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Negative hydrogen ion production in a helicon plasma source

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In order to develop very high energy (>1 MeV) neutral beam injection systems for applications, such as plasma heating in fusion devices, it is necessary first to develop high throughput negative ion sources. For the ITER reference source, this will be realised using caesiated inductively coupled plasma devices, containing either hydrogen or deuterium discharges, operated with high rf input powers (up to 90 kW per driver). It has been suggested that due to their high power coupling efficiency, helicon devices may be able to reduce power requirements and potentially obviate the need for caesiation due to the high plasma densities achievable. Here, we present measurements of negative ion densities in a hydrogen discharge produced by a helicon device, with externally applied DC magnetic fields ranging from 0 to 8.5 mT at 5 and 10 mTorr fill pressures. These measurements were taken in the magnetised plasma interaction experiment at the Australian National University and were performed using the probe-based laser photodetachment technique, modified for the use in the afterglow of the plasma discharge. A peak in the electron density is observed at ~ 3 mT and is correlated with changes in the rf power transfer efficiency. With increasing magnetic field, an increase in the negative ion fraction from 0.04 to 0.10 and negative ion densities from $8 \times 10^{14} \text{ m}^{-3}$ to $7 \times 10^{15} \text{ m}^{-3}$ is observed. It is also shown that the negative ion densities can be increased by a factor of 8 with the application of an external DC magnetic field. © 2015 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4931469>]

I. INTRODUCTION

Next generation magnetic fusion reactors, such as the prototype reactor, ITER, and its successor the demonstration power plant, DEMO, will require Neutral Beam Injection (NBI) systems capable of producing neutral hydrogen or deuterium beams with particle energies in excess of 1 MeV, as part of their overall plasma heating systems.¹ In conventional NBI systems, positive ions are collected and accelerated to high energies through an electric field, before being neutralised in a gas cell. Unfortunately, at MeV energies, the neutralisation efficiency of positive ions falls to negligible values. It is therefore necessary to develop NBI systems, which operate using negative ions, due to their much higher neutralisation efficiency at high energies. This presents a new set of challenges, owing to the difficulty of both producing and manipulating negative ions.²

ITER's negative ion source will be required to supply more than 40 A of D^- extracted current from a total extraction area of 0.2 m^2 , operated at a fill pressure of 0.3 Pa or less.² These specifications can be met by a source capable of producing a large volume of plasma with negative ion densities of approximately 10^{17} m^{-3} at the extraction grid.³ Presently, this will be achieved using caesiated Inductively Coupled Plasma (ICP) devices, in which caesium is evaporated into the plasma chamber, lowering the work function for the surface production of negative ions, thus allowing the device to reach the negative ion densities required.² Although caesiated ICP

devices are capable of meeting the specifications required for ITER's NBI system, there are some aspects of such devices which are not ideal. First, a steady supply of caesium must be evaporated into the chamber, requiring a reservoir of caesium that must be regularly replaced, which in a device such as ITER is a complicated and undesirable process. Caesium is also difficult to work with, reacting violently with air, and negative ion production in caesiated sources is highly sensitive to fluctuations in caesium dynamics during operation.¹ Second, it is well known that inductive coupling is a relatively inefficient process and is only capable of a maximum plasma density of around 10^{19} m^{-3} , leading to very high power requirements of around 90 kW per driver in the ITER reference source.¹

Obviously, it would be desirable to develop a negative ion source capable of operating at lower powers and without the need for regular maintenance due to the use of caesium. In a recent publication, Briefi and Fantz⁴ proposed that helicon coupled devices may be suitable alternatives, capable of achieving these goals. Helicon sources are capable of producing very high plasma densities (up to around 10^{20} m^{-3}) with a very efficient power deposition mechanism, in which propagating electromagnetic waves are launched by the antenna and supported by an externally applied DC magnetic field, depositing energy deep into the plasma's core, rather than just at the edge, as in the case of inductive coupling.⁵ They are also capable of operating at lower pressures than ICP devices, which can improve the efficiency of the negative ion extraction system by decreasing collisional losses. Due to their high plasma density and low electron

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temperature, it was proposed that they would be able to produce enough negative ions in a hydrogen discharge to satisfy requirements for a NBI source without requiring caesiation and at lower operating pressures and rf powers.

