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Development of spectrally selective imaging system for negative hydrogen ion source[a)]

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A spectrally selective imaging system has been developed to obtain a distribution of H_α emissions at the extraction region in a hydrogen negative ion source. The diagnostic system consisted of an aspherical lens, optical filters, a fiber image conduit, and a charge coupled device detector was installed on the 1/3-scaled hydrogen negative ion source in the National Institute for Fusion Science. The center of sight line passes beside the plasma grid (PG) surface with the distance of 11 mm, and the viewing angle has coverage 35 mm from the PG surface. Two dimensional H_α distribution in the range up to 20 mm from the PG surface was clearly observed. The reduction area for H_α emission caused by beam extraction was widely distributed in the extraction region near the PG surface. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4842318]

I. INTRODUCTION

A distribution of negative hydrogen ion (H^-) and its extraction behavior are the important contents to produce a homogeneous beam which is a critical issue for stable and high-power operation for a large-scaled and high-energy neutral beam injectors (NBI) that used arc discharge H^- sources[1,2] and will use radio frequency (RF) discharged source.[3] In the extraction region near the plasma grid (PG) surface, a reaction of mutual neutralization between H^+ and H^- ions is one of the important destruction processes for H^- ions. In addition, excited-state ($n = 3$) neutral hydrogens are produced by this reaction, and it emits hydrogen Balmer-α spectrum (H_α) during the transition of energy level ($n = 3 \rightarrow 2$). For this reason, an optical emission spectroscopy (OES) diagnostic for hydrogen Balmer line emission had been carried out in the negative ion source for monitoring negative ion densities.[4] In order to investigate behavior of H^- ions, we developed an imaging diagnostic method with a high voltage insulation for negative ion source for NBI.

In this paper, we present a spectrally selective imaging system for H_α emissions. Two dimensional H_α image was observed in the extraction region in the range to 20 mm from the PG surface. The intensity of H_α emission dropped during beam extraction, the area of which was widely distributed in the extraction region.

II. CONFIGURATION OF A SPECTRALLY SELECTIVE IMAGING SYSTEM

Figure 1(a) shows a cross-section of the 1/3-scaled negative hydrogen ion source in the National Institute for Fusion Science (NIFS). A source hydrogen plasma produces by arc discharge in the driver region, and it flows to the extraction region passing through the magnetic filter field in order to reduce an electron temperature for enhancement of H^- production. Protons and neutral hydrogen atoms are converted to H^- ions at the Cs-covered PG surface with a low work function faced the discharge.

An optical diagnostic port with an optical sapphire window was arranged on the side wall of the bias insulator between the magnetic filter flange and the PG flange. A line of sight (LOS) of the imaging system passed through the center of the viewing port arranged parallel to the PG surface with the distance of 11 mm. The viewing angle has coverage from the magnetic filter flange to the PG surface as shown in the photograph of the extraction region (Figure 1(b)) taken from the viewing port. Most of the viewing area for imaging system is inside the angle of $\theta = 5°$, and the observable area is $z = 35$ mm from the PG surface at the center of ion source ($x = 0$ mm). In the photographic image, the left-hand side area which is behind the filter flange is the direction of driver region; the H^- ions are extracted to the right-hand side passing through the PG apertures. The size of the PG aperture is 12 mm in diameter, and its edge is conical in shape with a diameter of 16 mm. The interval distance of PG apertures is 19 mm along the y-axis. Therefore, a row of the PG apertures appears as a quadrangle shape in the photograph as shown in Figure 1(b).

Figure 2 shows a configuration of a spectrally selective imaging system. We arranged three optical filters (i.e., a neutral density filter to reduce the amount of light, an infrared ray (IR) cut filter to remove IR components from the filament radiation, and an interference band path filter to use as wavelength selector) in front of an aspherical lens. The central wavelength of the interference band path filter is 656 nm in normal incidence with 10 nm full width at half maximum (FWHM). When the incidence angle of the incoming light with the wavelength of 656 nm increases to 5°, the central

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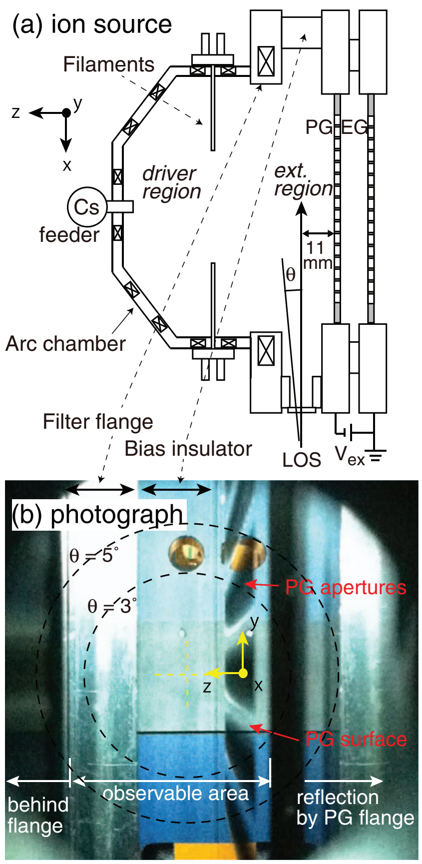

