Diagnostics tools and methods for negative ion source plasmas, a review

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Abstract

Plasma parameter measurements for negative hydrogen (H\(^-\)) ion sources have been playing an important role in clarifying fundamental physics related to negative ion production and destruction processes. Measured data of beam properties, such as H\(^-\) current density with the co-extracted electron current and the emittance, were correlated to local concentration of charged particles and temperature often characterized by Langmuir probes and optical emission spectrometry. Langmuir probes coupled to pulse lasers quantified local H\(^-\) ion densities from early days of H\(^-\) ion source development, while the cavity ring down photodetachment method removed Langmuir probes from contemporary large-size high power density ion sources. Technological progress has made source plasma diagnostics possible during beam extraction, which has thrown light on the transport of H\(^-\) ions during the application of the extraction electric field. The advancement of plasma diagnostics for high intensity H\(^-\) ion sources are summarized in this report together with recent results from the research and development negative ion source being operated for collaborative research programs at National Institute for Fusion Science.

1. Introduction

High intensity proton beams offer possibilities to understand physics laws governing nature as ring accelerators boost up the energy of injected protons formed from high current density beams of negative hydrogen (H\(^-\)) ions by letting them electron stripped through charge exchange foils [1, 2]. Large current high energy neutral beams of hydrogen isotopes produced from negative deuterium (D\(^-\)) beams will heat up and drive current in torus plasma confined in the ITER nuclear fusion experiment facility [3, 4]. Improvements of beam sources that produce H\(^-\) ions directly increase the proton beam intensity of a high energy accelerator, and enlarge plasma heating power of the neutral beam injection system for a nuclear fusion experiment device.

Optimization of H\(^-\) ion sources utilized in these applications requires two important steps: production of negative ion rich plasma, and formation of sheath structure suitable for H\(^-\) extraction while minimizing the amount of co-extracted electron current. The invention of ‘magnetic filter’ by Ehlers and Leung [5], realized an efficient extraction system for H\(^-\) ions from a volume of hydrogen plasma [6]. They showed that the proper separation of the ion source plasma into high temperature ‘driver region’ and low temperature ‘extraction region’ by means of applying a transverse magnetic field realized an ideal system for H\(^-\) ion extraction. Data obtained with a Langmuir probe verified the two regions of different electron temperature were created by the magnetic filter [7]. Meanwhile, Bacal showed that sizable amount of H\(^-\) density can be present in a hydrogen arc discharge [8], and the method employed to prove the model of negative ion production was based upon negative ion density measurement by laser induced photodetachment [9]. Plasma diagnostics thus have played an important role to deepen understanding how H\(^-\) ions are produced and distributed in the plasma volume.

The photodetachment method becomes popular to quantify H\(^-\) ion density in a H\(^-\) source for plasma heating of fusion experiments under an intense discharge condition [10]. The method verified that H\(^-\) ions are
produced in a pure hydrogen discharge through a two steps process; formation of rovibrationally excited hydrogen molecules, and successive electron attachment to the excited molecules. Bacal and Hamilton indicated negative hydrogen and negative deuterium ions increased in proportion to the third power of electron density in the density range below $10^{10}$ cm$^{-3}$. This functional dependence is consistent with negative ion production by a nonlinear process such as dissociative attachment to excited hydrogen molecules and $\text{H}^-$ loss by diffusion [9]. A good review by the original inventor has been published [11] and substantial technological advancements were reported including the system development not to insert a probe to collect photodetached electrons. High power density of contemporary $\text{H}^-$ ion source plasma limits the usage of electrostatic probes as the heat load due to plasma exposure can quickly damage the inserted probe. In early days, electrostatic probes were the important diagnostic method to study factors influential on the negative ion production, destruction, and transport mechanisms [12]. They are still useful tools that yield wide variety of information on how the ion source performs to produce $\text{H}^-$ ions and they produce data that are useful to understand physics governing the $\text{H}^-$ ion production in an ion source [13].

Plasma diagnostics through optical emission spectroscopy does not disturb plasma operation like Langmuir probes, and Fantz developed the models necessary to diagnose $\text{H}^-$ containing ion source plasmas [14]. The method is particularly suitable to investigate high density plasma confined in ion sources for accelerators [15]. Until the time a more sophisticated laser assisted method is implemented [16], optical emission spectroscopy in the vacuum ultra-violet wavelength range was utilized to estimate the production rate of ro-vibrationally excited hydrogen molecules in plasma [17]. Diagnostic methods for negative ion source and $\text{H}^-$ ion beams continuously have deepened the understanding of physics processes related to $\text{H}^-$ ion formation and extraction. Some good review papers were published in the past summarizing plasma diagnostics and the $\text{H}^-$ ion source physics clarified by the obtained results [11, 18, 19]. A decade has passed since these review works were published, and it is the aim of the current paper to summarize tools and methods for clarifying physics of $\text{H}^-$ ions by reporting the present status of plasma diagnostic activities of $\text{H}^-$ ions being operated at the National Institute of Fusion Science.

