Identification of the extraction structure of $\text{H}^-$ ions by $\text{H}_\alpha$ imaging spectroscopy

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Abstract. Extraction structure of negative hydrogen ions ($\text{H}^-$) (i.e. the regions where $\text{H}^-$ ions are effectively extracted from the plasma) was obtained using hydrogen Balmer-$\alpha$ ($\text{H}_\alpha$) imaging spectroscopy and cavity ring-down spectroscopy. The $\text{H}^-$ ion density increases after caesium (Cs) seeding through a surface conversion process on a Cs-covered plasma-grid (PG) surface. We found a reduction in the $\text{H}^-$ density during beam extraction after Cs conditioning, and the same signal reduction appeared in the $\text{H}_\alpha$ intensity caused by the reduction in the excited hydrogen ($n = 3$) population, which in turn is caused by the decrease in the mutual neutralization process between positive and negative hydrogen ions. We clearly observed the reduction structure of the $\text{H}_\alpha$ emissions in the extraction region; the structure expands at optimal Cs conditioning. From this result, the $\text{H}^-$ ions, which are produced at the PG surface, release to the extraction region and widely distribute during arc discharge. We conclude that the reduction of the $\text{H}^-$ density is caused by the particle loss due to beam extraction from the PG apertures.

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1. Introduction

Understanding the behaviour of negative hydrogen (H\textsuperscript−) and deuterium (D\textsuperscript−) ions is of great interest in fusion research for the improvement of neutral beam injection (NBI). NBI systems that use a negative ion source have successfully worked at the Large Helical Device (LHD) \cite{1} and JT-60U \cite{2}; they provide a high-energy neutral beam for injection into the plasma for heating and current drive \cite{3–7}. A larger-scale D\textsuperscript− source using radio frequency (RF) discharge has been designed for NBI at the International Thermonuclear Experimental Reactor \cite{8}. For this use, the source must provide a stable 1 MeV neutral beam for 1 h using wide acceleration grids and multiple apertures. Therefore, uniform beam production and extraction techniques are necessary to maintain high power and stable operation. In these ion sources, H\textsuperscript− ions are produced by the conversion of protons and neutral atoms on the caesium(Cs)-covered plasma-grid (PG) surface, which has a low work function, and directly faces the discharge. Distribution of the H\textsuperscript− ions and their extraction mechanism are important factors for these negative ion sources to ensure high power and stable operation \cite{9–11}. In contrast, the behaviour of H\textsuperscript− ions in the extraction region and its extraction structure near the PG surface (i.e. the regions where H\textsuperscript− ions are effectively extracted from the plasma) are not well understood.

Recently, numerical studies using Monte-Carlo transport simulations of the H\textsuperscript− ions in the extraction region have been carried out \cite{12–18}. The optimal H\textsuperscript− extraction model, which would encompass the many complex features of the system, such as the composition of the charged particles, the boundary of the extraction apertures and the formation of the extraction meniscus has not yet been proposed. Moreover, the experimental observation of the behaviour of H\textsuperscript− is insufficient to verify the numerical calculations. Therefore, we need an experimental approach to identify the behaviour of H\textsuperscript− in the extraction region for an actual hydrogen negative ion source.

The point that requires experimental clarification is the absolute value of the H\textsuperscript− density and its behaviour in the extraction region of the negative ion source. According to Langmuir
probe measurement, a hydrogen ion–ion plasma forms in the extraction region near the PG surface under optimal Cs conditioning \cite{19, 20}. It is considered that the charge neutrality of the plasma is maintained by the balance of positive and negative hydrogen ions with few electrons being involved. To determine the \( H^- \) density, a suitable diagnostic method using cavity ringdown spectroscopy (CRDS) has been developed by Quandt \cite{21}, and it has been applied to an RF-driven negative ion source \cite{22} as well as our arc-driven source \cite{23, 24}. This tool is capable of showing the \( H^- \) growth caused by the Cs conditioning in the extraction region close to the PG surface, but it is difficult to determine the \( H^- \) distribution for a single discharge because the alignment of the cavity mirrors and laser path is delicate.

