18pE-5

Review of ion source development for industrial applications and neutral beam injectors for fusion

産業応用及び核融合中性粒子入射装置用イオン源開発のレビュー

Masanobu Tanaka
田中政信

Innovative Collaboration Organization, Kumamoto University
2-39-1, Kurokami, Chuou-ku, Kumamoto-shi 860-8555, Japan
熊本大学、イノベーション推進機構 〒860-8555 熊本市中央区黒髪2-39-1

Ion sources have been developed for both industrial applications and neutral beam injectors (NBI) of fusion devices. An ion source is composed of three main parts, which are a plasma generator, an ion beam extraction electrode system, and insulation supports of electrodes. Multidiscipline research subjects are required for the three parts, such as filamentless discharges for long life time, negative ion production for the plasma generators, low beam divergence, beam focusing, control of magnetic beam deflection for the electrode system, and stable insulation of vacuum gaps and insulator surfaces for the insulation supports. This paper briefly shows research works on the subjects.

1. Introduction

Ion sources have been developed for varieties of applications such as medical accelerators [1-3], industrial applications [4,5], and NBI for fusion [6-15]. Main subjects of the R&D are ion production with plasma generators, electrostatic ion beam extraction from the plasma with electrodes, and electrical insulation of the electrodes and supports. This paper briefly reviews the former two subjects of the works. The medical and industrial applications were reviewed for works in Hitachi, Ltd. Fusion ion source was researched in collaborations among JAEA, NIFS, ITER organization, and Hitachi, Ltd..

2. Microwave ion source for medical accelerators

Medical accelerators are recently developed for ion beam therapy [1]. Advantage of the therapy is concentration of irradiation effect on cancer position by control of beam energy. All permanent magnet [APM] microwave ion sources were developed for higher availability of the accelerators, which needs no maintenance of filaments and coils for conventional sources [2].

2.1 *APM microwave hydrogen ion source*

The ion source is with next two types of permanent magnets as shown in Fig. 1 [2].

1. 16 pole cusp magnets set on outer surface of a cylindrical chamber for plasma confinement.
2. A set of magnets around the chamber for axial magnetic field to couple microwave to plasma.

High density hydrogen plasma was generated and ion beam current of 65 mA (330 mA/cm^2, 87%proton), 30 keV is obtained [2]. It is equivalent to conventional sources with coils. Difficulty in APM plasma generation was precise tuning of the axial field, which is sensitive to beam current. The sensitivity was lowered by the cusp magnets. It is considered to enable high density plasma generation by APM without coil tuning.

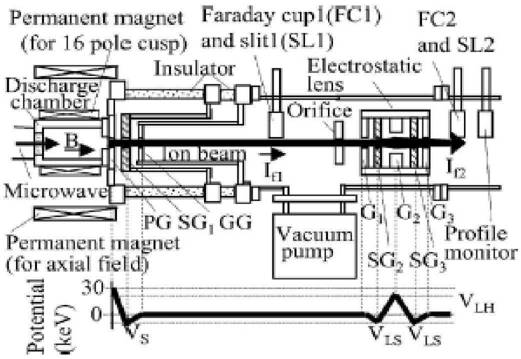

Fig.1 APM microwave ion source and focus lens [2]

2.2 *Ion beam transport and focus*

Ion beam of 30 keV is transported to the electrostatic lens focusing the beam for matching to accelerator. A novel five-grid electrostatic lens with two electron suppression grids (SG) shown in Fig.1 was developed to confine electrons for beam space charge neutralization, which reduce beam transport loss to 30% from 70% without SG [3]. 40mA ion beams were focused to 1-2 mm diameter.

3. RF bucket ion source for ion beam milling

Bucket ion sources for neutral beam injectors [6] were applied to industrial applications such as milling for micro-structure of hard disks [4].

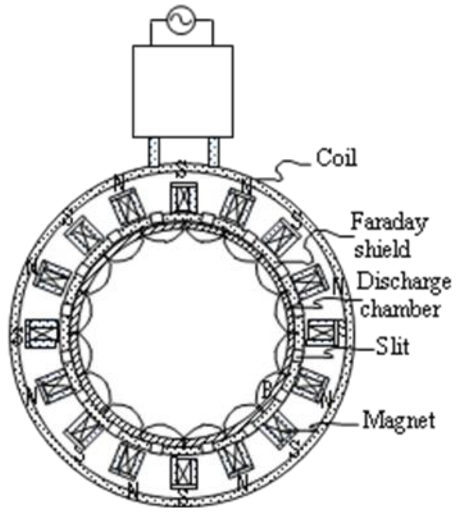

Fig.2 Outline of RF bucket ion source [5]

An RF bucket ion source was developed for higher availability without filaments and active ions like oxygen as shown in Fig. 2 [5]. The RF source chamber is insulator cylinder with surrounding RF coil. Outer surface of the cylinder is surrounded by faraday shield with multi slits. Multi cusp magnets are set inside the coil between slits on the shield to confine plasma. It enables high throughput process with long life time and no disturbance in induction coupling of RF power to plasma.

