High density hydrogen plasma for negative hydrogen ion production in HELicon Experiment for Negative ion source (HELEN-I)

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Large-scale fusion reactors like ITER are going to require very high-energy neutral beams (NB) (>1MeV) for plasma heating purposes as well as diagnostic neutral beams (DNBs) [1]. To realize this, negative ion sources are a better alternative to the conventional positive ion sources because of their higher efficiency of neutralization [2]. The neutralization rate for the positive hydrogen ion beam is very small at high energies (>200 keV) and almost zero at energies in the order of several MeV, whereas the negative hydrogen ions (H^-) has a 60% neutralization rate at beam energy ~ 1 MeV [2]. The helicon plasma sources are yet another advancement on the conventional inductively coupled plasma (ICP) sources to produce high-density plasma for the production of negative hydrogen ions (H^-). In this paper, a compact helicon plasma source using a 13.56 RF power is described which has the potential to be used as an alternative to the conventional ICP sources. HELicon Experiment for Negative ion source (HELEN-I) [3] is developed with a focus on the volume production of negative hydrogen ions. There are two broad mechanisms for H^- ion production in the plasma:

1. Surface Production:

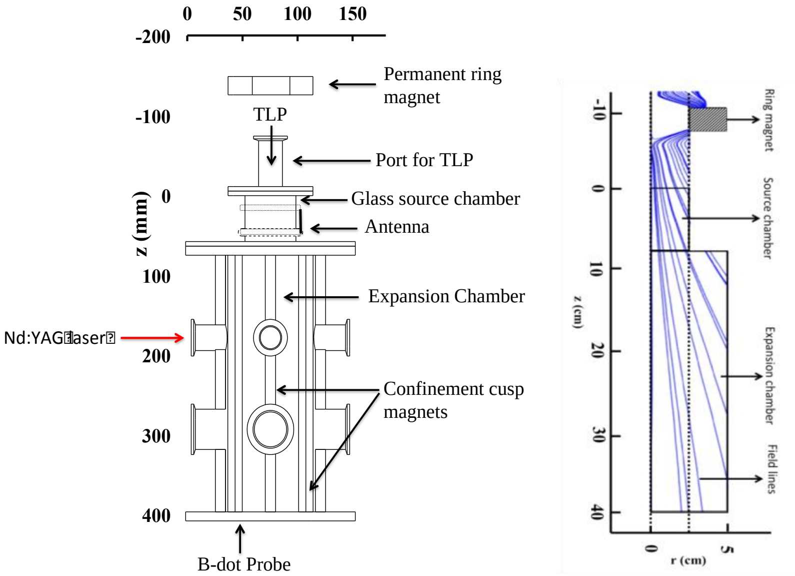
$$H_0^*/H_n^+ \xrightarrow[\text{function surface}]{\text{Low work-}} H^- \qquad (H_0^* = \text{energetic H atoms, } H_n^+ = \text{hydrogen ions})$$

2. Volume Production:

   i. $e_{fast} + H_2 \rightarrow H_2^*(v")$

   ii. $H_2^*(v") + e_{slow} \rightarrow H^-$

In the volume process, the H^- ions are created in two steps. In the first step fast electrons collide with hydrogen molecules to form vibrationally excited hydrogen molecules. Slow electrons get attached to these molecules in the second step to form H^- ions. From these reactions it can be seen that both fast and slow electrons are required in the plasma to form H^- ions. High electron density is also desirable for a good H^- yield. In the HELEN setup very high plasma density is achieved in the source region. Figure 1.a shows the experimental setup and the diverging axial field of the permanent ring magnet is shown in figure 1.b. The details of the experimental setup can be found in reference 1. The plasma expands in the diverging field into the expansion chamber where the it is confined by a full line cusp field configuration. This cusp field is formed using permanent NdFeB magnets aligned along the length of the expansion chamber. The cusp-field free region inside the expansion chamber is ~ 50 mm as shown in figure 2.



(a) (b)

Figure 1. a) Schematic of HELEN-I set-up, b) diverging axial field lines from the axial field magnet