On the other hand, optical emission spectroscopy (OES) for the \( H^- \) ion source has been developed at the Max-Planck Institute for Plasma Physics (IPP), Garching \cite{25}. Here the hydrogen Balmer-\( \alpha \) (\( H_\alpha \)) emission correlates with the excited-state hydrogen \((n=3)\) population density. According to the study of atomic and molecular processes in hydrogen plasma \cite{26, 27}, the excitation mechanisms are electron impact collisions (i.e. direct excitation with H, recombination with \( H^+ \), dissociative excitation with \( H_2 \) and dissociative recombination with \( H_2^+ \)), proton impact collisions with H and the mutual neutralization process which can be written as \( H^- m + H^- \rightarrow H(n = 3) + H_m (m = 1, 2, 3) \), where \( m \) is the number of atoms. In a pure hydrogen discharge at a low electron temperature (\( \sim 1 \) eV), the dominant excitation mechanism for \( H_\alpha \) emission is the dissociative recombination between an electron and \( H_2^+ \). However, as the percentage of negative ions increases with optimal Cs conditioning in a negative hydrogen ion source, the \( H_\alpha \) light emission created by the mutual neutralization process becomes dominant, because the excitation cross section of the mutual neutralization is of the same order as that of the dissociative recombination. Previously, we confirmed the relevance of the \( H^- \) density and the \( H_\alpha \) intensity measured using CRDS and OES, respectively, for the \( H^- \) ion source at the National Institute for Fusion Science (NIFS) \cite{28}. Both the \( H^- \) density and \( H_\alpha \) emission measured in the extraction region increased with Cs seeding. We also found a signal reduction for both signals during beam extraction. Consequently, we considered that a two-dimensional \( H_\alpha \) measurement has the ability to probe the extraction behaviour of the \( H^- \) ions, which is the clarification point for the negative ion source. Further, we developed this imaging diagnostic tool for \( H_\alpha \) emission \cite{29}, so as to obtain the reduction structure of \( H^- \) ions during beam extraction.

In this paper, we present an optical diagnostic method for \( H_\alpha \) imaging spectroscopy in the extraction region of a negative hydrogen ion source; the images of the \( H_\alpha \) emission distribution are presented as evidence. We also present an interesting structure of \( H_\alpha \) reduction caused by beam extraction, which is an aspect of the \( H^- \) extraction behaviour. These results suggest growth of the \( H^- \) distribution depends on the method of Cs conditioning. Finally, a relationship between the reduction in the \( H_\alpha \) emission and the \( H^- \) density owing to beam extraction is presented and discussed.

2. \( H_\alpha \) imaging spectroscopy for a negative ion source

Figure 1 shows a cross section of the one-third-scaled hydrogen negative ion source at NIFS. Hydrogen plasma is generated in the arc chamber by arc discharge. The extraction region near the PG surface is generated by the discharge region by magnetic filters to reduce the electron temperature and enhance the \( H^- \) production. We supplied Cs vapour from the backplate of the arc chamber to increase the \( H^- \) density through surface production. We installed a bias insulator between the magnetic filter flange and the PG flange to apply a bias voltage for the reduction.
in the electron extraction current, which is optimized at 2–3 V for the negative ion source for the NBI in the LHD. The line of sight (LOS) of the optical diagnostic tool arranged parallel to the PG surface is also shown in figure 1. The imaging system is installed on the sidewall of the bias insulator and its LOS also passes through the extraction region parallel to the PG surface with a gap of 11 mm. This LOS is parallel to the third row of PG apertures from the bottom of the arc chamber, while the Cs evaporator is located 9 cm above this LOS on the y-axis. Other support diagnostic tools (i.e. CRDS, OES and an electrostatic probe) are also installed on the bias insulator. The electrostatic probe is set 34 cm above the imaging LOS and the gap distance to the PG surface is 11 mm, which is same as the imaging system. The LOS for CRDS is arranged at 13 cm above the imaging LOS and the gap distance is 2 mm in this experiment. The Hα imaging system consists of three optical filters (i.e. a neutral density filter, an infrared cut filter and a narrow band pass filter), an aspherical lens and a charge-coupled device detector (CCD). A glass-fibre image conduit for the transfer of the optical image is set between the lens and the CCD to insulate the high voltage for beam extraction. This system acquires a 16-bit monochrome image of resolution 1292 × 964 pixels (width × height).