2. Electrostatic probe

Electrostatic probe measurement has been long utilized to understand plasma properties in ion source development for plasma heating applications [20]. In the extraction region of the $\text{H}^-$ ion source, negative ion density exceeds electron density and the current voltage, or $I$–$V$ trace differs strongly from the one taken for ordinary plasma with electron density close to the ion density. Presence of the filter magnetic field and/or the electron suppression magnetic field affects the current collection by the probe, and some care are needed to determine fundamental plasma parameters out of probe $I$–$V$ characteristics.

2.1. Plasma parameter measurement

A single electrostatic probe, or often called Langmuir probe can determine electron temperature, electron density and plasma potential. Leung utilized an electrostatic probe to confirm the effectiveness of the magnetic filter geometry coupled to a plasma electrode biased at a voltage with respect to the ion source chamber wall [21]. He also confirmed electron attachment to $\text{H}_2$ molecules in plasma of low electron temperature produced by injecting Xe into the discharge system [22]. Bacal measured the correlation between the $\text{H}^-$ density and the electron temperature in hydrogen plasma [23]. Fukumasa reported the spatial distributions of plasma parameters across the filter magnetic field [24]. Plasma potential was found important in understanding confinement and transport of plasma, while electron density and temperature determined production and loss rates of $\text{H}^-$ ions in plasma volume. In several cases, these parameters are utilized as input parameters for modeling reaction processes in the plasma [25]. More commonly, the high-energy component of the electron energy distribution function was estimated in order to evaluate the effectiveness of the plasma to produce rovibrationally excited hydrogen molecules [26].

In considerably strong magnetic field, some correction of electron density is required because of inhomogeneity of the Debye length to the probe tip due to the electron magnetization. The correction methods are described by Dote et al and Laframboise et al [27, 28]. Electron density can also be obtained by means of surface wave probe (plasma absorption probe), which has a co-axial structure of electrodes and insulators. Electron density is estimated from the absorption frequency of the standing wave rippling at the outer insulator shell and surrounding plasma by applying microwave to center feed line of the probe as described by Kokura et al [29]. Triveipiece et al wrote an article on the analytic forms of the absorption frequency and electron density [30]. A disadvantage of the surface wave probe is that the diameter of the probing part is larger than Langmuir probe and indicates the higher side electron density on the outer most insulator shell of the probe.
2.2. Negative ion density measurement

Difference in mass between electrons and negative ions reduces the saturation current of the positively biased probe as the ratio of negative ion density to electrons density becomes larger. Estimation of the ratio, however, cannot be made in a straightforward manner, but requires a lot of cautions. The presence of negative ions in the plasma modifies electrostatic potential structure around the probe sheath region, and the $I-V$ trace cannot be interpreted in the usual way of pure electron-positive ion plasma \[31\]. Stamate et al \[32\] introduced ‘test function’ to estimate plasma parameters including negative ion density. Amemiya had proposed a method to measure negative ion density based on the principle of ion-sensitive-probe \[33\] by utilizing magnetic field to exclude current signal due to electrons \[34\]. In the case that the negative saturation current for a positively biased probe is close to the values of positive ion saturation current with negative bias voltage applied to the probe, the ratio of positive saturation current to negative saturation current are sometimes used as the measure to discuss relative concentration of negative ions to electrons \[35\]. The discussion still continues to make use of probe $I-V$ characteristics to estimate negative ion concentration in plasmas \[36\].

2.3. Plasma flow measurement

Plasma flow can be measured with Mach probes \[37\]. Probes of this kind were utilized to measure plasma flow speed for magnetized plasmas to study plasma wall interaction \[38\]. The flow velocity of $H^−$ ions in the source plasma was determined by photodetachment technique \[19\], and flow of plasma charged particles in an ion source was measured with a structured probe \[39\].

3. Photodetachment diagnostics

3.1. Pulse laser photodetachment coupled to an electrostatic probe

The fundamental principle of $H^−$ ion density measurement by photodetachment relies on the release of an electron from the affinity level of an $H^−$ ion. Bacal detected the released electrons from the photodetachment reaction by inserting a probe in the region shone by the injected laser \[9, 40\]. The diagnostic principle is schematically illustrated in figure 1. All $H^+$ ions in the laser irradiated region are converted to pairs of a hydrogen atom and an electron. The saturation current to the positively biased probe recovers the value of electron density for the background negative ion containing plasma from the one for the electron density corresponding to the sum of negative ion density and electron density. The ratio of negative ion density to electron density obtained from the ratio of these values of saturation current was the main concern in early days. However, the method was soon recognized effective to estimate the temperature and/or velocity of negative ions by injecting two laser pulses \[41\]. The temperature and flow of negative ions alter the recovery time of the photodetachment signal \[42\], and hydrogen plasmas often contain two temperature components of $H^−$ ions as discussed by Ivanov \[43\].

