Negative ion studies on the RF plasma device MAGPIE

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Introduction

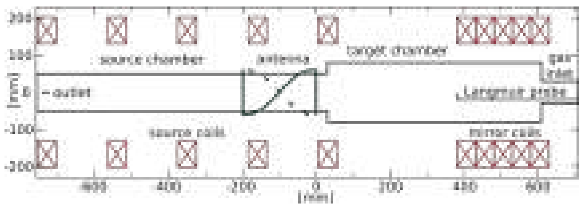
Negative ion sources are integral to the neutral beam injection (NBI) systems that are used to heat and refuel the fusion plasma in tokamaks. The ions are created (in a plasma), extracted, and accelerated, before being neutralised to produce beams of high-energy atoms. Negative ions are used rather than positive ions due to the neutralisation of negative ions being more efficient at high energy [1]. However, current negative ion source designs use inductively coupled plasma sources, which require a caesium catalyst in order to increase the reaction rate to a sufficiently high level [2]. As caesium is a highly reactive element and needs to be frequently reapplied, it is preferable to develop a negative ion source that is capable of achieving the necessary production rate without needing to use caesium. As a guideline, an approximate threshold for the density of negative ions that such a source must produce is $1 \times 10^{17}\,\mathrm{m}^{-3}$ [3].

It has been suggested that helicon plasma sources could be employed as caesium-free negative ion sources, due to their efficiency at producing high density plasmas with low electron temperatures [4, 5]. However, in order to achieve this, further research into the operation and optimisation of these sources is needed. We present results from a study of the helicon plasma device MAGPIE and its negative hydrogen ion population.

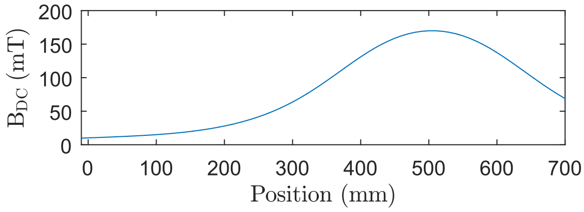
MAGPIE

The MAGnetised Plasma Interaction Experiment (MAGPIE) is a linear plasma device, operated using a helicon source [6]. The chamber is divided into a 1 m long borosilicate glass source chamber and a 68 cm long stainlesss steel target chamber (illustrated in Figure 1a). The neutral hydrogen gas feed is at the end of the target chamber, with the vacuum pump at the opposite end of the device. A Nagoya III antenna, 20 cm long and 12 cm in diameter with a 180° twist, launches helicon waves to heat the plasma. These waves are supported by an axial DC magnetic field, created by five solenoids around the source region and five around the target chamber.

In this work, we study a pulsed plasma created by driving the helicon antenna at 13.56 MHz at a power of 20 kW. The parameters used were: a pulse length of 40 ms; gas fill pressure of 10 mTorr; source field coil current of 50 A ($\sim$ 10 mT); and target field coil current of 800 A ($\sim$ 170 mT). The magnetic field profile produced by these coil currents is shown in Figure 1b.

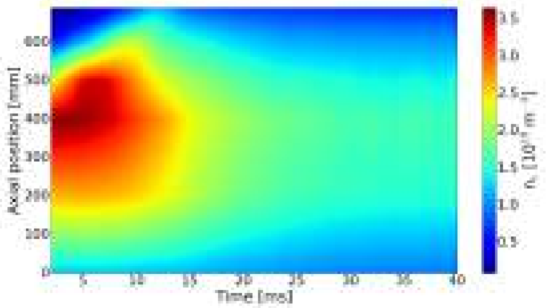


(a)

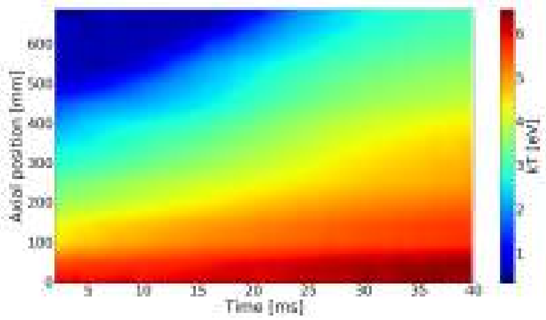


(b)

