Visualization of H^- Dynamics in Extraction Region of Negative-Ion Source by H_α Imaging Spectroscopy[*)]

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We developed a new imaging spectroscopy diagnostic tool for H_α emission and installed it on a negative hydrogen ion (H^-) source to investigate the H^- dynamics in the extraction region. During beam extraction, the H_α emission dropped; the same drop also appeared in the H^- density (as measured by cavity ring-down spectroscopy). The reduction in the H_α emission results from the reduction in the excited hydrogen population caused by mutual neutralization processes between H^+ and H^- ions, which in turn are due to a decrease in the H^- density. We find a reduction structure in H_α that is observed inside the plasma farther than 20 mm from the plasma grid (PG) surface. The result indicates that H^- ions produced at the PG surface accumulate in the extraction region, so we conclude that they flow toward the PG apertures.

Keywords: negative ion source, H^-, H_α, mutual neutralization, imaging spectroscopy

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A negative hydrogen (H^-) or deuterium (D^-) ion source performs high-energy neutral beam injection (NBI) at the Large Helical Device [1] and at JT-60U [2]. A high-current D^- source using RF discharge is designed for NBI at the International Thermonuclear Experimental Reactor [3]. The source must provide a stable high-energy (1 MeV) beam for one hour and uniform beam extraction from wide grids with multiple apertures. In these ion sources, H^- ions are produced by converting positive atomic ions and neutral atoms on the cesium-covered plasma grid (PG) surface, which has a low work function and faces the discharge. The uniformity of H^- production and its behavior are the key issues for stable high-power NBI operation. In contrast, the behavior of H^- ions in the extraction region near the PG surface is not well understood. Therefore, a diagnostic tool for H^- ions is necessary. We have adopted cavity ring-down spectroscopy (CRDS) to measure the H^- density in the extraction region [4, 5]. It revealed some level of reduction in the H^- density during beam extraction. This tool is effective for understanding H^- behavior, but it is difficult to obtain the H^- profile for a single discharge because the alignment of cavity mirrors and laser path is delicate.

On the other hand, optical emission spectroscopy (OES) for H^- ion sources has been developed at IPP Garching [6]. The H_α emission intensity is correlated with the excited-state ($n = 3$) population density of atomic hydrogen. According to the studes of atomic and molecular processes in hydrogen plasma [7, 8], 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, written as $H_m^+ + H^- \rightarrow H(n = 3) + H_m$ ($m = 1, 2, 3$), where m is the number of atoms. As the percentage of negative ions is increased, H_α light emission caused by the mutual neutralization process becomes dominant. We have confirmed the relevance of negative ions and the H_α signal strength measured by CRDS and OES, respectively [9], in the H^- ion source at the National Institute for Fusion Science (NIFS). It has been shown that the same signal reduction appeared in the H^- density and H_α intensity during beam extraction. Thus, two-dimensional H_α measurements can probe the behavior of H^- ions.

In this paper, we present an imaging spectroscopy diagnostic tool for H_α emission in the extraction region in the H^- ion source. We find a reduction structure in the H_α spectrum, which in turn is on account of a decrease in the H^- density during beam extraction.

The experimental setup is shown in Fig. 1. We used the 1/3-scaled negative hydrogen ion source at the NIFS to investigate the H^- dynamics in the extraction region. The source plasma was generated by arc discharge in an arc chamber. The extraction region near the PG surface was separated from the arc discharge region by a magnetic filter field in order to reduce the electron temperature. We also applied a bias voltage between the arc chamber and PG in order to reduce the electron extraction current. We had installed the CRDS for H^- measurement and OES tools on the side-wall of bias insulator, which was sandwiched