In their paper, Briefi and Fantz⁴ varied the externally applied magnetic field strength of a helicon device, measuring the atomic to molecular species ratio in hydrogen and deuterium plasmas as an approximate tracer for the negative ion density. They showed that the atomic to molecular species ratio increased with magnetic field strength and provided evidence of the so-called low-field peak⁶ observed at around 3 mT, inferring that a similar trend would be observed in the negative ion density. Here, we present results over a similar range of magnetic field strength, this time measuring the negative ion density more directly using the probe-based laser photodetachment technique.⁷ These measurements were performed in the MAGnetised Plasma Interaction Experiment (MAGPIE) helicon plasma device at the Australian National University.^{8–10}

II. EXPERIMENTAL SETUP

A. MAGPIE

The MAGPIE plasma device (see Fig. 1) is a linear helicon device constructed at the ANU primarily to examine fusion relevant plasma-surface interactions. For a full description of the device, see Ref. 8. MAGPIE consists of a 1 m long, 10 cm outer diameter borosilicate glass “source” chamber, connected to a 68 cm stainless steel “target” chamber. The plasma is heated by a 20 cm long, 12 cm diameter Nagoya III helicon antenna with a 180° helicon twist. The helicon waves are supported by an axial DC magnetic field generated by a set of five solenoids located around the source chamber, with a second set of five solenoids located at the end of the target chamber to study magnetic mirror and confinement configurations. In this work, only the source coils are operated and currents of 0 to 100 A are supplied to create an axially diverging

magnetic field strength of 0 to 8.5 mT in the source region. It should be noted that while MAGPIE is a helicon device, when no magnetic field is present to support helicon propagation, the coupling will be primarily inductive. While this device was primarily constructed to investigate plasma-surface interactions, due to its helicon antenna and its excellent diagnostic access, it also acts as a useful test bed for more general plasma physics and diagnostics. In this work, we investigate a hydrogen plasma discharge created by supplying 1000 W at 13.56 MHz and maintained at 5 and 10 mTorr.

B. Diagnostics

1. Laser photodetachment

Negative hydrogen ion densities were obtained in MAGPIE by employing the well established probe-based laser photodetachment technique (cf. Ref. 7), in which a 1064 nm Nd:YAG Quantel Brilliant B laser of 7 mm diameter is fired into a plasma around a doglegged, positively biased Langmuir probe. The laser detaches the weakly bound electron of the negative hydrogen ions, without ionising other species, leading to an immediate increase in the electron current drawn by the Langmuir probe proportional to the negative hydrogen ion density. This increase is the photodetachment current signal, I_{PD} . The photodetachment probe circuit is shown in Fig. 1. It consists of a 0–100 V Harrison 6116A variable voltage source in parallel with a grounded 22 μF capacitor to eliminate feedback from the voltage source; a 50 Ω resistor, across which the DC Langmuir probe current, I_{DC} , is measured; and a low pass filter, consisting of a 0.82 μF capacitor in series with the 50 Ω termination of a Tektronix DPO 3014 oscilloscope, through which the photodetachment signal can be measured. For this electrical circuit, it is necessary to multiply the increase in the electron current by a factor of two, as the current drawn by the probe flows down two paths of equal resistance. An example of the photodetachment signal is shown in Fig. 2.

FIG. 1. A diagram of MAGPIE and the photodetachment setup.

FIG. 2. An example photodetachment signal after averaging. The laser is fired at 0 μs , causing a near instantaneous increase in the current drawn by the probe, followed by a plateau and then a decay. The depth at which the plateau occurs is taken to be the photodetachment current, I_{PD} .