Figure 2 shows a photograph of the extraction region taken from the viewport used for imaging spectroscopy. The viewing angle has coverage from the magnetic filter flange to the
PG surface. Both sides of the image field are invisible behind the flange. The left-hand side is the arc discharge side, and the $\text{H}^-$ ions are extracted to the right-hand side passing through the PG apertures. The diameter of the PG aperture is 12 mm and the gap between the PG and extraction grid (EG) is 5 mm. We applied only negative extraction voltage between the PG and the EG which is grounded in this experiment (i.e. without beam acceleration) in order to exclude back streaming positive ions due to an acceleration voltage. A row of the PG apertures appears as a quadrangle shape in the image. To understand the positional relationship, we superimposed a wire frame in the $\text{H}\alpha$ image in order to show the containment of the major component inside the ion source.

3. Variation in $\text{H}^-$ density and hydrogen emission in hydrogen negative ion source

Figure 3(a) shows the waveform of the arc discharge power without Cs conditioning (i.e. a pure volume) and with Cs conditioning. Arc power for these discharges is held constant at 38 kW during beam extraction under the condition of 0.2 Pa hydrogen gas pressure and 0.2 V (i.e. low) bias voltage. The duration of the arc discharge is 9 s for each shot with an interval time of 2 min. The temperature of the PG surface varied in the discharge between 180 and 230 °C. The temperatures of the two Cs ovens were controlled in the range of 185–195 °C in the experiment; the Cs evaporation rate is estimated at 0.17 mg min$^{-1}$ for each oven. In the pure hydrogen discharge, we confirmed there were no Cs spectrum lines in the arc chamber using the visible spectrometer. Therefore we considered the Cs-free condition in the arc chamber before the Cs conditioning.

Figure 3(b) shows the $\text{H}^-$ density measured by CRDS at $z = 2$ mm from the PG surface. After Cs conditioning for 1000 min with 500 discharges, the $\text{H}^-$ density increases to $1.25 \times 10^{17}$ m$^{-3}$ from $0.3 \times 10^{17}$ m$^{-3}$ for the pure volume discharge. We determined the decrease in the $\text{H}^-$ density during a 1 s beam extraction with $-8.1$ kV extraction voltage ($V_{ex}$), as shown by the grey field in figure 3. The reduction value of the $\text{H}^-$ density ($\Delta n_{\text{H}^-}$) is 28% of the $\text{H}^-$ density close to the PG surface for the case with Cs conditioning.
Figure 3. Waveforms of (a) the arc discharge power, (b) the H\(^-\) density, (c) the electron saturation current on an electrostatic probe, (d) the H\(_\alpha\) intensities and (e) the H\(_\beta\) intensities. The bold and narrow lines show the case without Cs and with Cs, respectively. The grey area represents beam extraction period with \(V_{ex} = -8.1\) kV.

Figure 3(c) shows the electron saturation current \(I_{es}\) measured by electrostatic probe in the extraction region at \(z = 11\) mm from the PG surface. A large \(I_{es}\) current flows into the probe tip for the pure hydrogen discharge. The \(I_{es}\) decreases after Cs conditioning, which is a result of maintaining charge neutrality in the extraction region by increasing the number of H\(^-\) ions. We note that the signal waveform of the probe is influenced not only by electrons but also by H\(^-\) ions in the case of ion–ion plasma with Cs [20]. We considered that the actual electron density is relatively smaller during Cs operation than is expected by the waveform of \(I_{es}\) in the extraction region. We also found that the increase in the \(I_{es}\) current during beam extraction is caused by the influx of electrons into the extraction region from the discharge region.

