Characterization of hydrogen plasma in a permanent ring magnet based helicon plasma source for negative ion source research

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Abstract
HELicon Experiment for Negative ion source (HELEN-I) with a single driver is developed with a focus on the production of negative hydrogen ions. In the Helicon wave heated plasmas, very high plasma densities ($10^{18} - 10^{19}$ m$^{-3}$) can be attained with electron temperatures as low as $\sim 1$ eV in the downstream region. These conditions favor the production of negative hydrogen ions. In HELEN-I device at IPR, helicon plasma is produced using Hydrogen gas by applying a RF power ($P_{RF}$) of 800–1000 W at 13.56 MHz frequency. A Nagoya-III antenna is used to excite $m = 1$ helicon mode in the plasma. A permanent ring magnet creates the required axial magnetic field. The plasma is confined by a multi-cusp field configuration in the expansion chamber. The transition from inductively coupled mode to Helicon mode is observed near $P_{RF} \sim 700$ W with plasma density $\sim 10^{18}$ m$^{-3}$ and electron temperature $\sim 5$ eV in the driver and $\sim 1$ eV in the expansion volume. Negative hydrogen ion density, averaged over the line of sight, is measured in the expansion chamber by employing an optical emission spectroscopy diagnostic technique using $H_\alpha/H_\beta$ ratio and a laser photodetachment based cavity ring down spectroscopic diagnostic technique. The measured value of negative hydrogen ion density is in the order of $10^{16}$ m$^{-3}$ at 6 m Torr pressure and does not vary significantly with power, pressure and downstream axial magnetic field variation in the helicon mode. The negative ion density measurements are compared with theoretically estimated values calculated using a particle balance method considering different reaction rates responsible for negative hydrogen ion creation and destruction. It is to be noted that, at present, cesium is not injected in the plasma discharge to enhance $H^-$ ion density.

Keywords: negative hydrogen ion source, helicon plasma, cavity ring down spectroscopy, neutral beam, cesium, HELEN

(Some figures may appear in colour only in the online journal)

1. Introduction

Negative hydrogen ion ($H^-$) source based neutral beam injector is one of the most efficient auxiliary heating and current-drive sources in tokamaks. The design and operation of such sources in tokamaks, like ITER, require detailed knowledge of the plasma properties, especially the negative ion density. In this paper, we report the characterization of hydrogen plasma in a permanent ring magnet based helicon plasma source for negative ion source research.
systems for fusion plasma reactors [1, 2]. Recently, a great deal of interest has been drawn towards the development of high density negative ion sources for neutral beam applications. Consequently, research and development activities are set in motion in Europe, Japan and India for developing negative hydrogen ion sources for NBI systems to be used in large magnetic fusion reactors like ITER [3–6]. At high energies (>200 keV) the neutralization efficiency of positive hydrogen ion practically goes to zero. Whereas for H\(^+\) ion beam, above the beam energy desired for a conventional gas based neutralizer cell in a NBI system, the neutralization efficiency is still 60% [7]. Considering the reactions responsible for H\(^+\) ion production and destruction, it is found that low pressure, high density but low temperature hydrogen plasmas are suitable for an efficient negative hydrogen ion source [8–11]. The production of negative hydrogen ions takes place through two processes: (a) volume process and (b) surface process.

In the volume process, H\(^-\) ions are created in a two-step collisional reaction:

1st step: \(e_{\text{fast}} + H_2 \rightarrow H_2^+(\nu') + e\), (vibrational excitation of ground state molecule by energetic electrons). 2nd step: \(H_2^+(\nu') + e_{\text{low}} \rightarrow H^+ + H\) (vibrationally excited molecule form H\(^+\) ion through dissociative attachment (DA) of a low energy electron). Conventionally, a volume H\(^+\) ion source is divided into two operational parts, the ‘hot driver region’ where \(H_2\) molecules are vibrationally excited and the ‘cold extraction region’ where DA process takes place. Virtual division of the plasma into two different electron temperature regions is generally maintained inside a plasma volume by applying a transverse magnetic filter field [9]. Low electron temperature across the filter field, near extraction region of an ion source is desirable to prevent H destruction by fast electrons due to electron detachment (ED) reaction [7, 9]. The transverse filter field is also required to limit the co-extracted electrons in the accelerator channel; for ITER ion source, the specification is less than 1 electron per D\(^+\) ion. But, the filter field also reduces the electron density near the extraction, which is not a desirable condition for the production of H\(^-\) ions.