Introduction of Cs into a hydrogen discharge realizes high concentration of $H^−$ ions in the extraction region of the ion source but also adds additional complexity to use probes for photodetachment measurement. The photodetachment signal detected by a probe responds differently when the ratio of negative ion density to electron density is high \[44\], and also may have some effect due to Cs possibly adsorbed on the surface of the...
probe. Laser photons irradiate the surface of the probe as shown in figure 1, and can possibly ablate adsorbate on the probe surface. Nishiura and Sasao [45] investigated the photodetachment signal response by placing the collector probe outside of the laser, while Kajita et al [46] invented eclipse probe method to avoid superfluuous signal due to desorption induced by laser. Mass difference of the hydrogen ions and Cs\(^{+}\) ion can affect the dynamics of hydrogen positive ions and H\(^{-}\) ions and sheath formation. Charge exchange processes such as H\(^{+}\) + Cs → H(2s) + Cs\(^{+}\) and H\(^{+}\) + Cs\(^{+}\) → H + Cs change the ion species as the cross sections are considerably large, ~10\(^{-14}\) cm\(^{-2}\), in low energy range less than 100 eV [47–49]. When the atomic and ionic densities of Cs became comparable to those of hydrogen, the influence considered significant for the plasma characteristics. Whealton et al reported the influence Cs\(^{+}\) ions in the pre-sheath in their experimental measurement and simulation using a Double–Vlasov model for negative ion extraction [50].

3.2. Cavity ring-down photodetachment method

The insertion of probe to measure photodetachment signals should alter plasma condition, particularly the probe is biased positive with respect to the local plasma potential to collect electron saturation current. High power density plasmas in H\(^{-}\) ion sources heat up to damage probes as well as contaminate source plasmas by letting probe materials release due to heating and particle bombardment. A cavity ring-down configuration was adopted to study spatial profiles of negative ion density in an rf-plasma reactor [51]. Christ-Koch et al applied the technique to their high power density rf plasma for measurement of line of sight integrated negative ion density [52]. Tsumori et al revealed the H\(^{-}\) density near the extractor decreases by induction of extraction potential utilizing cavity ring-down photodetachment method [53], and the diagnostic system capable of estimating temperature of H\(^{-}\) ions was developed by increasing the laser intensity to realize absorption saturation [54].

3.3. Other laser photodetachment diagnostics

A pulse laser light source can be replaced with a moderate power density dc laser to measure detached electron signal using an electrostatic probe [55]. A method to deduce transport properties of negative ion plasma was proposed based upon dc laser photodetachment method [56]. Matsumoto et al coupled pulse Nd-YAG laser to a Faraday cup mounted outside of the ion source for detecting photodetachment signals [57]. The probability for local H\(^{-}\) ions to pass through the extraction hole to be a beam can be measured by this method [58].

4. Spectroscopic diagnostics

4.1. Plasma parameter measurement

Plasma parameters are measured based upon well-established theories of photon emission spectroscopy, and some good textbooks like the classical one by Griem [59] with others recently published [60] are available. For H\(^{-}\) ion containing plasmas, Fantz and Wunderlich compiled and proposed models describing hydrogen plasmas to deduce plasma parameters out of spectroscopic measurements [61]. Electron temperatures can be determined from line intensity ratios, while density can be estimated out of absolute intensity measurement. Performance of a RF H\(^{-}\) source was compared with that of an arc discharge source through optical emission spectroscopy by Fantz et al [62].

4.2. Negative ion density distribution

In the extraction region of the negative ion source with very high concentration of H\(^{-}\) ions, intensity of Balmer-\(\alpha\) (H\(_{\alpha}\)) light emission can be directly correlated to local H\(^{-}\) ion density. Based on this idea, Ikeda et al observed spatial distribution H\(_{\alpha}\) of light intensity near the extractor of their ion source with a narrow band optical interference filter [63], with the similar method that McCracken et al investigated the impurity transport in tokamak edge plasma [64]. The method assumes that the H\(_{\alpha}\) emission due to mutual neutralization of H\(^{-}\), i.e., H\(^{+}\) + H\(^{-}\) → 2H + h\(\nu\)(H\(_{\alpha}\)) predominates the local emission of H\(_{\alpha}\), from the H\(^{-}\) dominating extraction region plasma. The intensity of H\(_{\alpha}\) should be proportional to the loss rate of H\(^{-}\) for negative ion rich plasma provided the electron energy is lower than 1 eV [65]. An image representing the distribution of H\(^{-}\) ion density reduction associated with beam extraction was constructed by subtracting the two-dimensional intensity distribution of H\(_{\alpha}\) during beam extraction, from the distribution before induction of the extraction electric field. Beam extraction from the ion source reduced the H\(_{\alpha}\) intensity indicating reduction of H\(^{-}\) ion density due to change in electric field structure around the extraction holes. The extraction electric field was found affecting the negative ion density up to the plasma interior 30 mm deep from the plasma grid [65].

4.3. Vibrational/rotational states measurement

Photon emission intensity in VUV wavelength range has been correlated to efficiency of H\(^{-}\) production by volume processes [66], as it is considered proportional to the rate at which ro-vibrationally excited molecules are
formed in the plasma. The emission signals produced from laser-induced fluorescence can assign the initial ro-vibrational levels of hydrogen molecules [67], and indicate non-Boltzmann rotational distributions for the high vibrational states [16]. The method was utilized to diagnose H⁻ ion source plasma how the input RF power coupled to excite plasma particles [68, 69]. Molecular band emission spectra are also utilized to estimate rotational and vibrational temperatures [15, 70], and degree of dissociation [71] in H⁻ sources.

