Negative Ion Production in High Electron Temperature Plasmas

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In our recent experiment, it was found that intense negative ion beams could be extracted from high-density and high-electron temperature plasmas under a Cesium seeded condition. This indicates that such plasmas contribute to the surface production of negative ions, and that the negative ion production exceeds the destruction process via electron detachment. Thus, it has been suggested that highly ionized and dissociated plasmas are suitable for the surface production of negative ions. This paper reports the results of specific experiments to confirm the negative ion production in plasmas with high-electron temperature. In these experiments, high electron temperature plasmas were produced by (1) placing filaments (acting as cathodes) near the extraction area, and (2) reducing the magnetic filter strength, both to allow fast electrons access to the beam extraction area. The results support the production of high-density H^- ions even in plasmas with high-electron temperature. Also included is a discussion on the surface production mechanism of negative ions under a Cs-seeded condition.

Keywords: NBI, negative ion source, beam uniformity, surface production, magnetic filter

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In the JT-60U, large negative ion sources are under operation for plasma heating and current drive in fusion plasmas [1, 2]. At the present, one of the key issues regarding these ion sources is the generation of a uniform negative ion beam over a meter-wide extraction area, this being also essential in the ITER NBI [3].

The hydrogen negative ion in plasma [4, 5] has a large cross section of destruction (electron detachment) caused by collision with fast electrons (> 1 eV), which increases rapidly with electron temperature [6]. In the existing negative ion sources, a transverse magnetic field, called a "magnetic filter," is applied and the negative ions are produced in low temperature plasmas diffused through the magnetic filter. A previous experiment in the JAEA 10-ampere ion source [7] revealed that the negative ion destruction was enhanced in the high-electron temperature region localized in the ion source. Namely, a drastic reduction of local beam intensity has been observed in the region where local electron temperature is relatively high in a conventional "pure volume" condition.

However, the large ion sources of the JT-60U and even the ITER source operate under Cesium (Cs) seeded condition, where negative ion beam intensity is enhanced via a "surface production" process [8] of the negative ions. In a recent experiment regarding the Cs-seeded negative ion source [9], H^- ion beams of higher current density were obtained from the local extraction area where fast electrons are localized.

The present paper describes two experiments aimed at investigating negative ion production in plasmas with high electron temperature. In the first experiment, filaments acting as cathodes are placed near the extraction area, and in the second experiment the magnetic filter strength is reduced in order to allow fast electrons access near the extraction area, both under with and without Cs seeding.

A schematic of the JAEA 10-ampere negative ion source [10] is shown in Fig. 1. The ion source consists of a rectangular discharge chamber and an extractor. The dimensions of the discharge chamber are 480 mm in height, 240 mm in width, and 203 mm in depth. Arc discharge plasmas are struck between the vacuum chamber (anode) and four pairs of tungsten filaments (cathode) installed in the longitudinal direction. The chamber is surrounded by rows of permanent magnets which form a multi-pole line-cusp field for plasma confinement. A pair of relatively large permanent magnets is installed near the plasma

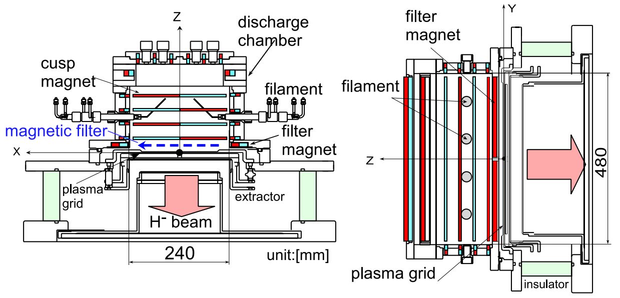

Fig. 1 Schematic of the JAEA 10-ampere negative ion source.

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grid (PG) to form a transverse magnetic field referred to as a "magnetic filter." In order to enhance the surface production process of negative ions, small amount (≈ a few hundred mg) of Cesium (Cs) is seeded in the chamber from a Cs oven mounted on the back plate of the chamber. The negative ions are produced on the surface of the plasma grid where the work function is lowered by vaporized and adsorbed Cs atoms. The negative ions are then extracted and accelerated through multi-apertures (each 9 mm in diameter) drilled in the rectangular area of 140 mm × 340 mm in the extractor. A Cartesian coordinate is defined as shown in Fig. 1. The origin of the coordinate system is on the center of the plasma grid surface, and the X and Y axes are set in the horizontal and longitudinal directions, respectively. Thus the Z coordinate is parallel but opposite the beam extraction.