In surface process, H\(^-\) ions are produced on a low work-function surface via surface conversion of energetic H atoms (H\(_0\)) or hydrogen ions (H\(_i\)) in the plasma [9]:

\[
\frac{H_0}{H_i} \xrightarrow{\text{work-function surface}} H^-.
\]

Low work-function surface is normally created by cesium (Cs) deposition, by injecting Cs vapor into the plasma. Surface process is more efficient than the volume process. However, despite the higher efficiency of surface process, there are some specific issues linked with the Cs dynamics. Recently, Kakati et al [11] have reported a proof of the principle negative hydrogen ion source based on a novel concept of surface assisted volume process using Cs coated tungsten dust dispersed in the volume. In this paper, we present a configuration for helicon wave heated plasma, which has high plasma density and low electron temperature, suitable for the H\(^+\) ion source without using the filter field or Cs in the set-up.

Briefi and Fantz [12] proposed the use of Helicon discharges for ITER reference source parameters and argued that the helicon plasma sources could be used as H\(^+\) ion sources for future NBI systems. The permanent ring magnet based helicon source presented in this paper has the potential to fall in this category. In this paper, we focus on the characterization of hydrogen plasma and subsequently include the negative ion measurement diagnostics in the helicon plasma source to measure H\(^-\) ion density. The paper is planned as follows: section 2 contains the details of the HELEN-I experimental set-up including different diagnostics. Section 3 describes different diagnostic techniques used for the H\(^-\) ion density measurement. The measurement results are shown in section 4. In section 5 we discuss and summarize the results.

2. Experimental set-up

A schematic of the experimental device is shown in figure 1. The apparatus consists of a 70 mm long glass plasma source of 50 mm diameter and an SS expansion chamber of 100 mm inner diameter and ~300 mm length. A permanent NdFeB ring magnet of magnetic field \(~4.6\) kG is placed above the plasma source to provide an axial field for the excitation of Helicon wave in the plasma. The separation between the magnet and the glass chamber is kept in such a way that magnetic field \(~40–100\) G is present in the glass chamber volume. The field strength in the source is varied by changing the separation between the magnet and the top flange.

The expansion chamber has an array of magnets arranged to form a multi-cusp field in the chamber. A more detailed description of the experimental apparatus is given in [13]. Figure 2(a) shows the diverging magnetic field in the source and expansion chamber when magnet center is 10 cm away from the top flange of the plasma source. Figure 2(b) shows the cusp field geometry in the expansion chamber forming a field free region of \(~50\) mm diameter.

Hydrogen plasma is produced by applying RF power to the Nagoya-III antenna (of 36 mm length) at 13.56 MHz to excite \(m = 1\) azimuthal helicon mode in the plasma. Optical emission spectroscopy (OES) and Laser aided negative ion density diagnostics are used in the set-up as shown in the figures 1 and 3. The light collecting optics is kept at the location \(z = 19\) cm for OES measurement. For the laser based cavity ring down spectroscopy (CRDS), the Nd:YAG laser beam enters into the expansion chamber through the diagnostic port as shown in the figure 3. The details of the diagnostics are given in the next section.

3. Diagnostic techniques

3.1. Electrical probes

Two axially movable triple Langmuir probes are used for measuring the plasma density at different locations in the plasma chamber. One of the probes is installed at the top for the axial measurements in the source and the other probe is introduced through the bottom flange, which is L-shaped and is used for axial as well as radial measurements in the expansion chamber. The probes are made from a 0.3 mm diameter tungsten wire and have three identical tips of length = 5 mm each. The axis of rotation of the L-shaped probe is kept slightly off-centered and
the radial profile is obtained by the rotation of the probe shaft. Triple probe is less prone to RF noise compared to an uncompensated single Langmuir probe. It gives a relatively reliable estimate of plasma density but the temperature value may be slightly overestimated [14]. A B-dot probe [15] is made from a 0.5 mm thick enameled copper wire. The probe head has a loop diameter of ∼2 mm and is used to detect the signature of the helicon wave field in the expansion chamber. The locations of the probes are shown in figure 1.