4.4. Plasma flow measurement
Doppler shifts of line spectrum emission produced data on plasma flow along the spectrometer’s line of sight from early days of magnetically confined nuclear fusion research [72]. Typical diagnostic system for the beam extracted from a H⁻ ion source usually include high resolution spectrometer to evaluate the beam divergence [73]. With high resolution spectrograph, slow plasma flow in the extraction region of the ion source can be also measured spectroscopically observing shifts and broadenings of emission line spectra [74].

5. Other diagnostics
Contemporary high intensity H⁻ ion sources have a Cs oven or dispenser to cover the plasma grid/electrode surface with Cs. Spectroscopic diagnostics can monitor the amount of Cs in a source [75], while a thermal ionization detector can measure the flux of Cs [76]. Rough estimation of the work function can be obtained from the photoelectric current produced by laser irradiation upon the low work function plasma grid [77].

6. Measurements with NIFS-RNIS
Research and development Negative Ion Source at the National Institute for Fusion Science (NIFS-RNIS) serves as a prototype ion source having nearly the same structure to the sources utilized for neutral beam injection heating of the large helical device (LHD) [78]. The RNIS device was used to be called the ‘1/3-scale ion source’ as the beam extraction area of the source is about one-third of the ion source equipped for the neutral beam heating of the LHD device. The source produced data necessary to design full size sources for LHD, and further serves as the supporting equipment for improving source operation procedures. The ion source facility offers a place for scientists and engineers to visit together for conducting joint research under the NIFS collaborative research program [79].

A schematic diagram of the RNIS is shown in figure 2 with the installed diagnostics components. These diagnostics tools characterize the plasma in the beam extraction region, as it directly affects the intensity and the quality of the extracted H⁻ beam. The main discharge region of the ion source that confines high energy electrons delivers low temperature plasma with hydrogen atoms and excited hydrogen molecules across the magnetic filter field. The transported particles form the plasma in the beam extraction region, or the volume between the plasma grid and the magnetic filter field. A dc power supply biases the plasma grid electrically isolated from the main discharge chamber. The diagnostic ports are installed on the insulator between the discharge chamber and the plasma grid as shown in figure 2. The increased thickness of the bias insulator from the original design has caused small changes in H⁻ density distribution and H⁻ beam profiles, but the source performance did not show large difference due to the increased volume of the H⁻ extraction region.

6.1. Plasma parameters
Local plasma parameters, electron temperature $T_e$, electron density $n_e$ and plasma potential $V_p$ are measured with Langmuir probes. In an ordinary plasma condition, electrons predominate the probe saturation current of negative charge species and the saturation current is far much greater than the positive ion saturation current as the mass of the plasma ions is far much greater than that of electrons. The probe $I$–$V$ curve obtained for a plasma in the extraction region of RNIS deviates largely from the one for ordinary electron-positive ion plasma; the positive ion saturation current is often comparable to the saturation current for negative charged species. In fact, electrons occupy a minor component of negative charged species in the plasma when the source is operated with Cs. In order to avoid evaporation of Cs atoms on the Langmuir probe tip, sweep voltage of 40 V peak to peak is continuously applied to the tip during the experiment. Heat capacitance of the tip with the radius of $\phi 0.4$–0.6 mm and of the length of 2–4 mm is light enough to increase the temperature of the tip by the bombardment of electron and ion fluxes. With aid of the temperature rise, no abrupt increase and unusual change of the saturation currents are observed. In the measurement with Langmuir probe, the probe holder made with ceramic has a possibility to perturb the plasma around the probe tip. Godyak and Alexandrovich [80] and Demidov et al [81] pointed out that probe holder with the dimension smaller than the Debye lengths of electrons and ions influenced measured plasma with the least perturbation. The influence of the probe holder is not clear. In the case of negative ion plasma with very low electron density, however, the sheath length is much
longer than electron sheath, because the temperature of positive ions does not differ from that of negative ions as described later. In addition, the diameter of the ceramic tube is made smaller to 2 mm near the probe tip. For these reasons, it is roughly assumed the influence of the probe holder is not so large.

Two Cs injection systems introduce Cs vapor into the plasma generator after running pure hydrogen discharge in RNIS Cs seeding operation. At the starting phase of Cs seeding, the saturation current of the negatively charge particles mainly consists of electrons and as the portion of saturation current due to $H^-$ ions begins to dominate, it steeply decreases. Injection of Cs as large as 80 mg reduced the ratio of the negative saturation current to the positive saturation current down to $1/3$ times the original value at the probe location 12 mm away from the plasma grid. Consumed Cs weight was obtained from the difference of the Cs weight filled before and the end of the experiment. Injected Cs was estimated this total Cs consumption and Langmuir’s equation of the Cs vapor pressure [82]. The time dependence of electron density and that of electron

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**Figure 2.** Cross-sectional view of NIFS R&D negative ion source and alignment of the diagnostics modules. The abbreviations of the corresponding modules, mm-IF: millimeter-wave Interferometer, $H\alpha$/Cs LAS: $H\alpha$/Cs laser absorption spectroscopy, DLP: directional Langmuir probe, DPP: directional photodetachment probe, CRD: cavity ring-down, OES: optical emission spectroscopy, $H\alpha$ CCD: $H\alpha$-filtered CCD imaging, and SWP: surface wave probe.
temperature, measured with a Langmuir-probe set at 12 mm away from the plasma grid, are shown in figure 3. The origin of the abscissa is set at the start time of the Cs introduction into the ion source. The figure clearly shows that the electron density decreased exponentially in the initial phase and became constant. In figure 3, increase of the electron density before Cs seeding is caused by the adjustment of the bias voltage from 2.3 to 1.4 V.