The negative hydrogen ion fraction, $\alpha = \frac{n_-}{n_e}$, can then be determined from the ratio $\frac{I_{PD}}{I_{DC}}$. The electron density is then calculated using an I-V characteristic generated using a commercially available rf-compensated Langmuir probe and combined with the measured negative ion fraction to produce a value for the negative ion density. The necessary values of probe bias and laser energy were obtained to ensure that the negative ion fraction was determined correctly.⁷

It was found that the rf pick-up on the Langmuir probe was comparable in size to the actual photo detachment signal. In order to measure the negative ion fraction accurately, we sought to minimise the rf component. While this has previously been accomplished using a rf compensated probe,¹¹ we were concerned that this may affect the photodetachment signal. To avoid the problem of rf pick-up, measurements were performed in the early afterglow of the plasma discharge, relying on the relatively long dynamic timescales of the negative ion population. I_{DC} measurements were taken immediately prior to the afterglow and I_{PD} measurements were taken at 20 μs into the afterglow, since I_{PD} does not vary significantly within the first 20 μs of the afterglow (see Section III). The signal is then averaged 512 times to further remove any background rf pick-up and random fluctuations. The timing of the system was controlled using the wavegen function of an Infiniivision DSO-X 2014A oscilloscope and the output of an SRS DS 345 function generator. The laser's flash lamp and the function generator are triggered by the Infiniivision wavegen; the function generator then triggers the plasma to turn off before the laser's Q-switch fires, in turn triggering the oscilloscope. This timing system involves a periodic jitter of 0.75 μs , due to a slight mismatch between the wavegen and the function generator's internal clocks, however, due to the long dynamic timescales of the negative ions and the averaging process, this does not noticeably affect the measurements.

2. Langmuir probe

A rf-compensated Langmuir probe by Impedans Ltd. and the associated Impedans ALP-150 control system were used to determine the electron density, plasma potential, and electron temperature. The tungsten probe tip was 0.125 mm in radius and 2 mm long. The EEDF was determined from the Langmuir probe I-V characteristic. The electron energy probability function (EEDF) is presented in this work, since on a logarithmic plot a Maxwellian distribution is a straight line. The electron densities (N_e) and effective electron

temperature (T_e) were determined from the EEDF, and the plasma potential (V_p) was obtained from the zero crossing of the second derivative.

3. Electrical measurements

A wattmeter placed between the rf generator and the matching network provided information on the forward and reflected power. For each operating condition, the system was rematched to obtain a minimum in the reflected power. The applied power was maintained at 1000 W when the magnetic field or gas pressure was adjusted. The rf current in the antenna was measured using a rf current probe that surrounds one of the electrical feedthroughs of the antenna. The output of the probe was connected to a digital oscilloscope using a 50 Ω terminator. The coil and plasma resistance as well as the power transfer efficiency were then determined using these measurements.¹²

III. RESULTS AND DISCUSSION

To validate our use of the photodetachment technique in the plasma afterglow, we first present results of the temporally resolved photodetachment measurements, ranging from 0 to 200 μs after the plasma is turned off, and demonstrate the relatively long timescales over which the N_{H^-} decays into the afterglow. These measurements were performed at 10 mTorr with 1000 W of applied power, for no magnetic field and for a magnetic field of 3 mT, which corresponds to a low-field density peak (Fig. 3). Since the rf pick-up did not fully decay until approximately 16 μs into the afterglow, the measurements before this point are not as reliable as measurements later in the afterglow. Despite this, it can clearly be seen in Fig. 3 that the decay constant of the photo detachment signal, and hence the negative ion density (N_{H^-}), is on the order of 50 μs . Therefore, by taking measurements at 20 μs , we can obtain values for the negative ion density within 20% of the discharge values. It is also worth noting that measurements of I_{DC} decay with an exponential timescale of $6.8 \pm 1.4 \mu\text{s}$, indicating that electrons decay over a

FIG. 3. Measurements of the decay of the photodetachment current into the afterglow, here shown up until 100 μs for clarity. It can be seen that the negative ions decay with a similar timescale over almost an order of magnitude of I_{PD} , both with and without an externally applied magnetic field.