3.2. Optical emission spectroscopy

A non-invasive diagnostic technique based on OES method has been used to measure the negative ion density. Fantz and Wünlerich [7] have demonstrated the OES based technique to measure the negative hydrogen ion density using H\(_{\alpha}\), H\(_{\beta}\) and H\(_{\gamma}\) Balmer lines. Light from the plasma is focused at one end of an optical fiber using a lens and is transmitted to the spectrometer entrance slit. The light is then allowed to fall on the detector through a dispersive medium and wavelength resolved intensity profile is recorded. In hydrogen plasma, H\(_{\alpha}\), H\(_{\beta}\), H\(_{\gamma}\) and H\(_{\delta}\) Balmer series lines from atomic transitions and Fulcher band from the molecular transitions are dominant.

In case of low pressure and low temperature hydrogen plasma, the processes contributing to the population of excited state of atomic hydrogen leading to H\(_{\alpha}\) emission are listed in table 1. The population coefficients for these processes can be calculated as a function of plasma parameters from collisional radiative (CR) model. The individual contribution of each species to the Balmer lines for different plasma parameters have been discussed in [7]. Out of all the processes listed in table 1, the contribution from the mutual neutralization (MN) of H\(^-\) ions to H\(_{\alpha}\) emission (having rate coefficient, \(X_{H_{\alpha}^+}^{\text{eff},H^-}\)) dominates for the electron density range 10\(^{16}\)–10\(^{17}\) m\(^{-3}\). The effective rate coefficients for MN, \(X_{H_{\alpha}^+}^{\text{eff},H^-}\), are independent of electron temperature as the process involves interaction of ions only [7]. The line ratios H\(_{\alpha}\)/H\(_{\beta}\) from all the processes, listed in table 1 show weak dependency on plasma density. Only the process of ‘MN’ shows strong dependence on electron density for the line ratio H\(_{\alpha}\)/H\(_{\beta}\). Due to this dependence of Balmer lines on H\(^-\) density, the value of the line ratio H\(_{\alpha}\)/H\(_{\beta}\) can be used for the measurement of negative ions. These assumptions hold good only

Figure 1. Schematic of HELEN-I set-up.
for low pressure plasmas (<1 Pa or 7.5 m Torr). At higher pressures, other factors also become important like self-absorption of Lyman lines and dissociative recombination of H$^+$, adding another channel of radiative process apart from the processes listed in table 1. Thus, at higher pressures, this analysis might give erratic results [7]. Effective excitation and MN are the two dominant processes for the quantum number $p = 3$ and $p = 4$ transition and responsible for these two lines. Hence, only these two processes are taken into account while calculating the line ratio $H_\alpha/H_\beta$. Thus the line ratio is given by:

$$
\frac{H_\alpha}{H_\beta} = \frac{n_H X_{H_\alpha}^{\text{eff},H} + n_H X_{H_\beta}^{\text{eff},H^+}}{n_H X_{H_\beta}^{\text{eff},H} + n_H X_{H_\alpha}^{\text{eff},H^+}}.
$$

Fantz and Wunderlich [7] have shown that the contribution of MN on the H$_\gamma$ and H$_\delta$ emissions is negligible. But, to obtain the H$^+$ density, we need to know the atomic hydrogen population. In order to determine the density of atomic hydrogen, absolute measurement of H$_\gamma$ line emission can be used. The line emission H$_\gamma$ is given by:

$$
H_\gamma = n_H n_e X_{H_\gamma}^{\text{eff},H}(T_e, n_e).
$$

Using equations (1) and (2), a relation can be obtained for the known value of electron temperature, $T_e$ and electron density, $n_e$

$$
n_{H^+} = \frac{H_\gamma}{n_e C_1 \left(1 - \frac{H_\alpha}{H_\beta} \frac{1}{C_2} \right) \left(1 - \frac{H_\alpha}{H_\beta} \frac{1}{C_3} \right)^{-1}},
$$