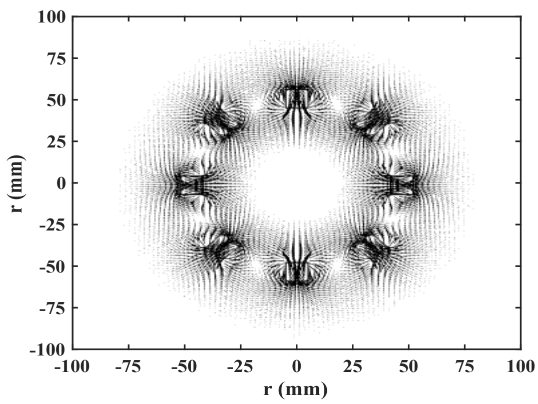
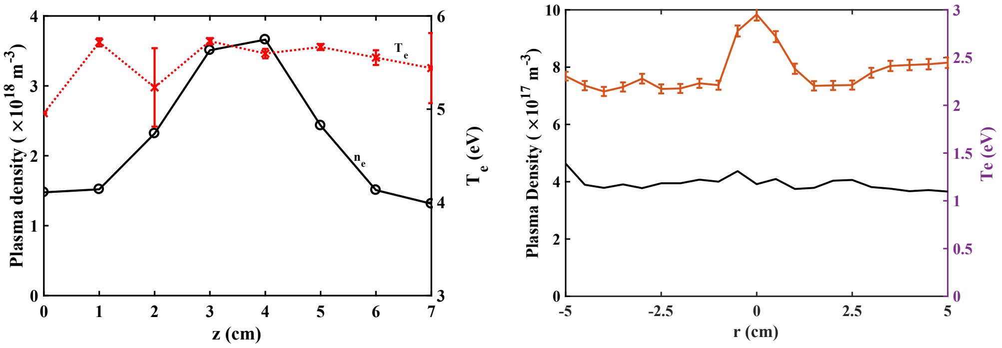


Figure 2. Multi cusp field lines from the confinement magnets in the expansion chamber

In the HELEN device at IPR, a Hydrogen gas helicon plasma is produced in a diverging magnetic field by applying RF Power of 13.56 MHz at 800-1000W using a Nagoya-III antenna for exciting m = ±1 azimuthal mode in the plasma [3] at 6 mTorr pressure. The characteristic density jump from inductively coupled mode to Helicon mode is observed at P_{rf} ~ 800 W with plasma density ~ 2×10^{18} m^{-3} and electron temperature ~ 5-6 eV in the source chamber [3]. The plasma follows the magnetic field lines downstream where the plasma density decreases to 9×10^{17} m^{-3} and the electron temperature is 1-2 eV as shown in figure 3.



(a) (b)

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

Figure 3.a. shows the axial density and temperature profiles in the source region, whereas figure 3.b shows the radial density and temperature profiles in the expansion chamber at z = 19 cm. The electron temperature goes down from 5-6 eV near the antenna to nearly 1 eV in the expansion chamber. This adiabatic cooling of electrons is attributed to the magnetic expansion of the plasma [4]. The electron cooling plays a major role in the formation of H^- ions.

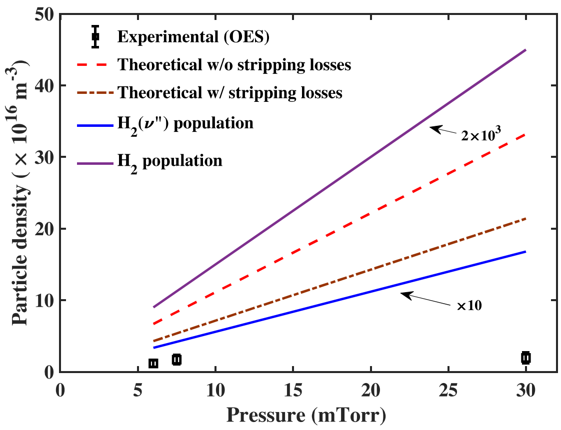


Figure 4. The theoretically obtained value for the H^- density is plotted with the experimental values (same as figure 12.b). The H_2 molecule density and the density of vibrationally excited $H_2(\nu")$ molecule is also shown to compare the destruction and generation processes

The higher electron temperature in the source region enables the vibrational excitation of the hydrogen molecules. These molecules are transported to the expansion region where the low temperature electrons, through dissociative attachment, form H^- ions.

The population of H^- ions formed in the expansion chamber is estimated through a optical emission spectroscopy diagnostic. The details of the diagnostic technique are described in the article by Fantz [5] and its application in HELEN is described by Pandey et al [6]. The results from the OES diagnostic are shown in figure 4. It can be seen from the figure that a considerable amount of H^- ion formation takes place in the plasma. A theoretical estimate is also made using a particle balance model [6]. The particle balance model does not take into account the transport of different species and hence deviates from the experimentally measured values.

The proposed helicon source using permanent magnets is a cost effective and incredibly convenient alternative in terms of handling and maintenance as compared to the conventional caesium based negative hydrogen ion sources. The negative hydrogen ion density is measured by Spectroscopy and lies in the order of 10^{16} m^{-3}. Substantial H^- ions formation takes place in the plasma without Caesium (Cs) injection thus eliminating all the problems associated with Cs dynamics.

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