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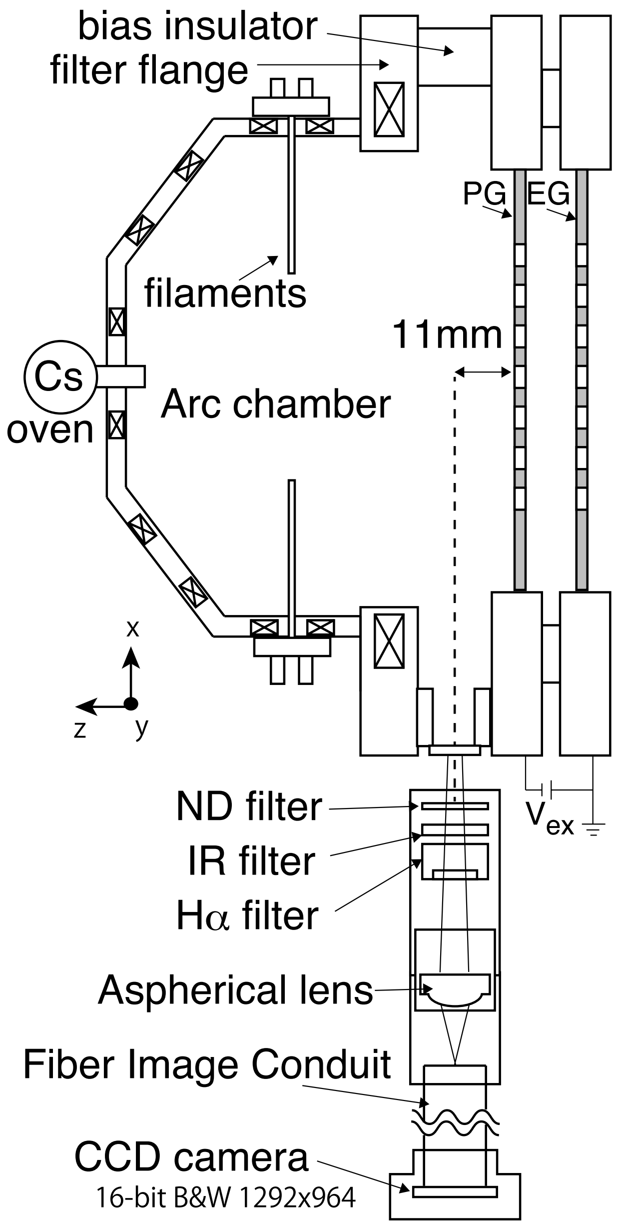

Fig. 1 Schematic drawing of negative hydrogen ion source and H_α imaging spectrometer.

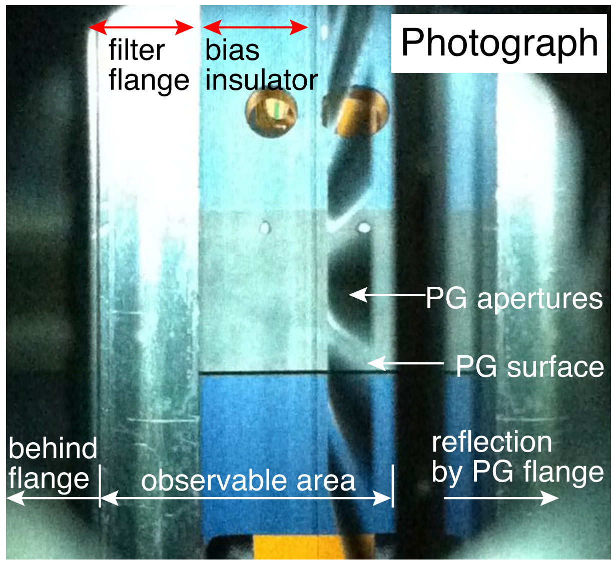

Fig. 2 Photograph of the extraction region taken from the viewport for H_α imaging.