In RNIS Cs seeding operation, a Cs injection system directs Cs vapor to the sidewall, and the discharge plasma transports Cs to the plasma grid. After the initial Cs seeding procedure, the source is maintained in vacuum for about 12 h at room temperature. The electron density in the first discharge decreases further from that measured in the previous discharge before the empty interval. Further continuation of discharge in the initial Cs seeding does not decrease the electron in the extraction region anymore, and the reduction in electron density by putting this empty period is considered attributable to slow migration of Cs on the ion source wall. This Cs seeding procedure realizes a plasma with the H\(^{-}\) ion density surpassing the electron density. An ordinary Langmuir probe analysis does not guarantee enough accuracy for the measurement of the ratio of electron density to negative ion density under this condition. Thus, the electron density is compared with a surface wave probe at RNIS. The electron density results obtained with the surface wave probe for Cs seeded conditions were one- to two-order of magnitude lower than those without Cs \[83\]. The surface wave probe results have also shown that the dependence of electron density upon the plasma electrode bias resembles the dependence of the electron drain current upon the plasma electrode bias \[84\]. Namely, the plasma electrons are the cause of co-extracted electron current.

Influence of Cs positive (Cs\(^{+}\)) ions to plasma transport and sheath formation has not been measured in RNIS. The density of Cs atoms measured with laser absorption spectroscopy is several times 10\(^{15}\) m\(^{-3}\) and the density is about two-orders of magnitude lower than those of hydrogen positive and negative ions. In addition, the Cs II spectrum is lower than the detection limit of optical emission spectroscopy in the RNIS, whose discharge power is limited within 50 kW and the electron temperature is 0.6–0.7 eV in the extraction region. On the other hand, the spectrum emitted from a Cs atom (Cs I) is clearly observed in optical emission spectroscopy. Although the influence of Cs is expected to be small as mentioned by Wunderlich et al, effect onto the plasma condition in the very vicinity of plasma grid with adsorbed Cs requires further investigation \[85\].

Electron temperature measurement confirms the effectiveness of magnetic filter field to reduce penetration of high temperature electrons into the beam extraction region. Insertion of Langmuir probes to the RNIS proved that the magnetic filter design of the first-generation full size negative ion sources successfully reduced the electron temperature for efficient electron attachment to vibrationally excited H\(_2\) molecules \[86\]. Electrons in the extraction region, even though they are the minor component of the negatively charged particles, play important roles in determining plasma properties and beam extraction characteristics. Spatial profiles of electron temperature and density are routinely measured at RNIS with those of plasma potential \[87\]. Spatial distributions of the plasma potential in the beam extraction region indicate the characteristic change of the plasma due to injection of Cs into the ion source. Injection of Cs into the source reduces the plasma potential in
the extraction region closer to the anode potential as shown in figure 4, which exhibits a strong correlation to the reduction of electron density shown in figure 3. In the meantime, the plasma potential of the driver region stayed constant against Cs injection. Figure 4 also shows the time dependent change of the floating potentials with that of plasma potential. These potentials exhibit a saturation behavior toward the anode potential corresponding to the reduction of electron component during Cs seeding.

Presence of Cs in the discharge also affects the electric field, or the plasma potential gradient in the beam extraction region [88]. The potential difference between the plasma grid and the plasma potential in the extraction region shows a strong correlation against the electron current co-extracted with H$^-$ ion current. The co-extracted electron current decreases first and then the H$^-$ ion current decreases when the plasma grid bias is raised from the anode potential to the plasma potential of the extraction region. The local electron density stays constant against further increase of plasma grid bias above the plasma potential. A similar correlation exists between the ratio of electron density to H$^-$ ion density measured in the region with the distance about 10 mm from plasma grid, and the ratio of extracted electron current to H$^-$ ion current [53]. This region corresponds to the magnetic structure where a lobe-shaped magnetic field line induced by electron deflection magnets protrude from the plasma grid. The calculated magnetic lines of force near the plasma grid are illustrated in figure 5. Here the lobe created by the magnets is called electron deflection magnetic (EDM) lobe for later discussion.

