J. Plasma Fusion Res. SERIES, Vol. 8 (2009)

Uniform Negative Ion Beam Extraction in a Cesium-Seeded Large Negative Ion Source with a Tent Magnetic Filter

H. Tobari, M. Hanada, T. Inoue, M. Taniguchi, M. kashiwagi, K.Watanabe, N. Umeda and K. Sakamoto

Fusion Research and Development Directorate, Japan Atomic Energy Agency (JAEA), Mukouyama 801-1, Naka 311-0193, Japan

(Received: 1 September 2008 / Accepted: 18 December 2008)

For improvement of spatial uniformity of negative ion beams, the external magnetic filter was replaced to a novel tent-shaped magnetic filter in the JAEA 10 ampere negative ion source. The tent filter geometry is based on new findings in surface production of negative ions in high electron temperature plasmas. In order to link the tent filter, the original line-cusp field configuration on the source chamber was re-arranged to form a symmetric magnetic field like the one commonly employed for many of positive ion sources aiming at high proton yield. This magnetic field configuration allows fast electrons emitted from cathode filaments to rotate azimuthally in the ion source by $B \times \text{grad}\, B$ drift. As the result, the source plasma with the tent filter showed a flat profile and the spatial deviation of extracted negative ion beam profile from a wide area of 340 mm × 140 mm in the tent filter was decreased to a half of that in the external magnetic filter. Spatially uniform plasma, that is, uniform particle flux onto the plasma grid generated negative ions with good uniformity with a highly symmetric magnetic field configuration.

Keywords: negative ion beam, NBI, uniformity, tent filter.

1. Introduction

Production of spatially uniform source plasma and particle beam is a crucial issue in various industrial and research field such as material processing or heating technology for fusion plasma with neutral beam. As to neutral beam injector (NBI) which is one of powerful tools for heating and current drive of fusion plasmas, negative ion beam of hydrogen or deuterium is extracted from negative ion sources, converted in neutral beams in neutralizers, and then injected into core plasmas. In the ITER NBI, deuterium negative ion beam injection is designed at 1 MeV, 40A (20 mA/cm^2) during long pulses of 3600 s through a long beam line over 20 m [1]. The ITER NB system requires the spatial deviation of negative ion beam extracted from a large area of 1.5 × 0.6 m^2 to be less than 10 %, otherwise excess heat load on acceleration grids and beam line components occurs due to beam divergence. Actually, in the JT-60U which is one of existing large fusion devices, such large heat load has been observed and it limits a long pulse operation [2]. This is due to non-uniform negative ion production across the extraction area of 1.2 × 0.45 m^2 that induces a local increase of beam divergence angle.

One of production process of hydrogen negative ions (H^-) is dissociative attachment of a low energy electron to a vibrationally-excited hydrogen molecule. A cross section of electron detachment of hydrogen negative ion steeply increases when electron temperature T_e exceeds 1 eV [3]. Thus, a transverse magnetic field called as “external magnetic filter” is utilized in front of the extraction area of a conventional negative ion source to lower the electron temperature. In past experiments in the JAEA, steep gradients in spatial profile of source plasma has been observed [4-6], and hence, the extracted negative ion beam profile also showed a steep gradient, from which beams of lower beam intensity were extracted from higher T_e region. Through the experimental and analytical studies, it was found that such strong localization of source plasma was caused by the $B \times \text{grad}\, B$ drift of primary electrons in the asymmetric magnetic field arisen from a link between the external filter and the line-cusp fields.

Another process of negative ion production is an electron capture on the surface. By seeding small amount of Cesium (Cs) vapor, a work function of plasma grid decreases and negative ion production called as “surface production” is enhanced as follows;

$$H^0, H_x^+(x = 1,2,3) + e^- \text{ on surface} \rightarrow H^- \quad (1)$$

In the previous studies in the JAEA [4-7], an increase of the beam intensity by a factor of 4 was observed with Cs-seeding. Moreover, a notable result was

author's e-mail:tobari.hiroyuki@jaea.go.jp

observed that the gradient of beam profile showed an opposite characteristics to that without Cs. Namely, higher beam intensity was extracted from higher T_e region.

The present paper describes new findings in surface production of H^- ions in the Cs-seeded negative ion sources. The paper also proposes improvement strategy for spatial uniformity of H^- ion beam based on these findings.