FIG. 4. Electron and negative ion densities for different source magnetic fields at fill pressures of (a) 5 mTorr and (b) 10 mTorr, here presented on the same scale.

much shorter timescale than negative ions, creating an ion-ion plasma for a few tens of μs in the plasma afterglow. Such pulsed ion-ion plasmas have a number of applications in processing and thruster technology^{13–15} and will be investigated in further detail in future publications.

Operating under similar plasma conditions to Briefi and Fantz,⁴ we vary the externally applied magnetic field strength over a similar range (0 to 8.5 mT) in hydrogen discharges and make direct measurements of the negative ion density using the laser photodetachment technique. Figs. 4(a) and 4(b) show the change in electron density (blue) and negative ion density (red) with a varying source magnetic field of 0 to 8.5 mT at an applied power of 1000 W and gas pressures of 5 and 10 mTorr.

The presence of a magnetic field can influence the EEDF due to collisions and cross-field diffusion of electrons. The effect is more pronounced for low-energy electrons and results in a decrease of the electron saturation current. To ensure that the Druyvesteyn method is still valid and can be used without correction, the probe radius, r_p , and Debye length should be less than the Larmor radius, r_L , of the electrons. For the maximum coil current, the magnetic field at the probe location would be approximately 6.1 mT ($\sim 75\%$ of the magnetic field at the antenna). If we consider the photodetached electrons which are detached with an energy of ~ 0.41 eV, the minimum Larmor radius of these electrons would therefore be $r_L = 0.35$ mm, which is approximately three times larger than the probe radius. We are therefore safe to take the plasma as being unmagnetised in our analysis.

Evidence of the so-called low field peak^{6,16} is clearly observed at around 3 mT in the N_e measurements, although this is less clearly reflected in the N_{H^-} measurements. At 5 mTorr, it is observed that the electron density increases from $\sim 2.5 \times 10^{16} m^{-3}$ with no magnetic field to $\sim 1 \times 10^{17} m^{-3}$ at 3 mT, and then decreases to a value of $\sim 7 \times 10^{16} m^{-3}$ at 5 mT. The negative ion density increases from $\sim 2 \times 10^{15} m^{-3}$ with no magnetic field to $\sim 4 \times 10^{15} m^{-3}$ at 3 mT and then

remains fairly constant with further increases in magnetic field. There is little change in the electron density and its dependence on magnetic field at 10 mTorr. However, at 10 mTorr, a larger increase is observed in the negative ion density from $\sim 0.75 \times 10^{15} m^{-3}$ with no magnetic field to $\sim 6 \times 10^{15} m^{-3}$ at 3 mT. While it is well known that an applied magnetic field can significantly increase N_e in helicon devices, these measurements confirm that N_{H^-} will approximately track those increases in N_e . We observe as much as an 8 fold increase in N_{H^-} in Fig. 4(b), with negative ion fractions remaining between 4 – 10%. Due to the decreasing electron density and fairly constant negative ion density, the negative ion fraction increases with increasing magnetic field strength (Fig. 5). If similar negative ion fractions can be maintained at higher powers and densities, then this would be very promising for the prospect of using helicon devices as negative ion sources, given that plasma densities of $10^{20} m^{-3}$ are achievable in helicon devices.