The spatial distribution of plasma potential for Cs seeded operation differs from that for pure hydrogen operation. Followed by a large potential gap in front of the plasma grid, the spatial profile of the plasma potential for hydrogen operation exhibits the same slope against the change in plasma grid bias with respect the anode potential. This behavior of plasma potential is shown figure 6(a). The increase of plasma grid bias resulted the corresponding shift of the plasma potential in the extraction region. However, no distinct difference in the slope of the potential, or the electric field in the plasma, was observed. On the other hand, in the case of Cs seeded plasma, the electric field corresponding to the plasma electrode bias is formed in the extraction region plasma. The measured dependence of plasma potential profile upon the plasma grid bias voltage is shown in figure 6(b). The increase in the plasma grid bias changed the slope as plasma grid bias was elevated from 3.5 to 7.9 V.

Another difference of the Cs-seeded plasma is that the plasma potential in the extraction region becomes lower than the potential in the case of hydrogen discharge without Cs.

### 6.2. Negative ion density profile

Spatial distributions of H$^-$ density was measured with cavity ring-down method by setting the cavity path to make measurements along the direction perpendicular to the surface plane of plasma grid possible [53]. The distribution was expected to show an exponentially decaying profile against the distance toward the direction of the driver region as H$^-$ ions are assumed produced at the plasma grid surface in a Cs seeded negative ion source. Contrary to the expectation, the measured distribution exhibited an almost flat profile in the distance from 3 to 30 mm with respect to the surface of the plasma grid. The results obtained line averaged H$^-$ density have been compared with the spatial distributions of local H$^-$ ion density directly measured by the Langmuir probe.
photodetachment method. The two results were consistent, and the H\(^{-}\) density did not show a gradient towards the plasma grid surface. The \(I-V\) characteristics of Langmuir-probe showed negative saturation current comparable to the positive saturation current within the EDM lobe, and negative ion rich plasma filled up that region. The negative saturation current corresponding to electron component increases as a probe is moved toward the driver region passing through the EDM lobe.

The induction of extraction electric field should affect the local plasma parameters around the extraction holes. During the time the beam extraction electric field is induced, the density of H\(^{-}\) ions decreases and electron density increases correspondingly. The change in H\(^{-}\) ion density immediately proceeds from an equilibrium state before the beam extraction throughout the extraction region. The changes in the probe saturation currents and the H\(^{-}\) ion density measured by cavity ring down method are shown in figures (a) and (b). During the beam extraction, slope of the negative saturation current in the \(I-V\) curve increases; the saturation current is defined as an asymptotic line near the positive limit of applied sweep voltage and is defined independently of the floating and plasma potentials. This shows average mobility of the negatively charged particles becomes higher in during beam extraction. Since the density of H\(^{-}\) ions decreases in the extraction period as shown in figure 7(b), the observed increment of the negative saturation current can be attributed to the increased electron density in the region. The penetration of extraction electric field into the extraction region plasma is a three-dimensional problem in nature. For the purpose of obtaining a two-dimensional picture of H\(^{-}\) density change due to extraction, a CCD camera image was taken through a narrow-band interference filter at the wavelength of Balmer-\(\alpha\) (H\(_\alpha\)) line spectrum emission. Figure 8 shows a typical result. As shown in figure 8, the region of H\(^{-}\) ion...
density reduction due to beam extraction extends up to 20 mm from the plasma grid. The results also indicate that the largest reduction of the local $H^{-}$ ion density is observed near the extraction hole [90]. A precise measurement on $H^{-}$ ion density reduction near the extraction hole showed the three-dimensional structure of the density reduction distribution due to penetration of the field through the holes of the biased plasma grid.

The bias voltage of the plasma grid was found affecting the three-dimensional structure of the $H^{-}$ ion density [53] during beam extraction, and a hint to construct a spatial distribution of plasma potential is there in the figure 6. The electric field directed to the driver region penetrates into the extraction region plasma to transport $H^{-}$ ions from the plasma interior to the plasma grid creating a flow of negative ions toward the extraction hole. The structure of the $H^{-}$ ion flow field under the induction of extraction electric field was studied with a four electrode terminals electrostatic probe [91].

6.3. Negative ion temperature

Temperature of $H^{-}$ ions determines the recovery time of the photodetachment signal and the probe diagnostics results indicate the $H^{-}$ ion temperature in the RNIS extraction region is in the order of 0.1 eV [92]. The $H^{-}$ ion temperature of 0.1 eV was considered too low to explain measure $H^{-}$ ion current density, as $H^{-}$ ions stop at the

Figure 7. Responses of negative ion rich plasma to the induction of a beam extraction field. Beam extraction field is applied from origin of the time to the time of 1 s, when the discharge power is turned off at the same time. (a) Typical waveform of negative charge saturation current $i_{es}$ and ion saturation current $i_{is}$ measured by an electrostatic probe, and (b) $H^{-}$ density measured with cavity ring-down method. Time interval of the extraction field induction is indicated by yellow shades in the figures. The operational pressure is 0.2 Pa and it does not changes during plasma discharge and beam extraction as well as in the cases of figures 3 and 4.