Figures 3(d) and (e) show the H\(_\alpha\) and H\(_\beta\) line intensities, respectively, at \(z = 11\) mm. The H\(_\alpha\) emission was obtained by imaging system with the exposure time of 60 ms. The H\(_\beta\)
emission is measured by OES. The exposure time in Cs case is 40 ms. However, the time resolution of the H$_\beta$ emission for pure volume is poor with the exposure time of 1 s because of the OES system used for confirmation of Cs lines in the arc chamber. The H$_\alpha$ emission intensity is increased by Cs conditioning because of an increase in the excited-state hydrogen population due to the mutual neutralization process between H$^+$ and H$^-$. The contribution of the dissociative recombination process between H$_2^+$ and electrons for H$_\alpha$ emission appears to be decreased by Cs conditioning, because we found that the decreasing H$_\beta$ intensity is caused by a decreasing electron density. In the case of a pure volume discharge, H$_\alpha$ and H$_\beta$ increase with beam extraction, which is consistent with the increased $I_{es}$ signal and is due to the increase in the electron flux. On the other hand, for a discharge with Cs, we find a reduction in the H$_\alpha$ emission during beam extraction. This reduction results from the decrease in the excited-state hydrogen population created by the mutual neutralization processes, which in turn results from a decrease in the H$^-$ density. Similar changes in the hydrogen Balmer lines were also observed in RF negative hydrogen ion sources [27]. At the same time, we observed constant H$_\beta$ signals during beam extraction in Cs operation because this is due mainly to the electron density. Thus, the influence of the electrons on the process of H$_\alpha$ emission during beam extraction is negligibly small in the rich H$^-$ ions at optimal Cs condition. Here the reduction value of the H$_\alpha$ intensity owing to beam extraction is defined as $\Delta H_\alpha$, which is the key value to understand the H$^-$ behaviour.

4. Distribution of H$_\alpha$ emission in the extraction region

Figures 4(a) and (b) show the spectrum images of the H$_\alpha$ distribution taken by the imaging spectrometer in the extraction region before beam extraction (i.e. only with the arc discharge) and during beam extraction, respectively. Strong reflections of the tungsten-filament radiation and H$_\alpha$ emissions from the discharge region appear around the filter flange and the PG apertures. We also confirmed that similar reflection signals only electrified filaments with and without IR cut filter. In the region at the bias insulator at the centre of the LOS, we did not observe such a large reflection. From the spectrometer measurements, we estimate the background filament radiation to be about 5% at the centre of the line of sight ($z = 11$ mm). The meaningful area for H$_\alpha$ emissions is considered as $z = 20$ mm from the PG surface, shown as the white area in figure 4(c). As shown in the horizontal profile along the $z$-axis for the LOS centre (figure 4(c)), the H$_\alpha$ intensity for the arc discharge only, plotted as a solid line, gradually decreases toward the surface of the PG. The vertical distribution of the H$_\alpha$ for the centre of the LOS is uniform in the extraction region, as shown in figure 4(d). As seen in the horizontal profile, the H$_\alpha$ line intensity does not change at the filter flange and PG surface during beam extraction. This result indicates that the reflection component of the H$_\alpha$ emission and the filament radiation from the discharge area located on the left-hand side of the image before beam acceleration and during beam extraction are the same. For the bias insulator close to the PG apertures, the H$_\alpha$ intensity varies depending on the applied extraction voltage shown as dotted lines in figures 4(c) and (d); the H$_\alpha$ emission is reduced near the PG surface at the upper side of the image.

5. Variation in $\Delta H_\alpha$ distribution by Cs conditioning

Figure 5 shows the distribution of $\Delta H_\alpha$ in the extraction region for the different types of discharges. The distribution images of $\Delta H_\alpha$ were produced by subtracting the image acquired
Figure 4. Figures (a) and (b) are the spectrum images of H$_\alpha$ in the hydrogen discharge with Cs in the extraction region before and during beam extraction, respectively. Wireframes of the major components are superimposed on the images. Figures (c) and (d) are the intensity profiles before (solid line) and during (dotted line) beam extraction along the $z$-axis and the $y$-axis, respectively. The white area represents the meaningful area for H$_\alpha$ emission.

before beam extraction from the image acquired during beam extraction. Here the decrease is represented in red, the constant zone in green and the growth in blue. The white area is signal saturation on image pixels caused by the reflection of filament radiation. For a constant background and with constant arc discharge, the observable area for $\Delta$H$_\alpha$ distribution expands to $z = 35$ mm from the PG.

