (F. W. BELL model 7030, Sypris, Orlando, FL).

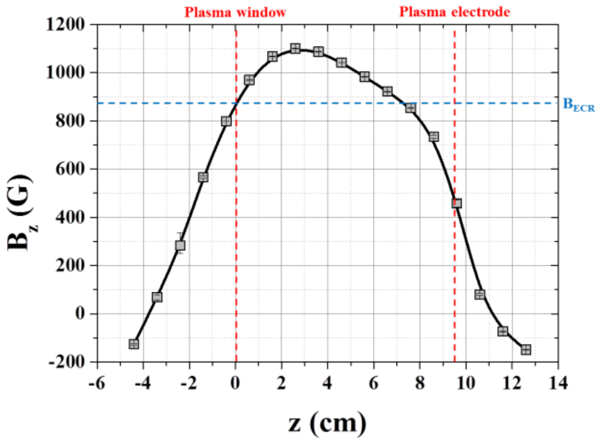

Fig. 4. The measured magnetic flux density distribution along the chamber axis of the KAERI ECR ion source.

Note that the region where $B_{ECR} < B < 1.3B_{ECR}$ accounts for about 70% of the inner chamber length along the centerline, and the stray field is reduced from 450 G to 0 G within 1.5 cm. This indicates that the assembled ion source satisfies fully the above two design considerations.

The ion source body and plasma electrode of the KAERI ECR ion source were made of copper. These copper structures include water-cooling jackets, which leads to protection of the chamber and magnets from thermal load caused by the plasma. A quartz plate together with a boron nitride (BN) plate is utilized as an RF window. The BN plate keeps the RF window from thermal shock damage by backstream electrons.

3. First Results of the Compact Permanent Magnet ECR Ion Sources

For investigating beam characterization of the commercial ion source, we devised a system that consists of a Faraday cup, a plasma electrode and extraction electrode with apertures of 3-mm diameter, and measured preliminarily deuterium ion beams using the system. The Table II shows the extracted beam current as a function of extraction voltage at a fixed microwave power of 350 W.

Table II: The extracted beam current as a function of extraction voltage at a fixed microwave power of 350W.

Extraction voltage	Beam current density
0 kV	14.7 mA/cm^2
1 kV	57.7 mA/cm^2
2 kV	63.0 mA/cm^2

The gas pressure was set at 1mTorr D_2. Because the beam current density of 63.0 mA/cm^2 at the extraction voltage of 2 kV corresponds to about 50 mA at an aperture diameter of 10-mm diameter, it is confirmed that performance of the commercial ion source is enough for the neutron generator.

Recently, the first plasma of the KAERI ECR ion source was ignited as shown in Fig. 5.

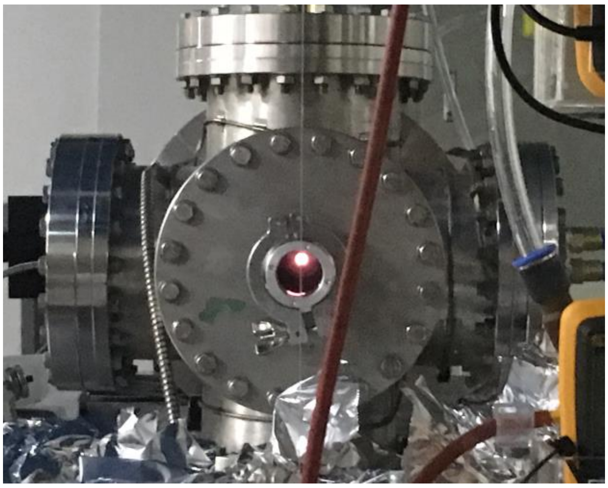

Fig. 5. The first plasma of the KAERI ECR ion source.

A Langmuir probe system and a dedicated extraction system together with a Faraday cup for the plasma and beam characterization of the ion source are currently under construction. More details on the measurement and experimental results will be reported soon.

4. Summary

For developing a versatile and mobile D–D neutron generator with a neutron yield rate of over 10^{10} neutrons per second, two compact permanent magnet ECR ion source systems have been designed and fabricated using a commercial ion source and a self-developed ion source called KAERI ECR ion source. The KAERI ECR ion source has been devised to enhance the electron heating and to minimize the deflection of the ion beams. Several preliminary experiments for characterization of the ECR ion sources have been carried out. Together with elaborate plasma and beam diagnostics, a more accurate characterization will be done soon.

REFERENCES

[1] T. Taylor and J. S.C. Wills, A High-current Low-emittance DC ECR Proton Source, Nuclear Instruments and Methods in Physics Research, Vol.A309, p.37, 1991.
[2] L. Neri, L. Celona, S. Gammino, D. Mascali, G. Castro, G. Torrisi, B. Cheymol, A. Ponton, A. Galatà, G. Patti, A. Gozzo, L. Lega, and G. Ciavola, Improved Design of Proton Source and Low Energy Beam Transport Line for European Spallation Source, Review of Scientific Instruments, Vol.85, 02A723, 2014.
[3] S. Gammino, L. Celona, G. Ciavola, F. Maimone, and D. Mascali, Review on High Current 2.45 GHz Electron Cyclotron Resonance Sources, Review of Scientific Instruments, Vol.81, 02B313, 2010.