Figure 8. (a) Schematic cross-sectional view of the NIFS R&D negative ion source showing the configuration of interference filter CCD camera at $H\alpha$ wavelength and (b) the image taken by the interference filter CCD camera through a viewing port installed at the bias insulator. The signs to indicate the positions of ‘A’ to ‘D’ in (a) correspond to those in (b). In the $H\alpha$ intensity image in (b) red color shows the decrease of $H\alpha$ emission intensity which is assumed proportional to the rate of mutual neutralization between $H^{+}$ and $H^{-}$ ions. The operational $H_{2}$ pressure is 0.2 Pa.
region of any negative potential barrier in the plasma before reaching the extraction hole. Thus, a new diagnostic method has been developed to confirm the H⁻ ion temperature of the RNIS extraction region plasma. This method puts in excess laser intensity into the cavity region to destroy substantial portion of the H⁻ ions in the cavity. The cavity-ring-down-time decreases as the H⁻ density in the cavity region increases due to the transport of H⁻ ions from the surrounding volume replenishes electron component in the laser path [93]. Theoretical curves for a given H⁻ line integrated density and a temperature can be drawn to compare with experimental data. Figure 9 shows the comparison between the model calculation and experimental data. The estimated H⁻ ion temperature ranges from 0.1 to 0.15 eV based upon this method and is comparable to the values obtained from photodetachment recovery time measurement using a Langmuir probe.

The probe having four electrode terminals is utilized to measure plasma transport in the extraction region, because the probe structure enables measurement of the flow velocity as well as the temperature of H⁻ ions in the plasma. The measured H⁻ ion temperature in the extraction region of RNIS appears to be the order of 0.1 eV from the measurement of recovery time, while the same kind of recovery signal should appear when H⁻ ions flow in one direction. The schematic diagram of the probe system to determine the flow speed of H⁻ ions by detecting a photodetachment signal is shown in figure 10. Four probe terminals are arranged around the center post, that blocks H⁻ ion flow toward any direction. The probe structure is aligned parallel to the plasma grid, so that the system can measure the H⁻ ion flow with respect to the direction perpendicular to the plasma grid plane. One may intuitively think from figure 9 that the center stem blocks the H⁻ ion flow, and the probe in the downstream plasma detects photodetachment recovery signals only due to thermal component. The observed signals exhibited more complicated situation which is illustrated in figure 11. Provided the probe rotation is adjusted so that H⁻ ions flow from probe A to probe C. The observed signal indicated that the plasma flow from the upstream determines the recovery time of probe A, while the flow to the downstream determines the recovery time of probe C. Both components are present for probes B and D to affect their recovery time.

Through estimating the average H⁻ speed \( v_A \) for probe A and \( v_C \) for probe C from their measured recovery times, the thermal speed \( v_{th} \), and the flow speed \( v_{flow} \) of H⁻ ions can be separated from the following relations.

\[
\begin{align*}
    v_A &= v_{th} + v_{flow}, \\
    v_C &= v_{th} - v_{flow}, \\
    v_{th} &= \frac{1}{2} (v_A - v_C).
\end{align*}
\]

Flow speed of H⁻ ions at any location can be determined from \( v_{flow} = \frac{1}{2} (v_A + v_C) \). The obtained flow speed of H⁻ ions toward the extraction hole is typically 400 m s⁻¹ and smaller than H⁻ ion thermal velocity. Again, any potential barrier of the order of 1 V can stop the H⁻ ion transport in plasma after escaping from a sheath potential localized at the plasma-grid surface.

Local electric field sensitive to the plasma grid bias appears near the grid as Cs is introduced into the discharge [13]. With the very low kinetic energies of H⁻ ions measured by photodetachment methods, local electric and magnetic fields determine the transport of H⁻ ions toward the extraction hole. A three-directional position manipulation system controlled the location of the four electrode Langmuir probe to obtain a two-
dimensional flow pattern of \( H^- \) ions in the extraction region. A stream graph is constructed from the measured data of flow vectors during the beam extraction to intuitively understand the flow direction. The measured area and the streamlines of \( H^- \) ions are indicated in figures 12(a) and(b), respectively. It is clearly seen that the streamlines come from the plasma grid surface and turn at the region above the edge of the extraction hole with the distance about 20 mm from the plasma grid, and then they direct back toward the extraction hole. The flow-speed distribution appears not to satisfy the Liouville’s theorem; the flow speeds at the right and left lower corners are faster than that at center. The flow, however, is represented in a two-dimensional distribution and the flow in the direction normal to the figure need to be considered. Although the area measured with the directional photo-detachment probe is in a part of extraction region, the obtained structure of \( H^- \) flow provides the information of the extracted \( H^- \) distribution penetrated deeply into the extraction region. Both the thermal speed and flow speed of \( H^- \) ions are low in our measurement, and the small velocity in the direction perpendicular to the beam extraction axis leads to the observed low beam divergence of about 5 mrad \([94, 95]\), the 95% beam emittance of 43.2 ± 6.4 mm mrad (corresponding to the normalized 95% emittance of 0.59 mm mrad) \([96]\), which can be deduced solely from the contribution due to a space charge effect.
7. Discussion

