Ion heating and density production in helicon sources near the lower hybrid frequency

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Abstract
We report measurements of electron density and perpendicular ion temperatures in an argon helicon plasma for five different rf antennas: a Nagoya type III antenna, a ‘Boswell’ saddle coil antenna, a 19 cm long m = +1 helical antenna, a 30 cm long m = +1 helical antenna, and a 19 cm long m = +1 helical antenna with narrow straps. The general properties of the source as a function of rf power and neutral pressure are reviewed and detailed measurements of electron density, electron temperature and ion temperature as a function of magnetic field strength and rf frequency are presented. The experimental results clearly indicate that for all antennas, the electron density is maximized when the rf frequency is close to and just above the lower hybrid frequency. The ion temperature is maximized when the rf frequency is less than 70% of the lower hybrid frequency. Ion temperatures in excess of 1 eV for 750 W of input power have been observed. These results suggest that the mechanisms responsible for coupling energy into the ions and electrons are distinct and therefore helicon sources can be configured to maximize electron density without simultaneously maximizing the perpendicular ion temperature. Enhanced ion heating is not a desirable feature of plasma sources intended for use in plasma etching, thus operational regimes that yield high plasma densities without increased ion heating might be of interest to industry.

1. Introduction
One of the motivations for the development of low-pressure, inductively coupled sources for plasma processing has been the belief that the collisionless sheaths in such sources would make it possible to etch high aspect ratio (narrow and deep) trenches in wafers [1]. In typical high-pressure discharges (20–100 mTorr), ions gain perpendicular energy through collisions with neutrals as they are accelerated through the collisional sheath at the front surface of the wafer. Because of their lower operating pressures, typically 1–20 mTorr, and high plasma densities, helicon sources have been promoted as an ideal source for rapid, high aspect ratio etching [2, 3].

The bulk of helicon source research has focused on understanding the mechanism responsible for the high ionization efficiency in helicon sources [4, 5], understanding the structure of the wave fields in helicon sources at both large and small magnetic fields [6, 7] and understanding the role of antenna geometry in plasma production efficiency [8–10]. However, higher plasma densities alone are unlikely to provide sufficient justification for the plasma processing industry to begin widespread use of helicon sources. What is required for industrial acceptance of these types of low-pressure, inductively coupled sources is clear evidence of significant advantages over existing processing sources. For example, some groups have focused on developing helicon sources capable of processing large-area substrates [11] while others have examined the relationship between notch formation and the duty cycle of the source [12].

One possible impediment to the widespread use of helicon sources for high aspect ratio etching is the recent observation of high, $T_i \approx 1$ eV, intrinsic ion temperatures in our low-pressure, argon, helicon plasmas [13]. The ion distribution is highly anisotropic with $T_{i\perp} \gg T_{i\parallel}$ [13]. There are some reports of argon ion temperatures on the order of 1 eV in other helicon sources [14], but typical measurements of argon ion temperatures in other sources are on the order of 0.07 eV [15]. Thus, although they can operate at low pressures, helicon
sources may be prone to the same over-etching problems that plague high-pressure plasma sources. Understanding and minimizing ion heating in helicon sources is critical if such sources are to be used for high aspect ratio etching.

A recent theoretical study suggests that absorption of ions in acoustic turbulence in helicon sources could result in enhanced heating [16], but there have been no detailed theoretical studies of ion heating in helicon sources. The increase of the perpendicular ion temperature with increasing magnetic field (while the electron density and temperature remain constant) and the anisotropy of the ion temperature [13] suggest that collisional equilibration with the hotter electrons cannot be responsible for all of the observed ion heating. The heating rate for ions due to collisional equilibration with electrons (including a loss term for ion energy confinement) is

$$\frac{d}{dr} \left( \frac{3n_i kT_i}{2} \right) = n_i v_{ie}^2 k(T_e - T_i) - \frac{3n_i kT_i}{2\tau_{EI}}$$ (1)

where $v_{ie}^2$ is the ion–electron collisional equilibration frequency [17], $\tau_{EI}$ is the ion energy confinement time and $n_i$ is the ion density. For steady-state parameters typical of the experiments to be reported here: $n_i = 1.0 \times 10^{13} \text{ cm}^{-3}$, $kT_e = 3.5 \text{ eV}$, and $kT_i = 1 \text{ eV}$, equation (1) reduces to the statement

$$\tau_{EI} = 7.5 \times 10^{-3} \text{ s.}$$ (2)