Figure 2. Simulated magnetic field lines in the system are shown: (a) diverging axial field lines from the axial field magnet, (b) multi-cusp field lines from the confinement magnets in the expansion chamber.
Table 1. Processes contributing to excited state of atomic hydrogen.

| Processes | Expression |
|-----------|------------|
| 1. Recombination: H⁺ + e → H(p) | $C_1 = \frac{X_{H_0}^{eff,H}}{X_{H_2}^{eff,H}}$ |
| 2. Dissociative recombination: H₂⁺ + e → H(p) + H | $C_2 = \frac{X_{H_0}^{eff,H}}{X_{H_2}^{eff,H}}$ |
| 3. Effective excitation: H + e → H(p) + e | $C_3 = \frac{X_{H_0}^{eff,H^-}}{X_{H_2}^{eff,H^-}}$ |
| 4. Mutual neutralization: H⁻ + H⁺ → H(p) + H | $C_4 = \frac{X_{H_0}^{eff,H^-}}{X_{H_2}^{eff,H^-}}$ |
| 5. Dissociative excitation: H₂ + e → H(p) + H + e | $C_5 = \frac{X_{H_0}^{eff,H^-}}{X_{H_2}^{eff,H^-}}$ |

where, $C_1 = \frac{X_{H_0}^{eff,H}}{X_{H_2}^{eff,H}}$.

The factor $C_1$ represents the ratio of effective excitation rate coefficient for $H_0$ and $H_2$ divided by the effective MN rate coefficient for $H_i$ emission. The factor $C_2$ can be interpreted as the line ratio $H_0/H_2$ when the excitation takes place from atomic hydrogen only. The factor $C_3$ represents the line ratio $H_0/H_2$ when the excitation takes place from negative hydrogen ions only. These factors can be calculated using CR model for known plasma parameters [16].

3.3. CRDS

The CRDS technique, developed by O’Keefe and Deacon, is based on the measurement of the absorption rate of a light pulse confined within a closed optical cavity [17]. It is a very sensitive diagnostic technique developed to measure the density of particles present in trace amounts [18, 19], e.g. negative hydrogen ion in the present case. Recently, Agnello et al have shown that CRDS can be used for measuring the H⁻ ion density in a hydrogen helicon plasma where the H⁻ ion population is small compared to the H⁺ ions [20].

When a photon of energy higher than the electron affinity of H atoms (0.75 eV) enters into a cavity formed by two highly reflecting mirrors at the two ends of the cavity volume filled with H⁻ ions, loosely bound electron in H⁻ ion is detached by the laser photon due to laser photodetachment (LPD) reaction and the corresponding photons are considered as absorbed. In the present experiment, a beam from a Nd: YAG (Innolas make) infrared laser of 1064 nm wavelength is fed into the plasma in the expansion chamber, as shown in figure 3, through a 99.97% reflecting mirror, $m_1$ (attached to left side port at $z = 19$ cm from the endplate). Only 0.03% of the photons go into the cavity. The port on the opposite end of the laser entrance attached to a long (900 mm) trapping cavity also has a mirror, $m_2$, identical to $m_1$. This arrangement of two highly reflecting mirrors forms an optical cavity where the laser pulse suffers multiple reflections between these two mirrors. As a result, the laser pulse makes multiple passes through the plasma volume. In each of these trips through the plasma medium, a fraction of total number of photons gets absorbed with time. As a result, a temporally decaying laser intensity profile is recorded by a photodetector kept just outside the cavity to receive the photons transmitted through $m_2$. The decay time, known as ring down time (RDT) is used to calculate the density of H⁻ ions inside the plasma. The laser beam is 2 mm in diameter with a pulse width of ~6 ns. The maximum beam energy can be as high as 180 mJ. The energy of 1064 nm photon is 1.2 eV, which is sufficiently higher than the electron affinity (0.76 eV) of H atom to form H⁻ ions. Therefore, a 1064 nm photon is sufficient for photodetachment of the electron from the H⁻ ion. In vacuum, without plasma or H⁻ ions, the exponential decay is relatively slow (decay time = $T_1$) due to unavailability of absorbing medium for 1064 nm wavelength of photon. In this condition, the laser is scattered less. However,
in the case of a medium (plasma with $H^-$ ions) the interaction is stronger and thus the decay is faster (decay time $= T_2$). Thus, we measure the decay time for the two signals to compute the negative hydrogen ion density from the relation