Figure 5(a) is the case of a pure hydrogen discharge. The $\Delta$H$_\alpha$ strongly increases during beam extraction for the whole area of the extraction region. It indicates either an increase of the hydrogen density or the electron density or the electron temperature. Since the feeding gas pressure and the arc discharge power stay constant during beam extraction, the neutral hydrogen
Figure 5. Spatial distribution of $\Delta H_\alpha$ in the extraction region for (a) a pure hydrogen discharge, (b) after Cs conditioning for 340 min with 170 discharges and (c) after Cs conditioning for 1000 min with 500 discharges. The duration of the arc discharge is 9 s for each shot with 1 s of beam extraction. The same extraction voltages were applied in all three cases.
density is considered to be constant in this experiment. We also confirmed the constant electron temperature of 1.3 eV measured by the electrostatic probe. As shown in figure 3(c), the $I_{es}$ signal, which is strongly dependent on the electron density, increased. And also the Hβ emission, which is mainly due to dissociative recombination process, also increased as shown in figure 3(e). These two results indicate that the electron density in the extraction region increased with beam extraction. We observed the 9 A high extraction current in the pure volume discharge; it is mostly electron currents which include small negative ions. It is reasonable to think that the extracted electrons from the PG apertures flowed from discharge region to extraction region. Therefore the $\Delta H_\alpha$ distribution shows the contribution of the dissociative recombination process by electrons widely distributed in the extraction region in pure volume discharge; even so, a small hollow structure appeared beside the PG apertures. This is consistent with the small reduction in H− density shown in figure 3(b).

Figure 5(b) shows the $\Delta H_\alpha$ image after 340 min (with 170 discharges) with Cs conditioning. The reduction structure shown in red clearly appeared beside the PG apertures. We found that the reduction area expanded to the upper side of the image near the Cs evaporator. Although the $H_\alpha$ reduction appeared near the PG surface, the increasing area remains in the upstream region in the left-hand side of the image. At the reduction area, it is clear that the electron excitation process for $H_\alpha$ emission replaces the mutual neutralization process between H− and H+ ions, which is owing to the increasing proportion of H− ions. Therefore, the reduction phenomenon comes from the PG where there are many H− ions produced by Cs-covered surface. Figure 5(b) also shows the small increase in $\Delta H_\alpha$ (in blue) at the inner surface of the PG apertures. This is the reflection signal of the $H_\alpha$ emitted around the filter flange area. The mirror image structure caused by the reflection signal appears on the right-hand side of the PG; this structure is in agreement with the reflection image on the photograph shown in figure 2.

Figure 5(c) shows the $\Delta H_\alpha$ image after 1000 min (500 discharges) with Cs conditioning. The reduction area has spread in the direction of the bottom side of the image, and has also expanded to the inside of the plasma farther than 30 mm from the PG surface. The extraction current decreases to 4.4 A with the condition of low $I_{es}$ current (figure 3(c)). The electron temperature of 2.3 eVs is stay constant during beam extraction. We found a strong spot-like reduction in the region close to the PG surface ($z < 10$ mm) beside the apertures, which have tails to the left side of the image. The result of this $\Delta H_\alpha$ distribution leads to the speculation that the H− ions are widely distributed in the extraction region because of the optimal Cs conditioning. On the other hand, we also found that the asymmetric $\Delta H_\alpha$ distribution remains after 1000 min Cs conditioning at the bottom of the image where the last PG aperture row is close to the bottom chamber wall. We considered that the asymmetric $\Delta H_\alpha$ distribution results from a fraction of the element of negative ions and electrons due to the different Cs conditioning on the PG surface. If the $\Delta H_\alpha$ distribution reflects reduction structure of the negative ions, this asymmetric distribution correlates with the beam distribution extracted from the aperture. According to the previous study of the uniformity of negative ion beam, the same beam asymmetry appeared at the peripheral region near the chamber wall [9–11]. However, it is not evident whether the beam distribution was under the influence of $\Delta H_\alpha$ distribution, because we did not measure the beam distribution owing to the non beam acceleration in this experiment. The comparison of $\Delta H_\alpha$ distribution and the beam distribution should be investigated in the future.
Figure 6. Profiles of $\Delta H_\alpha$ along the $z$-axis through the PG apertures (UA and CA) and at the PG surface (SU) for the hydrogen discharge with Cs conditioning after 1000 min.