FIG. 1. (a) Cross-section drawing of the negative hydrogen ion source. The optical viewing port is equipped in the side wall of the bias insulator. (b) Photograph of the extraction region taken from the viewing port for imaging system. The viewing angles of $\theta = 3^\circ$ and $\theta = 5^\circ$ are represented in dotted circles.

wavelength of the filter decreases 0.6 nm which is sufficiently smaller than the FWHM. Therefore, the variation of the incidence angle has little effect on the imaging measurement.

An incidence light is focused on the surface of a glass fiber image conduit which is 6.4 mm in diameter and 30 cm in length; each fiber element has the size of 12 μm in diameter. We covered the image conduit with a black polyolefin tube for shade of ambient light. The image conduit works as translation of an optical image to a charge coupled device (CCD) detector (Sony: ICX445ALA) keeping high voltage insulation for beam extraction. The size of the CCD is 4.8 mm in width and 3.6 mm in height with 1292 × 964 pixels (width × height). Each square sensor element has the size of 3.75 μm. Therefore, about 400 × 300 optical fibers are effective on the CCD sensor, the resolution which is sufficient to obtain the spatial distribution of H_α emission. The specification of maximal frame rate of the camera with full resolution and monochromatic 16-bit mode is 26 fps. We operated 13 fps frame rate for data acquisition using 60 ms exposure time with image processing.

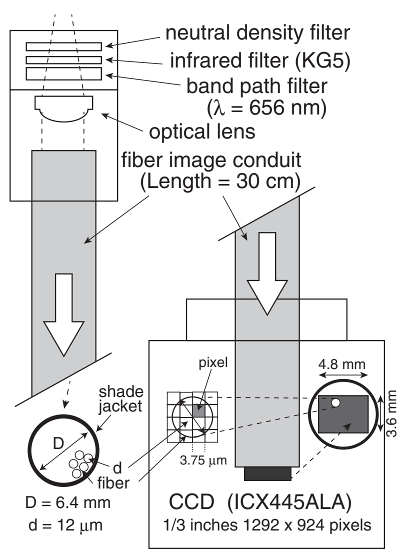

FIG. 2. Optical configuration of the spectrally selective imaging system which consists of optical filters, a quartz lens, and a fiber image conduit. Spectral image is detected by a CCD detector.

III. SPATIAL DISTRIBUTION OF H_α EMISSION IN THE EXTRACTION REGION

Figures 3 shows the optical images for the wavelength of 656 nm taken by the imaging system in the 50 kW hydrogen arc discharge. We superimposed a yellow line as the envelop on the image of the major components to show the positional relationship inside the ion source. Figure 3(a) shows the case without IR cut filter. The exposure time of the CCD sensor is 20 ms which is limited by strong reflection signals for IR radiation from a tungsten filament observed at the magnetic filter

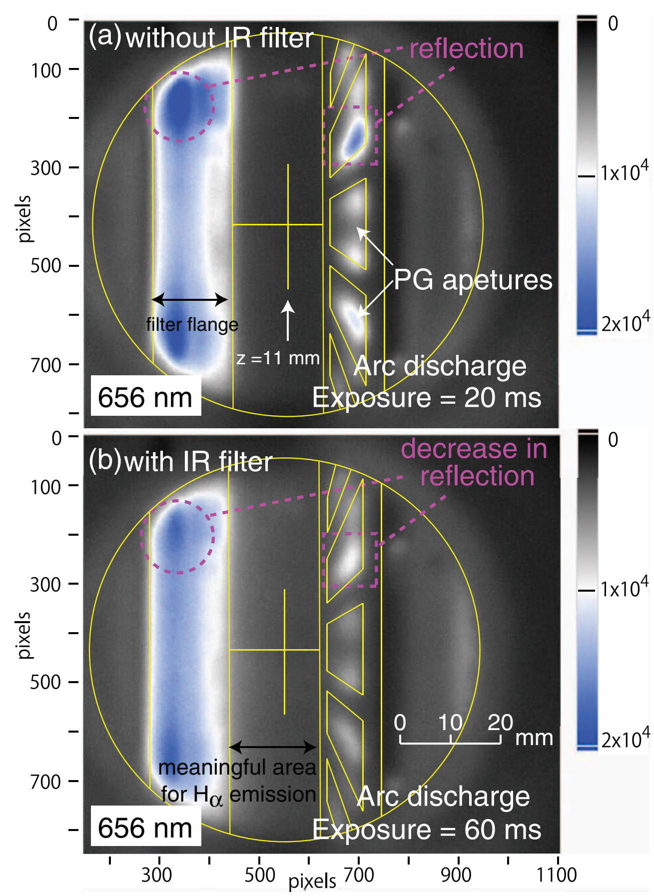

FIG. 3. Spectral images for the wavelength of 656 nm in the 50 kW arc discharge (a) without IR filter and (b) with IR filter. Strong reflection signals owing to filament radiation appeared on the filter flange (dotted circle) and the PG apertures (dotted square) were reduced by the IR filter.