$$n_{H^-} = \frac{L}{d \sigma} \left( \frac{1}{T_2} - \frac{1}{T_1} \right).$$

where, $L = 120$ cm is the total length of the cavity, $d = 10$ cm is the length of absorbing medium traversed by the photon, $\sigma = 3.5 \times 10^{-17}$ cm$^2$ is the photodetachment cross-section or photon absorption cross-section [21].

A detailed description of present CRDS system is given in [22] and parametric CRDS study of negative ion density variation in HELEN is reserved for future publication but a report is available in [23]. A schematic of the laser triggering system is shown in figure 4. The input trigger for the RF Generator also serves as the input trigger for the function generator, which generates the input signal for triggering the laser after a delay of 50 ms.

Both OES and CRDS measure the line averaged $H^-$ ion density, but due to axial magnetic field and associated cusp magnetic field structure in the present Helicon source, a non-uniform profile of $H^-$ ion density is expected. So, a local $H^-$ ion measurement is needed to study the profile. To measure local $H^-$ ion density the LPD diagnostic is under development.

4. Results and discussion

4.1. Measurement of plasma parameters

The typical signature of helicon mode operation is identified as a sudden increase in optical light emission and in ion saturation current drawn by the Langmuir probe. Earlier work in the HELEN-I device was done on Argon plasma, where the RF power was applied to a single loop antenna to produce the plasma and excite $m = 0$ helicon mode in the plasma [13]. With argon gas and loop antenna, the helicon plasma was obtained at RF power $\geq 200$ W marked by a sudden rise in plasma density. But, with hydrogen gas the characteristic density jump marking the transition to the helicon mode was not observed when hydrogen plasma was created using a single loop antenna. This is because the single loop antenna is unable to create sufficient induction field inside the plasma [24]. Therefore, some other type of antenna has to be used in place of the loop antenna for helicon wave excitation. Melazzi and Lancelotti [25] have compared different antennae for helicon wave excitation in the plasma namely, single loop, Nagoya type-III and the fractional helix antennae. They showed that the antenna current density is not spatially uniform, and that a correlation exists between the plasma parameters and the spatial distribution of the current density. Through this performance characterization of different antennae they concluded that the single loop works better than the other two type of antenna for low plasma densities, but for higher plasma densities Nagoya type-III is the most efficient. Considering this, a Nagoya-III type antenna is used to create the hydrogen helicon plasma. Figure 5 shows the ion saturation current rises suddenly in hydrogen plasma with a Nagoya antenna and RF power greater than 400 W. In the case of hydrogen plasma, no such transition in density is seen with the loop antenna. Figure 6 shows the plasma density obtained above 400 W for different magnetic field values in the source.

It can be seen from figure 6 that the helicon plasma mode exists after 700 W. Further diagnosis is done at 800 W, where the hydrogen plasma is helicon wave heated and has attained a density of $\sim 2 \times 10^{18}$ m$^{-3}$. Figure 7 shows the axial profiles of electron temperature and density. The $d$ value is the separation between the permanent magnet and the top flange ($z = 0$). The magnetic field in the source decreases as $d$ is increased.

For the three $d$ values 10 cm, 12 cm and 14 cm, shown in the figure, the corresponding dc magnetic field values at $z = 0$ are $\sim 40$ G, $\sim 55$ G and 86 G respectively. For a fixed $d$, the value of the magnetic field decreases as we go downstream and is around 4, 6 and 7 Gauss, respectively, at $z = 19$ cm for the three cases considered. The location $z = 19$ cm has a diagnostic port for radial measurements in
the expansion chamber and the H\textsuperscript{−} ion measurements are carried out at this axial location. This is discussed in the next section.