6. Reduction structure of $H_\alpha$ emission during beam extraction

Figure 6 shows the profiles of the $\Delta H_\alpha$ along the $z$-axis; here the lines of (upper apertures: UA), (center apertures: CA) and (surface: SU) are the profiles through the upper apertures, centre apertures and at the PG surface, respectively (figure 5). The $\Delta H_\alpha$ observed inside the area of $z < 4$ mm, as shown by the grey-coloured area, is disabled because of the short integral distance of the LOS that is blocked by the PG surface. We first found that the $H_\alpha$ reduction expands widely to 30 mm from the PG surface in three profiles. This result indicates that the $H^-$ ions are widely distributed in the extraction region before beam extraction using arc discharge. Then, it is apparent that the $H_\alpha$ reduction increases as the plotting point approaches the PG for the cases of the UA and CA profiles passing through the PG apertures. That the negative ions are lost in the region of the apertures during beam extraction is clear. On the other hand, in the SU profile, a weak $H_\alpha$ reduction appeared near the PG surface while there is a strong $H_\alpha$ reduction in the area $10 \text{ mm} < z < 20 \text{ mm}$. This indicates that the production locations of the negative ions are present on the PG surface, and the influence of its production expands to 20 mm from the PG surface at least during beam extraction. It is likely that a similar reduction response occurs between the emission and the $H^-$ density and the $H_\alpha$ emission. The $H^-$ ions distributed in the extraction region compensate for the reduction of the $H^-$ ions close to the PG aperture. Therefore, more probable reason seems to be that the reduction of the $H^-$ density is caused by the particle loss due to extraction as the negative ion extraction is current limited.

Figure 7(a) shows the variation in the $\Delta H_\alpha$ profile along the $z$-axis at the centre ($y = 0$). The horizontal and vertical axes show the distance from the PG and the $\Delta H_\alpha$, respectively. In the case of pure hydrogen discharge, the dominant excitation process for $H_\alpha$ emission is the dissociative recombination of $H^+_2$ and electrons; the $\Delta H_\alpha$ for the whole area of the extraction region is a positive value because of the electron flow. $H_\alpha$ reduction appears from a position near the PG surface, as shown in the $z$-profile with Cs operation after 340 min. This shows that the
Figure 7. Panels (a) and (b) show the variation in the $\Delta H_\alpha$ profiles along the $z$-axis and the $y$-axis, respectively, for the pure hydrogen discharge (circles) and discharge with Cs conditioning after 340 min (squares) and at 1000 min (triangles). The configuration of the PG apertures is represented in (b).

reaction of mutual neutralization increases close to the PG surface ($z < 15$ mm) and is caused by an increase in the $\text{H}^-$ density owing to surface production. The reduction area expands to the whole area of the extraction region ($z < 30$ mm) after 1000 min of Cs conditioning. Therefore, it is appropriate to consider the production source of the $\text{H}^-$ ions existing at the PG surface.

Figure 7(b) shows the variation in the $\Delta H_\alpha$ profile along the $y$-axis at $z = 4$ mm from the PG. The horizontal and vertical axes are the $\Delta H_\alpha$ and the distance from the centre aperture, respectively. We find hollow structures on the $\Delta H_\alpha$, which are caused by the reduction in $\text{H}^-$ ions, at $y = 0$ and $\pm 18$ mm. This structure is consistent with the configuration of the PG apertures, which have a 12 mm diameter and a 19 mm interval. Comparing the pure volume discharge against the discharge with Cs conditioning after 340 min, the positive $\Delta H_\alpha$ distribution starts to change to a negative value in the upper side of the image near the location of the Cs evaporator (figure 1). Then the negative $\Delta H_\alpha$ area expands to the bottom after 1000 min.
Figure 8. Comparison of the spatial distribution of $\Delta H_\alpha$ at different extraction voltages, (a) $V_{ex} = -3.1\,\text{kV}$ and (b) $V_{ex} = -8.1\,\text{kV}$, which is same as in figure 5(c).

of Cs conditioning. The fact that a difference appears in the reduction in $H_\alpha$ caused by the reduction in $H^-$ ions by location suggests that the efficiency of the negative ion production varies depending on the distribution of Cs on the PG surface.