2. The JAEA 10 ampere source

A schematic illustration of the JAEA 10 ampere negative ion source [4-7] is shown in Fig.1. Dimension of the discharge chamber is 480 mm in height, 240 mm in width and 203 mm in depth. Arc discharge plasmas are produced between the vacuum chamber (anode) and four pairs of tungsten filaments (cathode) installed in the longitudinal direction. Rows of permanent magnets form multipole line-cusp field for the plasma confinement. A pair of relatively large permanent magnets is installed near the plasma grid (PG) to form the external magnetic filter. A Cs oven is mounted on the back plate of the chamber for seeding its vapor into the chamber. The H^- ions are extracted and accelerated electrostatically through multi-apertures (each 9 mm in diameter) distributed in a rectangular region of 140 × 340 mm^2 in the extractor. In the extraction grid, permanent magnets are embedded for bending trajectories of co-extracted electrons. In the present experiments, typical experimental conditions were as follows; the arc voltage was fixed at 60 V. An arc discharge power was 10-20 kW with pulse duration of 1.5 s and an operational gas pressure in the ion source was 0.3 Pa. A beam acceleration voltage was 20-40 kV with an optimized extraction voltage.

The plasma parameters near the extraction region were measured with a cylindrical Langmuir probe, which was made of a platinum wire of 0.5 mm in diameter. This probe was installed at X = 18 mm, Z = 14 mm and scanned in the longitudinal (Y) direction, where a Cartesian coordinate with the origin on the center of the plasma grid was defined as shown in Fig.1. The extracted H^- beam intensity was measured by a movable multi-channel calorimeter installed at 0.8 m downstream of the grounded grid.

3. Experimental Results

In the original external magnetic filter, longitudinal profiles of ion saturation current j_{is} and T_e and negative ion beam intensity I_{H^-} showed steep gradients as reported in refs.4-7. The arc-discharge voltage and also current were kept almost constant before and after Cs seeing, and profiles of j_{is} and T_e showed little difference in both Cs-seeding and without seeding operations. However, the

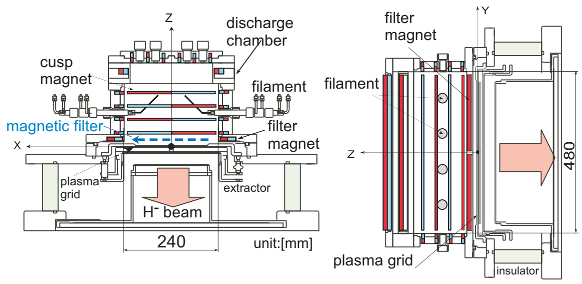

Fig.1 Schematic of the JAEA 10 ampere negative ion source figure.

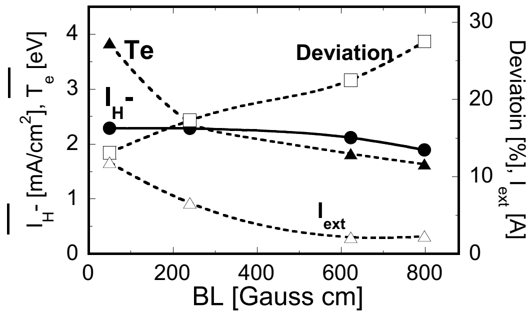

Fig.2 Dependence of averaged values over the extraction area of I_{H^-}(closed circles), T_e(closed triangles), deviation(open squares) and I_{ext}(open triangles) on the magnetic filter strength.

I_{H^-} profile under Cs-seeded condition showed a gradient in the opposite direction from that under the condition without Cs-seeding. Namely, the higher I_{H^-} was obtained from the region where the electron temperature is higher under Cs-seeded condition. This characteristic was also confirmed by varying the magnetic filter strength, which is summarized as Fig.2. In Fig.2, averaged I_{H^-} and T_e values over the extraction area were plotted as a function of the magnetic filter strength which is defined as a line integral of the transverse field component (B_x) from the surface of the plasma grid to the tip of the filament along the z-axis. The deviation is defined as the standard deviation of longitudinal profile of I_{H^-} normalized by averaged I_{H^-}. It is noted that spatial uniformity is improved by reducing the magnetic filter strength, which indicates that localization of the source plasma was induced by B × grad B drift of primary electrons. Here the I_{H^-} showed no reduction even though T_e was up to 4 eV. However, the co-extracted electron current I_{ext} increased with a reduction of the magnetic filter strength.

From these results, negative ion production and extraction in Cs-seeded condition can be described as follows;

(1) Surface production of negative ion is enhanced in highly ionized and/or dissociated plasma even with several eV of T_e, and hence higher I_{H^-} could be obtained without the conventional magnetic filter for lowering T_e.