4. Ion sources for NBI of fusion devices

Negative hydrogen ion sources have been developed for high energy NBI of fusion devices, because of high neutralization efficiency of negative ion (60%) at high energy [7-15]. Improvement of negative ion production efficiency was researched with magnetic filter and cesium injection into plasma generators [7-9]. Negative ion beam extraction and compensation of magnetic beam deflection was also researched with theoretical analysis and 3-D simulation [10-12]. The former works are described as follows.

Electrons extracted with ions are separated by magnetic field at the extraction grid (EG) with several keV to prevent electron acceleration. This causes slight deflection of ion beams by several mrad and can increase beam loss during beam transport to fusion devices (15-25m). Compensation of this deflection is very important and have been researched for JT-60U, LHD and ITER [7,10-12].

4.1 *Analysis of beam deflection physics*

The beam trajectory was analyzed considering both magnetic deflections and electrostatic lens effect at entrance and exit of apertures of EG with linear beam optics theory as shown in Fig.3 [10]. As a result, magnetic field displaced beam center

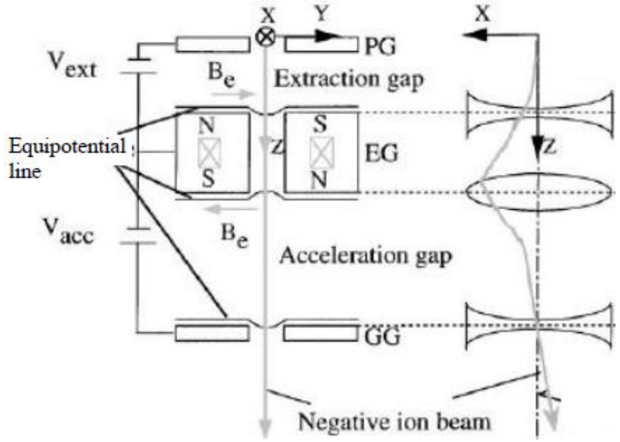

Fig.3 Theoretical model of beam deflection [10]

from aperture center by 0.5 - 1 mm at the exit of EG, where beam focus lens deflects beam to opposite direction to the magnetic beam displacement. This lens effect was found larger than the magnetic deflection. The deflection and the displacement can be compensated at a time by offset of aperture center of the EG exit [11,12].

4.2 *3-D beam trajectory simulation*

The beam deflection by the magnets was estimated and compensation of deflection was researched with 3-D beam trajectory simulation for a model of the LHD NBI ion source [10]. The estimated deflection angle is around 9 mrad and offset of grid apertures for compensation of the deflection were investigated [10,11]. 3-D beam trajectory simulation for ITER was conducted by JAEA in collaboration with ITER to compensate the deflection and space charge repulsion [12,15].

Acknowledgments

I would like to thank Hitachi, Ltd., JAEA, NIFS, ITER for offering me chances to work and supports.

References

[1] K. Hiramoto, Nucl. Instrum. Meth. **B261**(2007)786.
[2] M. Tanaka, Rev. Sci. Instrum., **79** (2008) 02B317K.
[3] M. Tanaka, *et al.*,Nucl.Instrum.Meth.**A**550 (2005) 74
[4] T. Sato, *et al.*, J. Vac. Sci. Technol. **A4** (1986) 784M.
[5] Masanobu Tanaka, Japan Patent, JPA 2008-128887.
[6] Y. Okumura, *et al.*, Rev. Sci. Instrum., **55** (1984) 1.
[7] T. Inoue, *et al.*, Plasma Devices Oper., **3** (1994) 211.
[8] Y. Takeiri, *et al.*, Rev. Sci. Instrum. **66** (1995) 2541.
[9] M. Tanaka, IEEE Trans. Plasma Sci., **25**(1997) 1412.
[10]M. Tanaka, *et al.*,Nucl.Instrum.Meth. **A449**(2000)22.
[11]M.Hamabe, *et al.*, Rev. Sci. Instrum., **72** (2001) 3237
[12]M. Kashiwagi, *et al., Proc. 3rd NIBS Symp., Jyväskylä, Finland, 2012, p. 227.*
[13]T. Inoue, *et al.*, Nucl. Fusion **46** (2006) S379
[14]Hemsworth, *et al.*, Nucl. Fusion, **49** (2009) 045006.
[15]L.R. Grisham et al., Fusion Eng. Des. **87**(2012) 1805