In the present experiment, the arc voltage was fixed at 60 V. The operational hydrogen gas pressure in the source was 0.3 Pa and the arc discharge power was 5 - 30 kW with a pulse duration of 1.5 s. The hydrogen negative ions H^- were extracted electrostatically by the potential difference between the plasma grid (PG) and the extraction grid (EXG) where the extraction voltage was tuned so as to extract the ions at the emission limited condition. The extracted ions were then accelerated at 20 - 40 kV for a beam pulse length of 0.5 s.

Plasma parameters such as ion saturation current density and electron temperature were measured using a cylindrical Langmuir probe whose tip is made of a platinum wire 0.5 mm in diameter. This probe is installed at X = 18 mm, Z (distance from the PG) = 14 mm, and is scanned in the Y (longitudinal) direction. The extracted negative ion beam intensity I_{H^-} was measured by a movable multi-channel calorimeter located 0.8 m downstream of the grounded grid. The calorimeter tips are made of molybdenum, each with a mass of 1 g and 5 mm in diameter. Nine tips are arrayed every 20 mm along the Y-direction on the calorimeter. The beam profile was measured in terms of the temperature rise of the calorimeter tips in the region of -175 mm $< Y <$ 185 mm.

In the original configuration of the 10-ampere source as shown in Fig. 1, the longitudinal distributions of plasma parameters (electron temperature T_e and ion saturation current density J_{is} at Z = 14 mm) show a steep gradient with higher T_e and J_{is} in the top region [7] (See Figs. 2 (a) and (b)). Analyses of electron trajectory [9] have confirmed that this localization is due to the $B \times$ grad B drift of fast electrons toward the top region of the ion source in the magnetic filter. In pure volume operation (without Cs), the lower beam intensity region locally existed in the longitudinal distribution due to the higher electron detachment reaction by the fast electrons in the top region of the chamber.

The arc-discharge voltage and current are kept almost constant before and after Cs seeding, and then the longitudinal distributions of the plasma parameters, such as electron temperature and density, show little difference even after Cs seeding. However, the beam intensity profile under a Cs-seeded condition shows a gradient in a direction opposite that in the pure volume condition. Namely, the higher current density of H^- ion beam is obtained from the region where the electron temperature is relatively high, as shown in Fig. 2 (c).

Note that the H^- ion beam intensity increased by a factor of 4 with the Cs seeding as shown in Fig. 2 (c). This enhancement suggests that the surface production of H^- ions under a Cs-seeded condition is much higher than the destruction of the H^- ions by the electron detachment in the plasma with high-electron temperature.

In order to produce plasma with high electron temperature in front of the PG, the filaments were bent toward the PG as shown in Fig. 3. The primary electrons emitted from the filaments are immediately trapped and bounce in the magnetic filter near the PG. As shown in Figs. 4 (a) and

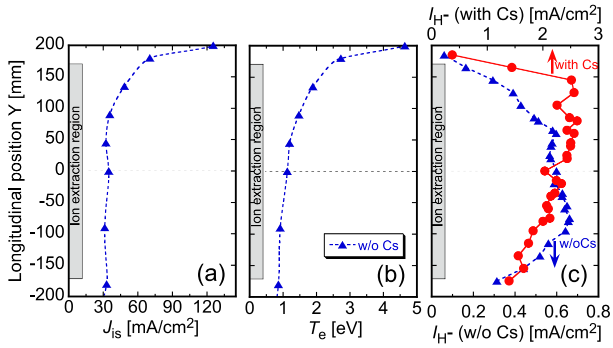

Fig. 2 Longitudinal distributions of (a) ion saturation current density J_{is}, (b) electron temperature T_e measured by the Langmuir probe at Z = 14 mm, and (c) H^- ion beam intensity with and without Cs seeding measured by calorimeter obtained in the original configuration with a magnetic filter of the 10-ampere source. P_{arc} = 10 kW, P_s = 0.3 Pa, V_{acc} = 40 kV.

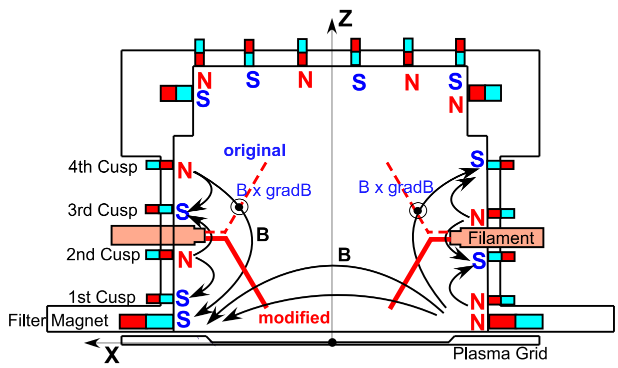

Fig. 3 Schematic of the magnetic field configuration with magnetic filter and modified filaments bent toward the PG. A stray magnetic field exists between the filter magnet and the 4th cusp line, and hence, primary electrons drift by $B \times$ grad$B$.