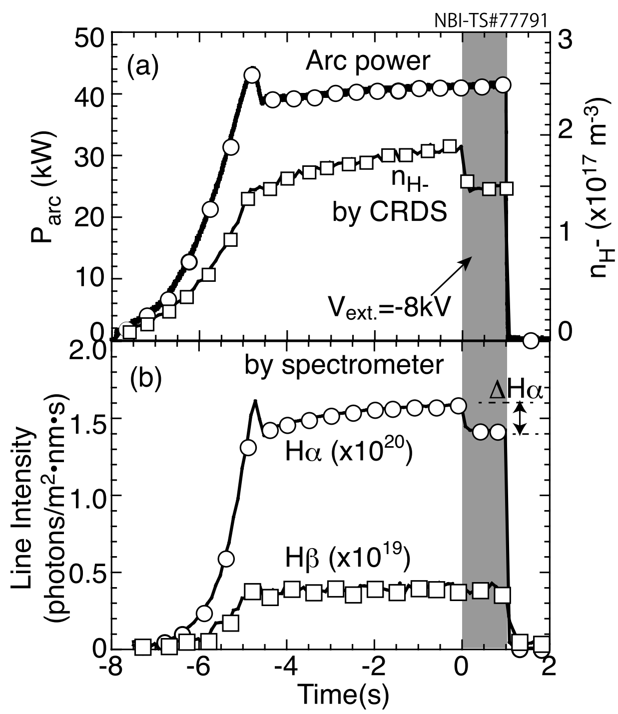

Fig. 3 (a) Waveform of arc discharge power and H^- density measured by CRDS. (b) Waveform of H_α and H_β intensities.

between the magnetic filter flange and the PG flange. In addition, the H_α imaging spectrometer was installed on the bias insulator. The line of sight was arranged parallel to the PG surface and passed through a 16-mm-diameter optical viewing port. The center of the line of sight was set beside the PG apertures at z = 11 mm from the PG. The optical system consists of three optical filters and an aspherical lens. A glass-fiber image conduit was used to transfer the optical images to a 1/3-inch charge-coupled device (CCD) detector (SONY ICX445) with a resolution of 1292 × 964 pixels (width × height) while maintaining the high-voltage insulation for beam extraction. The imaging system acquires 16-bit monochrome images.

Figure 2 shows a photograph of the extraction region taken from the viewport. The viewing angle covers the area from the magnetic filter flange to the PG surface. Both sides of the image field comprise the invisible area behind the flange. A row of the PG's apertures appears as a quadrangular shape on the image. To understand the positional relationship, we superimposed a wire frame on the spectral image to show the envelope of the major components inside the ion source.

Figure 3 (a) shows the waveform of the arc discharge power and the H^- density measured by CRDS at $z = 9$ mm from the PG under cesium seeding with a 0.2 Pa hydrogen gas pressure and 0.2 V (i.e., low) bias voltage. The discharge conditions remained constant before and during beam extraction with an extraction voltage of $V_{ext} = -8$ kV between the PG and extraction grid (EG). The EG was short-circuited by the grounded grid in this experiment. The H^- density increased to $1.9 \times 10^{17}\ m^{-3}$ in the 40 kW arc discharge and then decreased by 20% during beam extraction. We found the same signal drop on the H_α line intensity measured by OES at $z = 11$ mm, as shown in Fig. 3 (b). This reduction was 13% of the H_α emission intensity with only arc discharge. We also examined the H_β emission intensity using OES; it was not affected by the extraction voltage. Here the reduction in the H_α intensity due to beam extraction is defined as ΔH_α, which is the key value for understanding the H^- behavior.

Figure 4 (a) shows a spectral image of H_α taken by imaging spectrometer in a 40 kW arc discharge. Strong reflections from the tungsten filament radiation appeared around the filter flange and the PG apertures; however, we did not observe such a large reflection on the bias insulator. From the spectrometer measurements, we estimated the background filament radiation to be approximately 5% at the center of the line of sight. Thus, the observable area for the H_α distribution is on the bias insulator located up to $z = 20$ mm from the PG. The H_α emission intensity gradually decreases toward the surface of the PG, and the distribution along the vertical direction is uniform in the extraction region. Figure 4 (b) shows the distribution of ΔH_α produced by subtracting the image acquired before beam extraction from that image acquired during beam extraction. Here the decrease region, constant zone, and growth region are represented in red, green, and blue, respectively. For a constant background and with a constant arc discharge, the observable area of the ΔH_α distribution expands to $z = 35$ mm from the PG. In the region close to the PG surface ($z < 10$ mm), the reduction in the H_α signal beside the apertures is much larger than that beside the surface. We also found that the reduction in the H_α intensity is observed inside the plasma, farther than 20 mm from the PG surface. A large reduction in H_α appeared on the upper side of the image, where is the center of the ion source.