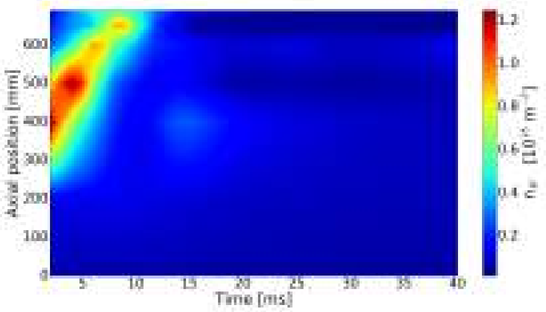
Figure 1: (a) Schematic diagram of MAGPIE. (b) The axial magnetic field profile resulting from a source field coil current of 50 A and target field coil current of 800 A.



(a) Electron density.



(b) Electron temperature.



(c) Negative ion density.

Figure 2: Evolution of the axial profiles of the plasma parameters and the frequency spectrum of the floating potential in MAGPIE throughout a 40 ms pulse.

The diagnostics included an axial dog-leg Langmuir probe, used for both conventional density and temperature analysis and for laser photodetachment measurements of the negative hydrogen ion density (in conjunction with a 1064 nm Nd:YAG laser) [7]. The probe was also used to record time series of the floating potential throughout the 40 ms pulses in order to analyse the frequency spectrum of modes present in the plasma. A *B*-dot probe was used to measure the *x* and *y* components of the radial magnetic field strength on axis throughout MAGPIE.

Observations

Initial studies aimed to maximise the observed density of negative hydrogen ions (n_{H^-}) in MAGPIE by optimising the operation parameters (the resulting values are listed in the previous section). In Figure 2 we plot the time evolution of the electron density, temperature and negative ion density along the axis of the MAGPIE target chamber for these parameters. An electron heating front propagates through the plasma from the source to the target region (Fig. 2b), and a transient peak n_{H^-} value of 1.25×10^{18} m^{-3} was achieved at an axial position of 500 mm. This is a factor of ten higher than the nominal threshold required for an NBI negative ion source. Further analysis of the plasma behaviour focused on this axial position.

From Figure 2, we see that the peak in n_{H^-} occurs in the region of lowest electron temperature (< 1 eV), and as the electron heating region propagates forwards, n_{H^-} decreases in front of it. Using the measured density and electron temperature values, we estimated the rate coefficients for the formation and destruction of negative ions at the 500 mm axial position throughout the 40 ms pulse. The results are plotted in Figure 3, along with the n_{H^-} profile, and we see that the change in magnitude of the rate coefficients does approximately coincide with the decrease in the negative ion density, as expected.

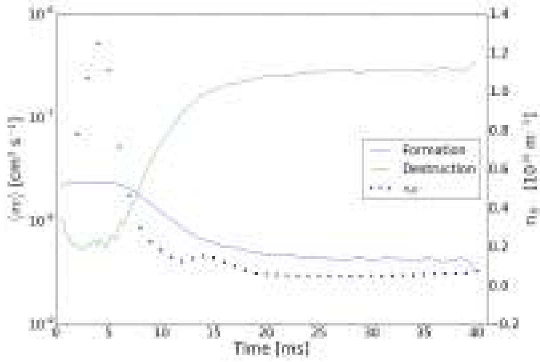


Figure 3: The estimated rate coefficients for negative ion formation and destruction throughout the pulse, with the measured n_{H^-} profile, both at 500 mm.

A spectrogram showing the evolution of the power spectrum of the floating potential at 500 mm throughout the pulse is shown in Figure 4. Also plotted are the estimated frequencies of the first and second Alfvèn wave harmonics, which were calculated using the ion density measurements at this position. There is reasonable qualitative agreement between the evolution of the calculated frequencies and that of the main peaks visible in the power spectrogram. We therefore infer that there may be Alfvènic activity occurring in the helicon plasma in MAGPIE.