Figure 8 shows the radial profile of the axial component of the helicon wave field, \( B_r \), measured using a \( B \)-dot probe calibrated at 13.56 MHz. The radial profile shows that the \( B_r \) is minimum at the center and maximum approximately at \( r = 2 \) cm, on both sides. This is a typical \( m = 1 \) mode helicon wave signature. Since \( B_r \propto J_\perp(k_z r) \), figure 8 is fitted with the Bessel function to calculate the value of \( k_z \), which comes out to be \( \sim1.8 \text{ cm}^{-1} \).

Figure 9 shows an axial wave magnetic field profile. The \( B_z \) profile shows an axial propagation and damping. The component \( B_z \) is damped after \( z = 11 \) cm, which indicates a wave absorption at that axial location. Further investigation is on-going to understand the phenomena.

Figure 10 shows the radial profiles of the plasma density and temperature in the expansion region where H\textsuperscript{−} ion density is measured. The ring magnet separation at \( d = 12 \) cm from the driver back-plate, is optimum as the plasma density is significantly higher and plasma temperature is significantly lower for that configuration, which are suitable for good negative ion yield.

We have measured the H\textsuperscript{−} density in the downstream region using several diagnostic techniques to show that the HELEN configuration is suitable for negative hydrogen ion formation. The results are shown in the following section. It is to be noted that the observed H\textsuperscript{−} density is lower than the electron or hydrogen ion (H\textsuperscript{+}) density. Moreover, in the presence of RF noise, extracting H\textsuperscript{−} ion signal is difficult.

### 4.2. Measurement of H\textsuperscript{−} ion density

#### 4.2.1. OES method

The method of \( H_\alpha/H_\beta \) line ratio is applied in HELEN-1 for the measurement of negative ion density [7]. The line emission is measured with Ocean Optics USB 4000 spectrometer. The spectrometer operates in the wavelength range of \( \lambda = 200\text{–}1100 \) nm with a spectral resolution of 2 nm. Emission light from the plasma is focussed to couple with an optical fiber using a lens and the light signal is transported to the spectrometer with the help of the optical fiber. The diameter of the collimating lens is 12 mm and focal length = 25 mm. A typical spectrum is shown in figure 11 and such spectra are recorded for three different working pressures and for five different magnetic field configurations.

The H\textsuperscript{−} density is 656 nm, H\textsuperscript{+} = 486 nm and H\textsuperscript{+} = nm lines are marked in the figure. These are the important emission lines for the calculation of H\textsuperscript{−} ion density measurement as discussed in section 3.2.

The H\textsuperscript{−} density is calculated using equations (1)–(3) and the result is shown in figure 12. The values of effective emission rate coefficients are calculated from the atomic data and analysis structure system [26]. H\textsuperscript{−} density of the order of \( 10^{16} \text{ m}^{-3} \) is obtained from the line ratio measurements at 800 W RF power. This measurement gives the H\textsuperscript{−} density averaged over the line of sight with \( \sim40\% \) error associated with the density values [7]. To verify the OES measurements a more sensitive technique CRDS is used. From equation (3) it can be seen that the H\textsuperscript{−} density values measured by OES depend inversely on the electron density. This is shown in figure 12(a) where, for the no field case, the H\textsuperscript{−} density is higher as the plasma density is lower. This indicates that in presence of axial magnetic field energetic electrons are better confined which increases the ED destruction process of the H\textsuperscript{−} ions. The presence of an axial field also improves plasma density due to higher ionization by those confined energetic electrons. This is because for \( B_0 = 0 \), the plasma is in inductive mode and not wave heated and the electrons are free to diffuse radially as well. Whereas, in the case of a non-zero axial magnetic field the electrons would try to follow the field lines as they are magnetized, helicon wave would be excited in the plasma and this would lead to more ionization.

#### 4.2.2. CRDS method

The CRDS system attached to the experimental set-up is shown schematically in figure 3. The preliminary results obtained from the two experiments are shown in figure 13 below. These values are obtained at 6 m Torr neutral pressure and 5 Gauss field (ring magnet is placed 12 cm from the RF driver back-plate) at the location \( z = 19 \) cm, where the CRDS data is taken.