7. Comparison between $\Delta H_\alpha$ and $\Delta n_{H^-}$

Figure 8 shows the comparison of the $\Delta H_\alpha$ distribution applied against an extraction voltage of $-3.1\,\text{kV}$ (in figure 8(a)) and $-8.1\,\text{kV}$ (in figure 8(b)) after 1000 min of Cs conditioning; here the image of figure 8(b) is same as figure 5(c). The arc discharge power is maintained constant during beam extraction, and the gas pressure and the bias voltage are set the same for both...
discharges. Comparing the two images, it is obvious that the higher extraction voltage produces a larger $H_\alpha$ reduction in the extraction region. However, the reduction structures are similar in both cases. This result indicates that there is a close relation between the reduction in $H_\alpha$ and the strength of extraction voltage by way of the $H^-$ ion density.

Figure 9 shows the reduction profile of $H_\alpha$ along the $z$-axis at $y = 0$ mm (i.e. through the centre of the PG aperture) for low and high extraction voltages. The deep reduction structure lies closer to the PG aperture in the region of $z < 10$ mm for the high extraction voltage ($V_{ex} = -8.1$ kV). To consider the relation between the reduction of $H_\alpha$ and the $H^-$ density, we compare these values close to the PG apertures $z < 5$ mm where negative losses occur due to beam extraction.

Figure 10(a) shows a plot of the extraction current ($I_{ex}$), the absolute value of the reduction $H^-$ density ($|\Delta n_{H^-}|$) and the reduction in the $H_\alpha$ intensity ($|\Delta H_\alpha|$) against the absolute value of the extraction voltage ($|V_{ex}|$). The current density of 10 mA cm$^{-2}$ for $I_{ex}$ is extracted at $|V_{ex}| = 8$ kV. Here, $I_{ex}$ is the drain current (i.e. mixed $H^-$ ions and electrons) in the circuit between the EG and a direct current extraction voltage power supply; it is linearly dependent on $V_{ex}$. Indicating data of a negative ion current and electron current is appropriate here, but they cannot be separated because we did not measure the ion current by a beam calorimeter due to non-beam acceleration in this experiment. The $|\Delta n_{H^-}|$ is observed at 2 mm from the PG surface; those reductions also depend linearly on the extraction voltage. There seems to be a close relation between the extracted current with a negative charge and the reduction in the $H^-$ density near the PG apertures. When the extraction current is 10 mA cm$^{-2}$, the $|\Delta n_{H^-}|$ is $3.4 \times 10^{16}$ m$^{-3}$. The current density $J$ is the product of the charged particle density $n$ and the drift velocity $v$. As we assume the extraction current is carried by $|\Delta n_{H^-}|$, the drift velocity $v = J/n = 1.85 \times 10^4$ m s$^{-1}$. The flow energy of the negative ion is estimated as 1.8 eV, a value close to the electron temperature in the extraction region of this source. A further important point is that the absolute value of the reduction in the $H_\alpha$ intensity measured at $z = 4$ mm, which is as close as possible to the position of $H^-$ measurement, also increases with the extraction.
Figure 10. (a) Extraction drain current $I_{ex}$ and the absolute value of $\Delta H_\alpha$ and $\Delta n_{H^-}$ increase as the strength of applied extraction voltage increases. The line for 10 mA cm$^2$ is represented. (b) Strength of $|\Delta H_\alpha|$ increased as the strength of $|\Delta n_{H^-}|$ increased in the optimal Cs condition.