The dominant volume production mechanism of H^- in low pressure plasma discharges is by dissociative attachment given by

FIG. 5. Negative ion fractions of the 5 mTorr and 10 mTorr discharges for different source magnetic fields.

where the metastable molecular negative ion H_2^- fragments into atomic hydrogen and H^- .¹⁷ In this process, ro-vibrationally excited hydrogen molecules play a significant role in negative ion production. In terms of destruction mechanisms, negative ion loss occurs through mutual neutralisation with H_3^+ ions ($\text{H}_3^+ + \text{H}^- \rightarrow 4\text{H}$) as well as H_2^+ ($\text{H}_2^+ + \text{H}^- \rightarrow 3\text{H}$) and electron detachment ($\text{e} + \text{H}^- \rightarrow \text{H} + 2\text{e}$). It should be noted that while mutual neutralisation with ions is important for all operating conditions, electron detachment becomes important for low pressures.

Changes to the plasma potential and the electron temperature are also observed, which display a minimum around 2 mT (Fig. 6). This minimum is due to increased electron-electron collisions with a frequency $\nu_{ee} \propto n\text{e}^{3/2}$, leading to increased energy transfer processes in the plasma.¹⁸ It has previously been found that two-step processes via atomic excited states control ionisation resulting in an increase in the ionisation frequency and a reduction of electron temperature with plasma density. The Maxwellization effect of the electron-electron collisions on the EEPF is displayed in Fig. 7. It is observed that for zero magnetic field the EEPF takes a Druyvesteyn-like distribution while with the magnetic field the EEPF becomes Maxwellian.

It is important to consider the implication that the electrical characterisation of the system will have on the plasma parameters as the source magnetic field is varied. The amplitude of the rf current through the antenna (I_{rf}) is related to the net power deposited in the plasma by

$$P_{\text{Fwd}} - P_{\text{Ref}} = I_{\text{rms}}^2 (R_{\text{ant}} + R_{\text{p}}), \quad (2)$$

where P_{Fwd} is the forward power, P_{Ref} is the reflected power, $I_{\text{rms}} = I_{\text{rf}}/\sqrt{2}$, R_{ant} is the antenna resistance, and R_{p} is the plasma resistance. The power transfer efficiency can then be determined by

$$\eta = \frac{R_{\text{p}}}{R_{\text{ant}} + R_{\text{p}}}. \quad (3)$$

The antenna resistance is first obtained by operating the system with no plasma and recording the antenna current.

FIG. 6. Electron temperature and plasma potential for the 10 mTorr, 1000 W discharge for different source magnetic fields.

FIG. 7. Electron energy probability functions for magnetic fields between 0 and 7 mT, indicating Maxwellization with the application of a magnetic field.

This gives a value of $\sim 0.53 \Omega$ and is in close agreement with that of LaFleur *et al.*¹⁶

Fig. 8 shows the change in plasma resistance with increasing magnetic field. It is observed that the resistance increases quickly from $\sim 0.2 \Omega$ at 1 mT to $\sim 0.8 \Omega$ at 3 mT and then decreases to $\sim 0.4 \Omega$ at 9 mT. This trend and values are in good agreement with the work of LaFleur *et al.* in an argon discharge. As a result of this changing resistance, the power coupling efficiency into the plasma is at a maximum around 3–4 mT (Fig. 8). This indicates that the maximum in the electron density corresponds to the maximum power transfer efficiency, as one might expect. Previous work by Celik *et al.*¹⁹ in a neutral loop discharge and LaFleur *et al.*¹⁶ in a helicon source have demonstrated that this increased power absorption at low magnetic fields may be due to collisionless wave damping.

FIG. 8. Plasma resistance and power transfer efficiency of the 10 mTorr, 1000 W discharge for different source magnetic fields.

IV. CONCLUSIONS

Using a probe-based laser photo detachment technique, we have determined the hydrogen negative ion density in a helicon plasma device operated at low source magnetic fields. We show that the negative ion density follows a similar trend to the electron density at low magnetic fields. At magnetic fields above 3 mT, the negative ion density remains fairly constant while the electron density decreases. This is in good agreement with observations by Briefi and Fantz⁴ who investigated the atomic to molecular species ratio. This is a promising first step in confirming the viability of helicon devices as negative ion sources for the NBI systems of next generation magnetically confined fusion reactors. The next step will be to perform measurements under conditions similar to the operational conditions of ITER's reference negative ion source, i.e., a maximum fill pressure of 0.3 Pa and a higher input power of tens of kW. If the required negative ion density of approximately 10^{17} m^{-3} can be achieved under these conditions, without the need for caesiation, it will present the helicon device as a very good alternative to the current ICP design. Furthermore, Briefi and Fantz⁴ noted significant differences in the response of a deuterium plasma discharge when compared to hydrogen, so a further important step will be to perform negative ion measurements with deuterium.