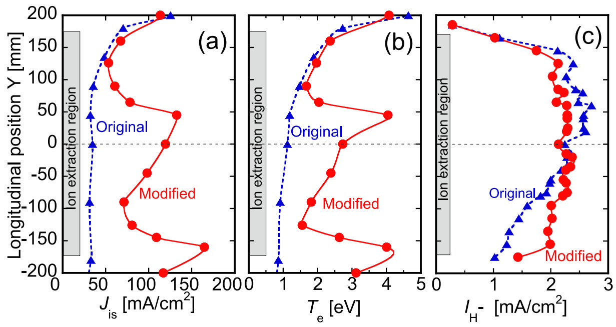

Fig. 4 Comparison of longitudinal distribution of (a) ion saturation current density, (b) electron temperature, and (c) H^- ion beam intensity between before and after modification of the filament location. P_{arc} = 10 kW, P_s = 0.3 Pa, V_{acc} = 40 kV.

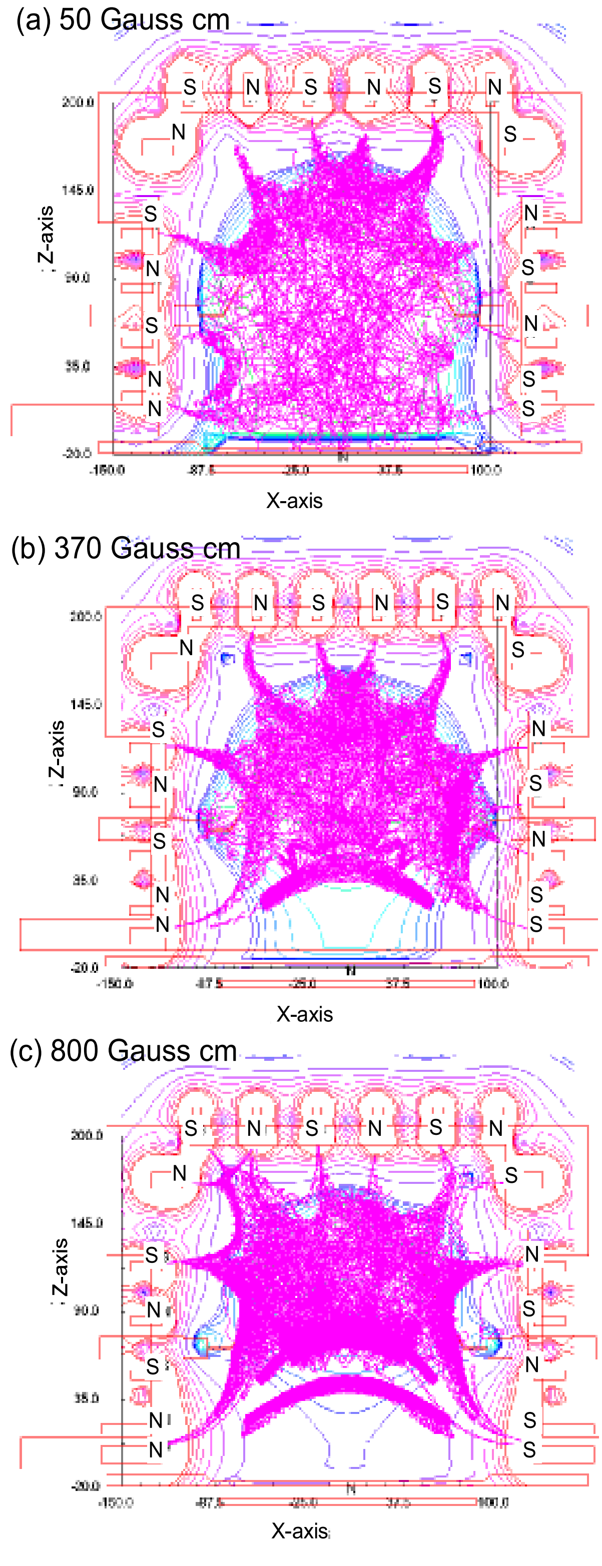

Fig. 5 Primary electron (E = 60 eV) trajectories on the X-Z plane in the magnetic filter strength of (a) 50 Gauss cm, (b) 370 Gauss cm, and (c) 800 Gauss cm.