The actual energy confinement time can be estimated from the ratio of the stored thermal energy to the input rf power needed to obtain these plasma parameters. Assuming half of the 750 W of forward power used is actually coupled into the plasma, an upper limit on the energy confinement time is given by

$$\tau_{EI} = \frac{(nk(T_i + T_e)) \text{volume}}{\text{Power/Volune}} \approx 3 \times 10^{-6} \text{ s.}$$ (3)

Since the collisional heating calculation requires an energy confinement time an order of magnitude larger, it is clear that ion–electron equilibration cannot be solely responsible for 1 eV steady-state ion temperatures. For an energy confinement time of $3 \times 10^{-6}$ s and the observed steady-state electron temperature, equation (1) predicts an ion temperature of 0.06 eV; in good agreement with the low ion temperature observations of Nakano et al [15]. In these calculations, we have neglected the important energy loss terms for ion cooling by elastic collisions and/or resonant charge exchange with neutrals. Inclusion of these effects would further reduce the expected steady-state ion temperature. Therefore, even if only a small fraction of the forward power (say 10%) is responsible for the observed plasma densities and electron temperatures, ion–electron collisional equilibration cannot explain the observed ion temperatures.

In this paper, we report measurements of electron density and perpendicular ion temperatures in an argon helicon plasma versus neutral pressure, rf power and magnetic field strength for a variety of antenna geometries: a ‘Boswell’ double saddle-coil [18], a Nagoya type III [19], and three different $m = +1$ helical antennas [20]. The highest densities are achieved with the $m = +1$ helical antennas as expected from theoretical results [9,21]. Unfortunately, these antennas also yield the highest ion temperatures. To investigate the relationship between density production and ion heating more thoroughly, detailed measurements of electron density, electron temperature and perpendicular ion temperature as function of source magnetic field strength and rf frequency were made for four antennas: the three helical antennas and the Nagoya III antenna. The magnetic field and rf frequency dependence of the electron density clearly indicates a correlation between density production and the lower hybrid frequency. Such trends are consistent with previous experiments [6,22–24]. What is remarkable, however, is that the perpendicular ion heating clearly peaks for rf frequencies approximately 70% of the lower hybrid frequency.

In the following sections, the experimental apparatus is described; neutral pressure, rf power and magnetic field strength scans for all five antennas are reviewed; and detailed magnetic field strength and rf frequency experimental results for four of the antennas are presented and discussed. The data presented here are for operation of the helicon source in the helicon mode unless otherwise stated.

2. Experimental apparatus

The HELIX (Hot HELIcon eXperiment) vacuum chamber is a 1.57 m long, 0.15 m diameter, Pyrex tube with four 2.54 cm ports located 0.3 m from one end. The Pyrex tube is attached at one end to a large aluminium chamber (4.5 m long, 2 m inner diameter) through a stainless steel bellows (see figure 1). A 560 l s$^{-1}$ turbomolecular drag pump is connected to the other end of the Pyrex chamber. Attached to the far end of the large chamber are two 1600 l s$^{-1}$ turbomolecular drag pumps. All three pumps are backed with diaphragm pumps to eliminate contamination by hydrocarbons. The base pressure in the system is typically $5 \times 10^{-8} \text{ mTorr}$. The inlet for the working gas is mounted in the flange between the end of the Pyrex chamber and the 560 l s$^{-1}$ pump. Typically argon, helium or a mixture of argon and helium is used. Constant pressure in the source is maintained with a feedback controlled, piezoelectric valve. Normal operating pressures for argon range from 1–10 mTorr. For the experiments reported here, only argon gas was used.

The steady-state HELIX magnetic field is generated with ten electromagnets whose positions were originally optimized to produce a uniform axial magnetic field of 0–1300 G [25]. For the second set of measurements reported here, the current in the second electromagnet was reversed to create a minimum field or ‘cusp’ region near one end of the rf antenna. For the cusp configuration, a typical axial field profile calculated with three-dimensional magnetic field modelling code is shown in figure 2. Hall probe measurements of the axial magnetic field are within a few per cent of the model calculations. The cusp configuration was chosen based on past observations of increased densities with a field–minimum configuration [26] and published reports of similar results by other helicon groups [27,28]. Although the single electromagnet between the source chamber and the large chamber was not used for these experiments, the source magnetic field extends far enough into the large chamber that most of the plasma generated in the source diffuses into the large chamber.

As shown in figure 1, four ports on the glass tube are arranged in a four-way cross pattern. Two opposing ports are used for swept frequency (26–40 GHz) microwave...
Figure 1. A schematic depiction of the helicon source connected to the large-space simulation vacuum chamber. Three sets of electromagnets are shown in diagram: the coils around the source, around the space chamber, and around the bellows connecting the two chambers. The current in the second electromagnet from the right end of the source is directed opposite to the other coils to create a field minimum (see figure 2). The position of the rf antenna, the antenna used for auxiliary ion heating, the crossing ports and the Langmuir probe are shown in the schematic diagram.