8. Discussion

8.1. Influence of the electron impact excitation process

It is important to note the influence of the electron impact excitation process on $H_\alpha$ emissions in the extraction region of the negative ion source. Through Cs seeding, $H^-$ ions produced at the PG surface are diffused in the extraction region and forming an ion–ion plasma close to the PG surface. Therefore, the charge neutrality is conserved with $H^+$ and $H^-$ ions in the plasma.
the low electron current condition less than 1% those of the ions [20]. In the high proton ratio (≈80%) hydrogen negative ion source for NBI, the main excitation mechanisms for H\textsubscript{α} emission in the extraction region are dissociative recombination and mutual neutralization. The dominant reaction is determined by the fractions of H\textsuperscript{−} ions and electrons. Hence, the dominant excitation mechanism for H\textsubscript{α} emission becomes mutual neutralization in the case of ion–ion plasmas because they have a large H\textsuperscript{−} fraction near the PG surface. Evidence for this scenario can be seen in the H\textsuperscript{−}, H\textsubscript{α}, H\textsubscript{β} and I\textsubscript{es} observations shown in figure 3. The small amount of electron penetration from the discharge region during beam extraction was observed with the electrostatic probe [20], which has been confirmed by particle-in-cell (PIC) simulations [17]. Optical measurement is also consistent with such electron behaviour in the pure volume discharge. This contribution to the hydrogen emission is considered to be negligibly small in the ion–ion plasma in optimal Cs conditions. To obtain more detail about the electron behaviour and the analysis of the H\textsubscript{α} excitation process, the local electron density needs to be measured. It is also useful to construct a realistic simulation model for ion–ion plasma with beam extraction in a hydrogen negative ion source.

8.2. Integral data analysis along the line of sight

Considering the line integral intensity for H\textsubscript{α} imaging spectroscopy, the measured H\textsubscript{α} intensity shows not only the mutual neutralization process but also other excitation processes such as dissociative recombination. In the peripheral region outside the extraction area, the electron excitation process might be an influential element owing to the low number of H\textsuperscript{−} ions because of less Cs conditioning, owing to the position of the Cs evaporator being optimized for maximal beam distribution. However, if the line integrated H\textsubscript{α} intensity contains such elements, the reduction value of the ΔH\textsubscript{α} reflects the reduction in H\textsuperscript{−} ions only in the extraction area near the PG apertures. Therefore, it is reasonable to suppose that the distribution image of ΔH\textsubscript{α} applies to the reduction structure of the H\textsuperscript{−} ions at the centre of the negative ion source, which is rich in H\textsuperscript{−} ions after Cs conditioning.

8.3. Extraction of negative ions

Surface produced H\textsuperscript{−} ions can reach PG apertures following two processes: one is direct recoil of H\textsuperscript{−} ion, which is considered the major process of H\textsuperscript{−} ion extraction in RF ion sources. Plasma potential of RF ion source is more than 20 V and positive ions accelerate towards the plasma grid. The positive ions are converted to H\textsuperscript{−} on the conical surface surrounding PG aperture with low work function, and the H\textsuperscript{−} ions gather at the PG aperture. This process is supported by numerical simulation of the RF ion source [16]. The other is a sequential process. The H\textsuperscript{−} ion produced on the PG surface moves to the source plasma initially, and changes direction by Lorentz force and charge exchange and/or elastic collisions with hydrogen atoms. The H\textsuperscript{−} ions relax their energies during this process, and some of them are extracted after arriving at a meniscus. In the former case, the H\textsubscript{α} reduction during beam extraction should concentrate around the conical surface of plasma grid. In our experiment, however, the H\textsubscript{α} reduction distributes widely in the extraction region. This feature corresponds to the latter case described above, and is consistent with the H\textsuperscript{−} distribution measured with CRDS [30]. The difference of the former and latter mechanisms of H\textsuperscript{−} production is caused by the plasma potentials in the RF ion source and filament-arc source; typically less than 30 V [19] and less than 5 V [20],
respectively. Based on the result of H$_{\alpha}$ imaging spectroscopy, we conclude that ‘stray’ H$^-$ ions are extracted from a wide extraction region in the filament-arc source.

9. Conclusion

The imaging spectroscopy diagnostic tool successfully worked to observe the distribution of H$_{\alpha}$ emission and its reduction structure in the extraction region in the negative hydrogen ion source. We found significant reductions in the distribution of the H$_{\alpha}$ emission, due to a decrease in the H$^-$ density caused by the decrease in the mutual neutralization process. This spectrum structure clearly shows that the reduction in the extracted H$^-$ ions generated at the PG surface is widely distributed in the extraction region. These results will have considerable impact on numerical analysis for the transport modelling of H$^-$ ions in the extraction region in negative ion sources. The diagnostic technique of H$_{\alpha}$ imaging spectroscopy, which is a powerful tool for experimentally determining the extraction behaviour and distribution of negative ions, will strongly contribute to the development of stable high-power operation for NBI.

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