It is observed that the negative ion signals become detectable only after a certain power threshold (600 W) is crossed [23]. There are certain factors leading to this result. It is already observed that for lower RF power when the plasma is not in the helicon mode, the plasma potential and electron temperatures are higher than that obtained in the helicon mode [13]. This leads to lower H\textsuperscript{−} ion yield.

Typical RDT plot of the CRDS experiment is shown in figure 13. The RDT is obtained by fitting an exponential function on the acquired data. Equation (4) is used to calculate H\textsuperscript{−} ion density for different cases using CRDS, where, time constant is \( T_1 \) is the reference (vacuum without plasma) decay time and \( T_2 \) is the decay time in the presence of the plasma.
Figure 14 shows a comparison between the H⁻ density measurements done by CRDS for two different RF power cases. From figures 12 and 14, it is observed that OES gives slightly less H⁻. CRDS in HELEN-I set-up is at \( z = 19 \) cm, which is at a distance of 12 cm from the driver mouth. To understand the experimentally obtained values of negative ion density from both OES and CRDS, a simplified particle balance calculation has been carried out based on the formulation given in [9]. By considering the dominant steady state production and destruction mechanisms of H⁻ ions, particle balance model can estimate the number density of H⁻ ions available in the source. The main processes responsible for the formation of negative hydrogen ions are vibrational excitation of H₂ molecule to vibrational levels, \( \nu'' > \nu \):

\[
e + \text{H}_2(\nu) \rightarrow e + \text{H}_2(\nu''); \nu'' > \nu
\]

and subsequent DA with low energy electrons. The H⁻ destruction processes include ED, MN and associative detachment (AD). The density of H₂(\nu'') is calculated by the relation given in [9], considering the plasma condition in the driver. In the calculations, cross-sections for \( \nu'' > 4 \) is considered, since below that vibrational level DA cross-section is significantly low [27]. In the present case, the observed driver plasma temperature is \( \sim 5 \) eV. For these parameters the number density of excited H₂ molecules is calculated by the following expression:

\[
n_\nu = n_{\text{H}_2} \frac{(f_e \langle \sigma v \rangle)_{\text{EV}}}{(f_e \langle \sigma v \rangle)_{\text{DA}} + (f_e \langle \sigma v \rangle)_{\text{Dis}} + (f_e \langle \sigma v \rangle)_{\text{Ion}}} + \frac{1}{n_e \tau_i}.
\]

(5)

where, \( n_\nu \) is the H₂(\nu'') density, \( n_{\text{H}_2} \) is H₂ density, \( f_e \) is the fraction of electrons participating in a given reaction, EV in the subscript corresponds to the \( \text{H}_2(\nu'') \) formation process by collision of \( \text{H}_2(\nu) \) with fast electrons (\( T_e > 20 \) eV). Dis and Ion are dissociation and ionization processes respectively, responsible for \( \text{H}_2(\nu'') \) destruction. \( \tau_i \) is the residence time of the molecule, taken to be \( \sim 10 \) \( \mu \)s considering molecules and neutrals at room temperature confined within the chamber.

Figure 7. The axial density (a) and temperature (b) profile is shown. The maximum density obtained is \( \sim 2 \times 10^{18} \) m⁻³ at 5 eV electron temperature with 800 W power and 6 m Torr pressure.

Figure 8. Radial field profile of \( B_r \) measured by B-dot probe.

Figure 9. Typical axial wave field profile measured by B-dot probe.
The formation of excited $\text{H}_2(v')$ molecules takes place mainly in the driver region due to high electron density and temperature there. After $\text{H}_2(v')$ are created in the driver, they get diffused to the expansion volume where electron temperature is low. This is conducive for $\text{H}^-$ production due to the high cross-section for DA and lower probability of $\text{H}_2$ destruction at low $T_e$. DA of electrons is the primary process by which $\text{H}^-$ ions are formed. The final expression for $\text{H}^-$ density is [9]:

$$n_{\text{H}^-} = n_e A_1 \int_E^{E+dE} E \exp\left(-\frac{1}{2} \frac{m v^2}{E_{\text{th}}^2}\right) \, dE.$$  (7)

Here, $A_1$ is the normalization constant; $n_e$ is the total electron density, $E_{\text{th}}$ is the mean thermal energy of the particle distribution and $E = \frac{1}{2} m v^2$ is the kinetic energy of the particles. Different production and destruction processes in equation (5) require electrons of different energies. For example, the EV process requires electrons with energy exceeding 20 eV [29]. Therefore, the population of electrons in the corresponding energy bin $dE$ is calculated and used in equation (5) to obtain the excited population of $\text{H}_2(v')$ molecules. This value is used in equation (6) to get the negative hydrogen density value.