Figure 2. Axial magnetic field strength versus position in the helicon source. The rf antenna is located to the left of the field minimum region.

Figure 3. Comparison of the number of microwave interference fringes (open squares) obtained at startup for 33.6 GHz microwaves and the downstream density measured with a Langmuir probe (filled circles) during pulsed operation of the plasma source. A typical error bar representative of the statistical error in the number of fringes is shown for the 100 G field data point. The statistical errors in the Langmuir probe data are smaller than the size of the data points used. Both diagnostics show the same relative changes in electron density as a function of source magnetic field strength.

interferometry measurements when the source operates in steady-state mode or for standard fixed frequency microwave interferometry measurements when the source is pulsed [29]. As the microwave source frequency is swept over a few GHz, the shift in phase and frequency of the beat pattern in the mixture of the signals from both legs of the interferometer is used to determine the peak line-of-sight electron density in steady-state plasmas [29]. A comparison of pulsed source microwave interferometry and downstream Langmuir probe measurements is shown in figure 3 to demonstrate the correspondence between the source density and the downstream probe measurements. Depending on the density profile, linear or parabolic, each of the microwave fringes corresponds to change in the peak density of $3.4 \times 10^{12}$ cm$^{-3}$ or $2.3 \times 10^{12}$ cm$^{-3}$, respectively [29]. Because the trends in the downstream Langmuir probe density measurements are identical to those seen in the microwave density measurements in the source, we will assume throughout this work that the plasma density is created in the source and flows into the large chamber downstream along the magnetic field. Given this assumption, the changes in downstream density observed in these experiments correspond changes in the source density as the system parameters are varied. The rf compensated Langmuir probe is mounted on a scanning stage for radial profile measurements of both electron temperature and plasma density [26, 30]. Because the magnetic field in the large chamber is only 10–70 G, this configuration is similar to a conventional plasma source plus processing chamber system. For all the experiments reported here, the magnetic field in the large chamber was maintained at 35 G and the electron densities and temperatures measured downstream in the expansion chamber with the Langmuir probe.

For laser-induced fluorescence measurements (LIF) [13, 31] of the perpendicular ion temperature in the source, 611.5 nm laser light from a tunable ring dye laser is injected perpendicular to the source magnetic field. The laser light is injected through the Pyrex vacuum chamber wall and the 461.0 nm fluorescent emission is collected perpendicular to the magnetic field through one of the four ports in the source chamber. The Ar II quantum state transitions corresponding to the absorption and emission lines are $(3d'f^2G_{9/2} \rightarrow (4p')^2F_{7/2}$, and $(4p')^2F_{7/2} \rightarrow (4s')^2D_{5/2}$, respectively. The injected light is linearly polarized before passing through the injection optics.
The combination argon ion pump laser and ring dye laser system and the details of the argon ion transitions used for the LIF measurements have been described elsewhere [13]. The 461 nm emission is detected with a 1 nm bandpass filtered photomultiplier tube. To separate the fluorescent emission from the background light, the laser beam is chopped and the chopping signal used as a reference for a lock-in amplifier that monitors the photomultiplier signal. Previous experiments have shown that, unless the source is operated at high pressure, the ion temperature in this source is highly anisotropic with \( T_R \gg T_I \) [13]. Typical parallel and perpendicular ion velocity space distributions for an argon plasma are shown in figure 4.

A schematic diagram of the rf matching circuit, transmission line, and a Nagoya III antenna are shown in figure 5(a). A 0–50 MHz, Wavetek Model 80 function generator supplies the rf signal to a steady-state ENI A1000 rf amplifier. The amplifier can operate over 0.3 to 30 MHz. The forward power from the amplifier and the reflected power from the matching circuit are monitored with separate Bird rf power meters. The matching circuit is a standard \( \pi \) circuit consisting of four variable capacitors. With the available capacitors, matching is possible over a wide range of frequencies, typically 6–18 MHz. For all the experiments reported here, the rf powers are based on measurements of the total forward power and the reflected power is maintained at less than 1% of the forward power. The transmission line between the matching circuit and the antenna consists of two parallel copper bars. The 2.5 cm gap between the transmission line feeds is the same for all of the antennas studied. Surrounding the transmission line is a grounded, solid copper tube. For the configuration of the matching circuit and transmission lines shown in figure 5(a), the accessible frequency range for each antenna depends primarily on the antenna’s inductance. When the antenna inductance is too small, the tuning capacitance is not sufficient to match the antenna impedance to the 50 \( \Omega \) output impedance of the rf amplifier. Note that the matching circuit is such that the rf signal to the antenna is balanced, i.e. neither side of the transmission line is grounded. Note also that the transmission line attaches at one end of the antenna. This configuration was chosen to eliminate the electric field discontinuity in the middle of the antenna that arises from the difference in phase between the two current feeds. When the feeds are in the middle of the antenna, the ‘cross-tube’ electric field (between the straps running along the axis of the discharge) undergoes an abrupt change in middle of the antenna. In other words, the capacitive coupling properties of the antenna are different when the antenna is fed from one end instead of the middle. Except for the saddle-coil antenna, the same attachment configuration was used with each antenna. The same matching circuit and transmission line was used with every antenna studied.