(b), the plasma near the PG contains energetic electrons locally and the plasma shows local peaks in the electron temperature and ion saturation current, suggesting that the trapped fast electrons effectively contribute to the production of plasmas with high electron temperature. The H^- ion beam intensity, however, shows a spatial profile with a substantial plateau without abrupt reduction of its intensity as shown in Fig. 4 (c). This might be described by the following process. The atoms and/or ions, as parent species of the negative ions, are produced locally by the fast electrons and the H^- ions produced on the surface are then ejected from the PG and accelerated by the plasma sheath. Here, it could be considered that hydrogen atoms with relatively high kinetic energy of a few eV, such as atoms dissociated through the Frank-Condon process, contribute to the surface production. The H^- ions, hence, with some energy leave the PG perpendicular to the surface. On the other hand, the surface-produced H^- ions should have momentum toward the PG in order to reach the beam extraction area. Thus, the H^- ions should have an interaction with particles, for example, single or double charge exchange with atoms and/or positive ions. The interaction with plasma particles and the transport process of the H^- ions [11] could also effectively flatten the spatial profile of the H^- ion beam intensity.

The discussion above would lead to the following hypothesis: since the dissociation and ionization of molecules, in order to yield atoms and/or ions as the parent particle of the H^- ions, is enhanced by fast electrons, high density negative ions could be produced even in plasmas with high electron temperature. This implies that the magnetic filter might not be necessary in the surface production-type negative ion source.

The magnetic filter of various strength was applied by changing the size of the permanent magnets. Figure 5 shows the trajectories of primary electrons (60 eV) in the magnetic filter. The filter strength (BL, unit: Gauss cm) was defined by 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. These trajectories indicate that the primary electrons travel randomly and easily access the PG in the case of magnetic filter strength

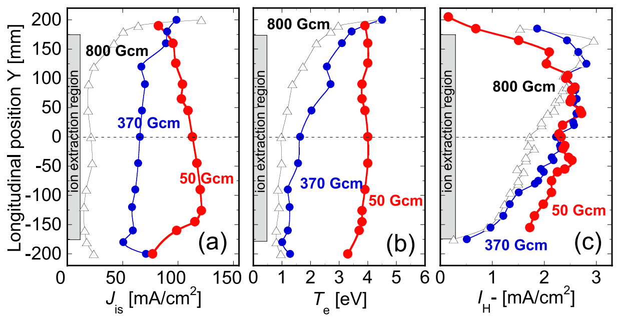

Fig. 6 Longitudinal distributions of (a) ion saturation current density, (b) electron temperature, and (c) H^- ion beam intensity at various magnetic filter strengths. P_{arc} = 10 kW, P_s = 0.3 Pa, V_{acc} = 40 kV.

of 50 Gauss cm. As the filter strength increases (370 and 800 Gauss cm), the electrons tend to be trapped in the magnetic filter and their access to the PG is restricted. This suggests decrease of electron density and temperature over the PG, and is experimentally confirmed as shown in Figs. 6 (a) and (b). In the case of BL = 800 Gauss cm, the average ion saturation current density and electron temperature are reduced to 20 % and 1/3 of those at 50 Gauss cm, respectively. The H^- ion beam intensity in three cases of magnetic filter strength is shown in Fig. 6 (c). From this result, it was confirmed that the H^- ion beam with a high current density is obtained even from high temperature plasma under a weak magnetic filter condition.

Here, the spatial uniformity of the H^- ion beam intensity was improved as the filter strength was decreased. This is because the plasma uniformity, and hence the H^- ion uniformity, is dependent on the $B \times \text{grad}\, B$ drift of primary electrons in the magnetic filter [12]. It could then be worthwhile to remove magnetic filter in the Cs-seeded negative ion source as a way to achieve a high-current density H^- ion beam with a high degree of uniformity. However, since the ratio of the co-extracted electron current to the H^- ion current is too high ($I_e/I_{H^-} > 10$) in the case of 50 Gauss cm, removal of the magnetic filter is not practical for high-power and long pulse ion sources, such as those of the NBI, in regard to the suppression of co-extracted electron current.

The present experiments in JAEA 10-ampere negative ion source confirmed that the H^- ion beam of high current density could be obtained even from plasmas with high electron temperature under a Cs-seeded condition. This could be attributed to the production of atoms and/or protons as the parent particle of negative ions in the plasmas with high electron temperature. This implies that a positive ion source of high proton yield could be a good negative ion source. However, this is not practical for high-power and long pulse ion sources, due to the excess co-extracted electron current. Hence, the suppression of co-extracted electrons, such as a use of the magnetic filter, is still necessary for the negative ion sources. In order to gain a better understanding of the physics in the negative ion source, further investigation of not only atomic/ionic reactions but also the transport process of atoms, protons, and the negative ions would be necessary.

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