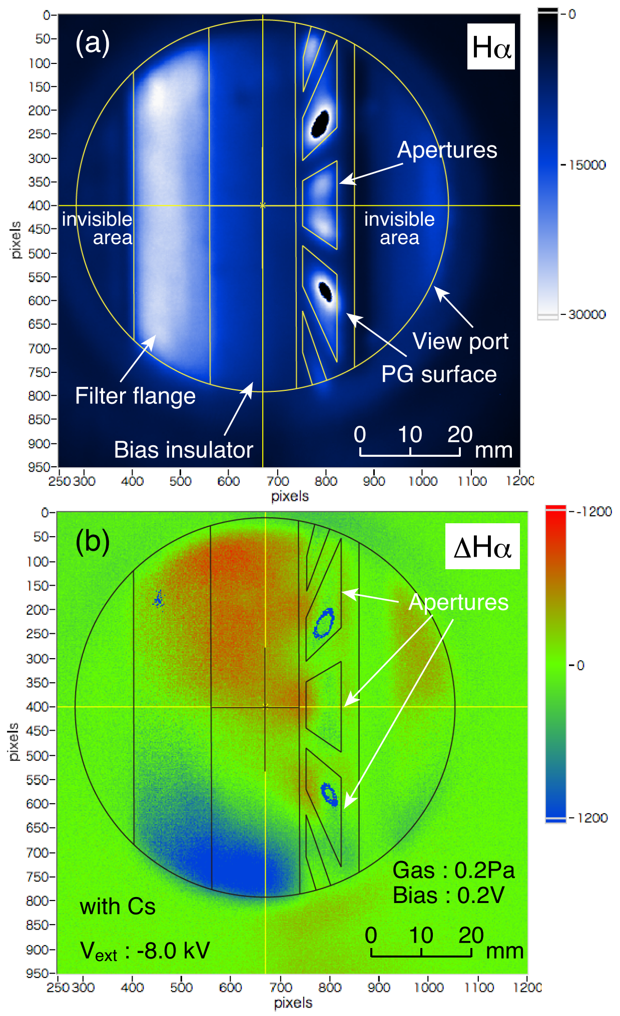

Fig. 4 (a) Spectral image of H_α and (b) reduction distribution of ΔH_α in the extraction region.

We speculate that the densities of the neutral hydrogen and positive hydrogen ions were not affected by the negative extraction voltage in the constant arc discharge condition. The H_β signal intensity (see in Fig. 3 (b)), which was affected mainly by dissociative recombination with H_2^+ and electrons, did not decrease during beam extraction. This result indicates that the effect of the electrons due to the negative extraction voltage is negligibly small in a rich H^- condition. Thus, the ΔH_α was mainly caused by the decrease in the excited hydrogen population that resulted from the mutual neutralization processes, which in turn were due to the decrease in H^- density. It is appropriate to show the ΔH_α distribution as the distribution of the reduction in H^- ions that have been extracted from the grid apertures. This suggests that H^- ions are widely distributed in the extraction region, and the center of the ion source is a H^--rich condition because of the position of the Cs feeder. This result is consistent with the H^- distribution measured by CRDS [10]. We understand that H^- ions produced at the PG surface penetrate the depth of the extraction region and then flow toward the PG apertures.

In conclusion, we investigated the H^- behavior in the extraction region in a negative ion source for NBI using H_α imaging spectroscopy. We found a significant reduction structure in the H_α spectrum, which in turn is due to a decrease in the H^- density during beam extraction. This result clearly shows that the motion of extracted negative ions generated at the PG surface is widely distributed in the extraction region. Therefore, H_α imaging spectroscopy, which is a powerful tool for experimentally determining the behavior and distribution of negative ions, will contribute to NBI with stable high-power operation.

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