flange and the inner surface of the PG apertures is shown in blue. These strong reflections must be removed to take a clear distribution of the H_α emission. We have achieved a reduction in these reflections by an IR cut filter (SCHOTT: KG5) which is a wide range heat absorption grass, as shown in Figure 3(b). The transmittance of the IR cut filter is 0.65 at 650 nm near the H_α wavelength; it decreases to 0.1 at 850 nm in near-infrared region. The relative sensitivity factor for CCD sensor is 1.0 at 590 nm, and it decreases to 0.88 at 650 nm. Since the relative sensitivity factor still remains 0.3 at 850 nm, the IR cut filter is effective to reduce the radiation signal in near-infrared region from the tungsten filament. We have observed H_α distribution with a low reflection signal with the 60 ms long exposure time. Therefore, the signal intensity of H_α emissions is of sufficient value to understand its distribution near the PG surface; the background filament radiation is estimated to be about 5% at the center of the line of sight ($z = 11$ mm) by comparison of spectrometer measurements.

Figure 4 shows the typical distribution of the light emissions with the wavelength of 656 nm along the z-axis at the LOS center ($y = 0$ mm) in a Cs conditioning discharge. The solid line and the dotted line are the time period of only arc discharge and during 1 s beam extraction with the negative extraction voltage ($V_{ex} = -8.1$ kV), respectively. The intensity of H_α emission inside $z < 4$ mm, presented in gray area, is invalid because the reflection signals of filament radiation from the PG apertures are overlapped with H_α signals. The intensity of H_α emission at the far position of $z = 18$ mm is higher than that at close position of $z = 4$ owing to the electron contamination.[5] The H_α signal intensity decreased 15% by beam extraction near the PG apertures. The electron temperature measured by an electrostatic probe is 2.3 eV at $z = 11$ mm. According to the study of atomic and molecular processes in hydrogen plasma,[6,7] the dominant excitation mechanisms for H_α emission are the dissociative recombination between an electron and H_2^+ and the mutual neutralization between H^+ and H^- ions in such low temperature plasma. As the percentage of negative ions increases (i.e., a few electrons) in optimal Cs condition for the negative hydrogen ion source, the H_α 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. Since the feeding gas pressure and the arc discharge power stay constant during beam extraction, the neutral hydrogen density considered to be constant in this experiment. We also confirmed the constant H_β emission which is mainly due to electron contributions. Therefore, the signal reduction for H_α emission owing to the beam extraction is the result from a reduction in the H^- ion density by way of mutual neutralization process. Similar reduction in the H_α emission line was also observed in RF negative hydrogen ion sources.[7] Since the reduction area for H_α emission distributes widely in the extraction region, the H^- ions generated at the PG surface are widely distributed during arc discharge in the optimal Cs condition, then it decreases caused by the particle loss owing to the beam extraction. Consequently, diagnostic of the reduction for H_α emission during beam extraction has the ability to probe the reduction of the H^- ions in the extraction region of the negative hydrogen ion source.

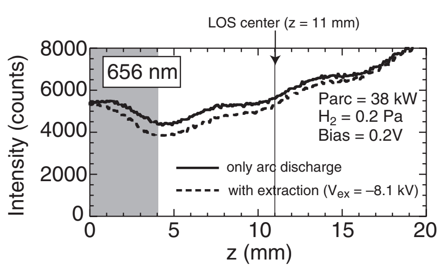

FIG. 4. Spatial distributions of the light signals with the wavelength of 656 nm in the direction normal to the PG surface. The solid line and the bold line are the time period at only arc discharge and during applied extraction voltage, respectively. The gray area inside of $z < 4$ mm is invalid for H_α intensity due to the overlapping reflection signals from the PG surface.

IV. CONCLUSION

The spectrally selective imaging system has been well performed to obtain the distribution of H_α emission in the extraction region of the hydrogen negative ion source. This diagnostic is utilized for understanding the behavior of H^- ions close to the PG surface. Therefore, it will contribute to verify a particle transport modeling using numerical calculation for a negative ion source, and also will contribute a stable and high-power operation for NBI in fusion experiment device.

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