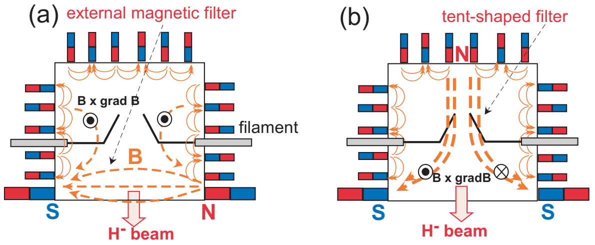

Fig.3 Schematics of two magnetic field configurations; (a) the original external filter and (b) tent-shaped filter.

(2) From a beam extraction point of view, it is preferable to apply an effective filter field acting as a suppressor of the co-extracted electron without undesirable particle drift resulting in plasma localization.

Based on the results described above, we applied a novel magnetic field configuration to the negative ion source instead of the conventional transverse magnetic filter. A tent-shaped filter for the co-extracted electron suppression was combined with a symmetric cusp field commonly employed in a positive ion source for high proton yield as shown in Fig.3. In this magnetic field configuration, even though energetic electrons also drift by $B \times \mathrm{grad}\ B$, the drift direction in the left side is opposite to that in the right side in Fig.3, which leads to azimuthal rotation of the energetic electrons [9]. This rotation of electrons would yield uniform flux of positive ions and atoms diffused onto the plasma grid. It should be noted that primary electrons are trapped inside the tent filter, and hence, co-extracted electrons are considered to be effectively suppressed. A comparison of longitudinal profiles of ion saturation current at Z = 14 mm between the external filter of 620 G·cm and the tent-filter configurations in the Cs-seeded condition is shown in Fig.4 (a). A gradient appeared in the profile in case of the external filter induced by the $B \times \mathrm{grad}\ B$ drift of fast electrons toward one direction. Note that even though the tent filter was not fully optimized due to limitation of existing grooves on the source wall for the permanent magnets, a uniform plasma was achieved in the region of

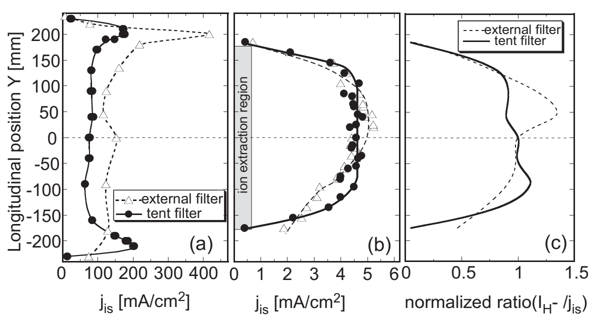

Fig.4 Comparison of longitudinal distributions of (a) ion saturation current density, (b) I_{H^-} and (c) their normalized ratio in the tent filter (closed circles) and the external filter (open triangles), respectively.

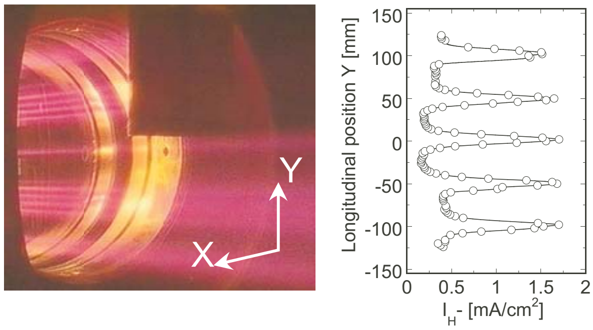

Fig.5 (left) A snapshot of the uniform H⁻ ion beam extraction with a small divergence angle in the tent filter, (right) the beam intensity profiles of longitudinally distributed five beamlets. In this photograph, beamlets extracted from peripheral apertures also appeared.

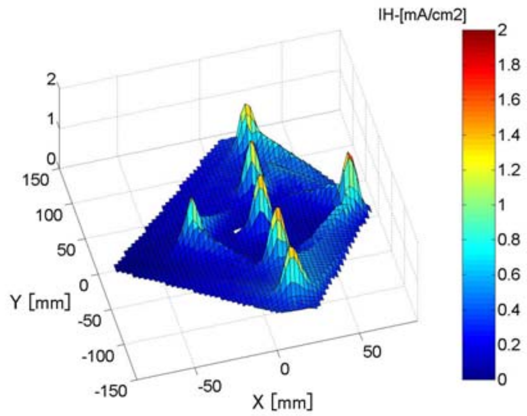

Fig.6 The surface plot of beam intensities of beamlets extracted from seven apertures.