Since the original work by Walther et al [97], a substantial part of extracted H\(^{-}\) ions have been believed originated at the plasma electrode surface in a Cs seeded H\(^{-}\) ion source. Leung et al indirectly proved that the H\(^{-}\) ions are produced at the surface of Ba seeded ion source showing the presence of H\(^{-}\) component in the beam with the energy corresponding to the potential of the Ba covered anode surface [98]. The present study on the H\(^{-}\) ion transport verified that there is a net flux of H\(^{-}\) ions from the plasma grid; the diagnostics system identified that H\(^{-}\) ions are actually formed at the surface of low work function plasma grid. The reason for observing a high density of H\(^{-}\) ions in the region distant from the plasma grid surface has been also clarified by the study of H\(^{-}\) ion flow. The surface produced H\(^{-}\) ions form a directed flow up to a region distant from the plasma grid; pseudo one-dimensional flow does not alter the flux density, and the flow keeps high H\(^{-}\) ion density up to the point as far as 20 mm from the grid. Surface produced H\(^{-}\) ions penetrated deep into the plasma changes the direction of the flow depending upon the electric and magnetic field structure determined by the combination of the EDM lobes and extraction electric field. Then, the H\(^{-}\) ions direct back toward extraction hole; some H\(^{-}\) ions penetrate into the local electric field connected to the extraction electric field under the interaction with the local magnetic field. Large H\(^{-}\) ion density due to enhanced transport of H\(^{-}\) ions at a deeper part of the extraction region may seem contradictory against high destruction rates of H\(^{-}\) ions by collisions with hydrogen ions and neutrals. The measured plasma potential distribution near the plasma grid forms the electric field in favor of transporting H\(^{-}\) ions toward the plasma grid.

Penetration of electrons into the region connecting the protruded extraction field and the EDM lobe regions is unfavorable not because of the H\(^{-}\) current reduction, but due to the enlarged co-extracted electron current that increases heat load to accelerator electrodes. The measured result of the two-dimensional H\(_2\) spectroscopy indicates the region of H\(^{-}\) ion density reduction intrudes into the extraction region plasma with a distance larger than the diameter of the extraction hole. The current geometry of the filter magnetic field and the EDM lobes does not seem to adequately separate electron rich driver region plasma from the extraction region plasma and insufficient shielding of electron transport results in transport of electrons into the extraction region. Electrons do not pass through extraction holes traversing the filter field region as strong electron suppression magnetic field present near the extraction hole bends them back to the plasma. However, they contribute to build up negative potential due to space charge for suppressing transport of H\(^{-}\) ions toward the extraction hole.

The integration of diagnostics results deepens the understanding how the electrons and H\(^{-}\) ions behave in the extraction region plasma. The measured temperature data for neutral hydrogen atoms are higher than those for H\(^{-}\) ions [13, 91, 93]. This H\(^{-}\) ion temperature lower than neutral atoms in the plasma suggests the possibility of local H\(^{-}\) formation in the extraction region. Ivanov et al showed the lower temperature component of volume produced H\(^{-}\) ions can be lower than 0.05 eV [99], based on the two-temperature component analysis proposed by Bacal et al [100]. Bacal attributed the reason for observing the two components to formation of H\(^{-}\) ions in regions of different plasma potential. In the extraction region of NIFS-RNIS, the flow of H\(^{-}\) ions stagnates at some distance from the plasma grid, letting H\(^{-}\) ions to exchange the momentum with heavier species to further decrease the temperature. The surface conversion process from atomic hydrogen to H\(^{-}\) limits the velocity component of H\(^{-}\) ions parallel to the surface to reduce the effective temperature. This is because the probability
for the $\text{H}^-$ ions to leave the surface is higher when their velocity component normal to the surface is larger [101]; they lose electrons in their affinity level as they go out from the surface with larger angle from the surface normal.

Inhomogeneity of the surface work function on the plasma grid can cause surface electric field in the direction parallel to the electrode causing additional mechanism to elevate $\text{H}^-$ ion temperature. However, homogeneity of Cs coverage on the plasma grid surface has not been confirmed yet. The precise mechanism how the injected Cs is lost from the source has not been clarified either. Future plasma diagnostics research programs at NIFS-RNIS include challenges to answer these questions.

8. Conclusions

Traditional and contemporary plasma diagnostics tools and methods are applied to clarify transport processes in the extraction region plasma of NIFS-RNIS. Through integrating the data obtained from the plasma diagnostics systems, fundamental mechanisms determining $\text{H}^-$ ion current intensity as well as the reason for observing more co-extracted electron current is understood. The $\text{H}^-$ ion flux originated at the plasma grid surface directs toward filter field region but stagnates at certain distance from the grid. The extraction electric field penetrates deep into the plasma to guide low temperature $\text{H}^-$ ions toward the beam forming electrodes in the region locally magnetized by the electron deflection magnets. The extraction electric field can protrude to the filter field region to introduce electrons into the area from which $\text{H}^-$ ions are transported toward the extraction holes. The larger electron to $\text{H}^-$ ion ratio in the magnetic filter field region enlarges co-extracted electron current passing through the accelerator. These understandings offer bases for better design of a large size $\text{H}^-$ ion sources; electromagnetic field structure that effectively separate extraction region plasma to the filter field region should further improve a $\text{H}^-$ ion source performance. The data obtained from the integrated plasma diagnostic system of RNIS yield information on the possible structure to realize more efficient extraction system through minimizing the co-extracted electron current.

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