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- ¹E. Speth, H. D. Falter, P. Franzen, U. Fantz, M. Bandyopadhyay, S. Christ, A. Encheva, M. Fröschle, D. Holtum, B. Heinemann, W. Kraus, A. Lorenz, C. Martens, P. McNeely, S. Obermayer, R. Riedl, R. Süß, A. Tanga, R. Wilhelm, and D. Wunderlich, *Nucl. Fusion* **46**, S220 (2006).
- ²R. Hemsworth, H. Decamps, J. Graceffa, B. Schunke, M. Tanaka, M. Dremel, A. Tanga, H. De Esch, F. Geli, J. Milnes, T. Inoue, D. Marcuzzi, P. Sonato, and P. Zaccaria, *Nucl. Fusion* **49**, 045006 (2009).
- ³S. Christ-Koch, U. Fantz, M. Berger, and NNBI Team, *Plasma Sources Sci. Technol.* **18**, 025003 (2009).
- ⁴S. Briefi and U. Fantz, *AIP Conf. Proc.* **1515**, 278–283 (2013).
- ⁵P. Chabert and N. Braithwaite, *Physics of Radio-Frequency Plasmas* (Cambridge University Press, Cambridge, 2011).
- ⁶F. Chen, *Phys. Plasmas* **10**, 2586 (2003).
- ⁷M. Bacal, *Rev. Sci. Instrum.* **71**, 3981 (2000).
- ⁸B. Blackwell, J. Caneses, C. Samuelli, J. Wach, J. Howard, and C. Corr, *Plasma Sources Sci. Technol.* **21**, 055033 (2012).
- ⁹C. Samuelli, B. Blackwell, J. Howard, and C. Corr, *Phys. Plasmas* **20**, 034502 (2013).
- ¹⁰C. Samuelli and C. Corr, *J. Nucl. Mater.* **451**, 211 (2014).
- ¹¹Z. Kiss'ovski, S. Kolev, A. Shivarova, and T. Tsankov, *J. Phys.: Conf. Ser.* **113**, 012012 (2008).
- ¹²V. Godyak, *Plasma Sources Sci. Technol.* **20**, 025004 (2011).
- ¹³C. S. Corr, P. G. Steen, and W. G. Graham, *Appl. Phys. Lett.* **86**, 141503 (2005).
- ¹⁴S. Banna, A. Agarwal, G. Cunge, M. Darnon, E. Pargon, and O. Joubert, *J. Vac. Sci. Technol. A* **30**, 040801 (2012).
- ¹⁵A. Aanesland, J. Bredin, L. Popelier, and P. Chabert, e-print [arXiv:1411.1538v1](https://arxiv.org/abs/1411.1538v1). Also submitted to the conference "CERN accelerator School – Ion Sources, 29 May – 8 June 2012, Senec, Slovakia (2012)."
- ¹⁶T. LaFleur, C. Charles, and R. Boswell, *J. Phys. D: Appl. Phys.* **44**, 055202 (2011).
- ¹⁷B. Jordon-Thaden *et al.*, *Phys. Rev. Lett.* **107**, 193003 (2011).
- ¹⁸V. Godyak, R. Piejak, and B. Alexandrovich, *Plasma Sources Sci. Technol.* **11**, 525 (2002).
- ¹⁹Y. Celik, D. Crintea, D. Luggenhölscher, and U. Czarnetzki, *Plasma Phys. Controlled Fusion* **51**, 124040 (2009).