Finally, a *B*-dot probe was used to measure the *x* and *y* components of the magnetic field strength from the antenna on-axis along the machine (the *z* component is approximately zero on axis for this antenna). The evolution through the pulse of the radial wavefield amplitude resulting from averaging these measurements is shown in Figure 5. The low values, particularly in the region of the peak negative ion density and low temperatures, suggest that the evolution of the plasma is not directly related to helicon wave heating.

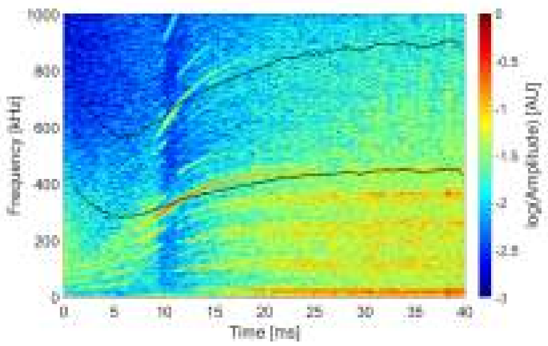


Figure 4: Power spectrum of the floating potential at 500 mm on axis, with the calculated Alfvèn frequencies overlaid.

Conclusions

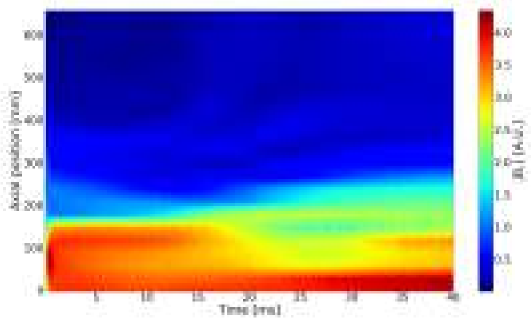


Figure 5: The time evolution of the axial profile of the average radial magnetic field strength from the helicon antenna.

We have observed the behaviour of 40 ms hydrogen plasma pulses in the helicon device MAGPIE. Peak negative ion densities of $1.25 \times 10^{18}\ \mathrm{m}^{-3}$ were measured, which coincided with the region of lowest electron temperature. This is consistent with the expected behaviour of negative ions, which are neutralised at high temperatures. Analysis of the power spectrum of the floating potential throughout the pulse revealed the possible presence of Alfvènic modes in the plasma after ~ 10 ms, coinciding with the passage of the electron heating front through the plasma. Magnetic wavefield amplitude measurements appear to suggest that the helicon wave propagation is not directly responsible for the evolution of the plasma.

The measured peak value of n_{H^-} shows promise for the use of helicon plasma sources for neutral beam injection systems, as it is an order of magnitude above the required threshold for NBI applications. However, it is clear that with these operating parameters the high density is a transient feature, whereas an NBI source would require high densities over much longer timescales in order to operate effectively. Further investigation of the properties of the plasma pulse is needed to better understand the plasma behaviour, with a view to increasing the duration of the peak negative ion density. An extension to the study of deuterium plasmas is also required in order to fully understand the implications for tokamak NBI applications [4].

Acknowledgements

Thanks are due to Michael Blacksell and Amy Shumack. We are grateful for the support of the Engineering and Physical Sciences Research Council [EP/K504178/1] and the Australian Plasma Fusion Research Facility, and funding by the Australian Government under the Super Science Initiative.

References

[1] K H Berkner et al., Nucl. Fusion **15**, 249–254 (1975)

[2] E Speth et al., Nucl. Fusion **46**, S220–S238 (2006)

[3] S Christ-Koch et al., Plasma Sources Sci. Technol. **18**, 025003 (2009)

[4] S Briefi and U Fantz, AIP Conference Proceedings **1515**, 278–283 (2013)

[5] J Santoso et al., Phys. Plasmas **22**, 093513 (2015)

[6] B D Blackwell et al., Plasma Sources Sci. Technol. **21**, 055033 (2012)

[7] M Bacal, Rev. Sci. Instrum. **71**, 3981–4006 (2000)