Sheath present on the radial boundary of the expansion chamber tries to electrostatically confine the relatively low energy negative ions in the plasma volume. However, axial loss is not restricted due to the absence any kind of confinement magnetic or electrostatic. Here, $\tau_-$ is the confinement time for $\text{H}^-$ ions before escaping to the axial walls. Assuming the $\text{H}^-$ ion temperature to be $\sim 0.1$ eV, confinement time $\sim 60 \mu$s. The $\text{H}^-$ density thus calculated from equation (6) for different pressures is plotted with the experimentally obtained $\text{H}^-$ density value obtained from OES and CRDS in figure 15. The equations give an estimate of the $\text{H}^-$ density in the same order as the values obtained in experiment for lower pressure but deviates from the experiment at high pressure. The theoretically expected density value shows a linear trend since it depends linearly on...
on the number of H₂ molecules present (equation (5)). But, since equations (5) and (6) only take into account the production and destruction mechanism at one particular location and not the transport of the species involved (H⁻, e, H₂(ν'') and H⁺), they can only be used to get an estimate of the expected particle density. The plot of theoretically expected density of H⁻ after including the stripping losses due to the collisions with energetic H atoms (AD reaction [31]) is closer to the experimental value at lower pressures.

\[
H^- + H \rightarrow e + H_2(\nu'') \quad \text{: Associative detachment reaction.}
\]

5. Conclusion and summary

A permanent ring magnet based hydrogen helicon plasma source has been developed. Performance characterization in hydrogen helicon plasma is reported in this manuscript. The plasma expands from the driver region to the expansion...
region due to the geometry as well as diverging field. This configuration is suitable for low electron temperatures and high plasma density in the downstream region of the plasma. The line integrated H$^-$ density is measured using two different diagnostic techniques namely CRDS and OES. The two diagnostics used give the H$^-$ density in the range of 10$^{16}$–10$^{17}$ m$^{-3}$. A particle balance model based calculation, considering the experimental plasma conditions, also predicts similar density values within the measured range. The theoretically estimated value is close to the OES measurements at low pressures. But at high pressure, the stripping losses become prominent. The stripping losses are due to collisions of H$^-$ ions with H$^+$ atoms, H$_2$ molecules, H$_3^+$ ions and electrons [31]. We have only considered the collisions with H atoms and electrons here and we see that the measured value deviates from the theoretically estimated value at higher pressures. The production of H$^-$ ions in the system is through volume process, without Cs injection. We are able to obtain a good yield of H$^-$ ions even without the Cs injection or the transverse filter fields. This is due to the temperature gradient achieved due to geometrical and magnetic expansion of plasma in the expansion chamber.

Injection of Cs vapor into the plasma volume converts the mode of plasma source operation from volume mode to surface mode, where H$^-$ ions are mainly formed on low work-function surfaces instead of collisional based volume process. In future, Cs injection has to be established in HELEN plasma source. In addition, research with filter fields and low temperature electron sources are planned in HELEN to improve the H$^-$ yield. A laser photodetachment based H$^-$ ion density measurement using Langmuir probe is under development for local density measurements to generate the H$^-$ ion density profiles.

In the present experiment, a single permanent magnet based helicon plasma driver is characterized. Many such drivers can be assembled in a matrix form and placed on the back-plate of a plasma chamber to illuminate a large area ion source. The concept of distribution or deployment of helicon drivers on the back-plate can be similar to that of present ITER negative ion source with eight inductively coupled RF plasma drivers [32] or like MEDUSA source [33].

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