Y = ± 150 mm by applying the tent filter. The density peak appeared at the top and bottom of its profile due to fast electrons trapped in local line-cusp field. Even so, the electron temperature also showed a flat profile at about 2 eV in that region. Figure 4(b) shows a comparison of I_{H^-} between the two filter configurations in the Cs-seeded condition. In contrast to the beam profile with a gradient in the external filter, that in the tent-filter showed quite uniform profile in the beam profile. The spatial deviation of beam profile with the tent filter decreased to 8 %, which was a half of that with the external magnetic filter. The normalized ratio of I_{H^-} to j_{is} across the extraction region as shown in Fig.4(c) kept near unity in the tent filter.

Figure 5 shows a snapshot of locally extracted H⁻ beamlets. Seven apertures on the centerline of the grid (five in the longitudinal direction and three in the horizontal one) were utilized by using a masking plate on the plasma grid. In addition to longitudinal profiles, horizontal (X) profiles of beam intensities and divergence angles (8.5 mrad) of each beamlet were also identical as shown in Fig.6. The 2D beam profile extracted from

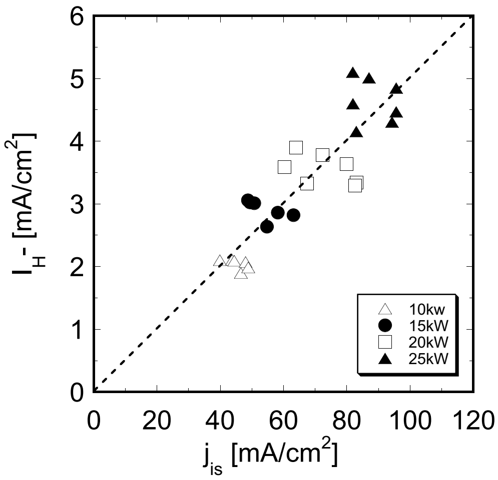

Fig.7 A correlation between the incident flux represented by positive ion flux at several positions in the longitudinal direction and the local beam current density at corresponding positions.

whole apertures in the area of 210 × 140 mm^2 was also measured in the subsequent experiment and that showed uniform profile, which satisfied the ITER requirement for the spatial uniformity [9].

These results show that it prefers a uniform flux of parent particle of negative ion for the surface production of negative ions onto the plasma grid with a low work function in Cs-seeded condition rather than forming low T_e region (<1 eV) with the external magnetic filter.

This characteristic was confirmed by measuring a correlation between the incident flux represented by positive ion flux at several positions in the longitudinal direction and the local beam current density at corresponding positions as shown in Fig.7. The local beam current density increased in proportion to the incident flux by increasing the input arc power, even though the T_e in the extraction area increased from 1.5 eV to 2.5 eV. The maximum beam current density at the exit of the grounded grid reached 12 mA/cm^2 extracted from the source plasma whose density was 8 × 10^{11} cm^{-3} keeping the uniformity satisfying the ITER NB requirement.

4. Conclusion

Characteristics of negative ion beam extraction in the tent filter configuration were investigated in the JAEA 10 ampere negative ion source. The present results emphasize that the production of highly ionized and highly dissociated uniform hydrogen plasma lead to the uniform negative ion beam extraction, which can be achieved by a highly symmetric magnetic field configuration. Thus, we summarize that a production of uniform incident flux of positive ions and/or atoms onto the surface of the plasma grid is a key factor for uniform negative ion production in Cs-seeded condition. This concept is an essential solution for improvement of spatial uniformity of negative ion beam independent of the production methods (arc, RF or ECR) of the source plasma.

[1] ITER EDA Final Design Report, ITER technical basis, Plant Description Document (PDD), G A0 FDR 1 01-07-13 R1.0, IAEA EDA documentation No. 24 (2002).
[2] M. Kuriyama *et al.*, Fusion Sci. Technol. **42** 410–23(2002).
[3] R. K. Janev *et al.*, *Elementary Processes in Hydrogen-Helium Plasma, Cross Sections and reaction Rate Coefficients* (Springer, Berlin, 1987).
[4] M. Hanada *et al.*, Nucl. Fusion **46**, S318 (2005).
[5] M. Hanada *et al.,* Rev. Sci. Instrum. **77**, 03A515 (2006).
[6] H. Tobari *et al*., Plasma and Fusion Research **2**, 022 (2007).
[7] T. Inoue *et al.*, Rev. Sci. Instrum. **79**, 02C112(2008).
[8] Y. Okumura *et al*., Proc. 16th symp. Fusion Technol., 1026 (1990).
[9] H. Tobari *et al.,* Rev. Sci. Instrum. **79**, 02C111 (2008).