The magnetic field direction was chosen so that the helical rotation of all of the \( m = 1 \) antennas was in the right-hand direction along the field, i.e. the antennas are \( m = +1 \) antennas. A schematic diagram of the ‘narrow strap’ 30 cm, \( m = +1 \), helical (NSH30) antenna is shown in figure 5(b). The antenna straps are all 1.8 cm wide and 0.16 cm thick and the antenna inductance is 1.02 \( \mu \)H. The antenna geometry used for the narrow strap 19 cm long, \( m = +1 \), (NSH19) antenna experiments is the same as shown in figure 5(b). For this antenna, the straps are all 1.8 cm wide and 0.16 cm thick and the antenna inductance is 0.20 \( \mu \)H. The ‘wide strap’ 19 cm long, \( m = +1 \), (WSH19) antenna is identical to the ‘narrow strap’ 19 cm long \( m = +1 \) antenna except that the straps are 2.54 cm wide and cut from 0.051 cm thick copper sheet. The ‘wide strap’ antenna inductance is 0.50 \( \mu \)H. Although the wider strips along the discharge tube should lower the antenna inductance, the inductance increase due to the wider straps around the discharge tube dominates the antenna inductance and results in an overall increase in the inductance of wide strap antenna. All three \( m = +1 \) antennas were cut from single sheets of copper and folded around the tube so that the only non-permanent connections are in the loops around the discharge tube. The transmission lines were silver-soldered directly to the antenna feeds.

The double saddle-coil, or ‘Boswell’, antenna is shown in figure 5(c). The antenna is 19 cm long with 2.5 cm wide straps that are 0.16 cm thick. The Boswell saddle-coil antenna inductance is 0.21 \( \mu \)H. The Nagoya III antenna (shown in figure 5(a)) is also 19 cm long with 2.54 cm wide straps that are 0.051 cm thick. The inductance of the Nagoya III antenna is 0.20 \( \mu \)H.

3. Performance comparison of all five antennas

The perpendicular ion temperature and downstream plasma density as a function of neutral pressure in the source are shown in figure 6 for all five antennas. For these measurements, the source magnetic field was held fixed at 800 G, the rf frequency was 9 MHz, and the rf power was 500 W. Given that the inductances of the NSH19, the Nagoya III, and the saddle-coil antennas are nearly identical, the power coupled into the antenna for a fixed amount of forward rf power should be nearly identical. Therefore, differences in the densities and ion temperatures generated by these three antennas reflect the differences in the efficiency by which these antennas couple energy into the plasma. Figures 6(a)–(c) indicate that the Nagoya III and NSH19 antennas generate similar plasma densities, while the plasma densities obtained with the saddle coil are approximately 30% smaller. More striking is the difference in ion temperatures between these three antennas. The maximum ion temperature achieved with the Boswell saddle coil and Nagoya III antennas is 0.25 eV. The NSH19 antenna ion temperatures...
are larger by at least a factor of two for all the pressure values in the scan and the maximum ion temperature of 0.6 eV is achieved at the lowest pressure in the scan.

The trends in the electron density versus pressure shown in figures 6(d) and (e) for the WSH19 and NSH30 antennas are consistent with the results for the NSH19 antenna. The larger error bars for these data sets are due to uncertainties in the cross-calibration between the Langmuir probe tip used for the NSH30 and WSH19 measurements and for probe tip used for the saddle coil, Nagoya III, and NSH19 measurements. The drop in density and increase in perpendicular ion temperature at low pressure for all five antennas was observed in previous measurements [13]. The leveling off in density above a threshold pressure is also consistent with previous measurements in HELIX [13] and other helicon sources [32].

Noticeably different are the ion temperatures for the WSH19 antenna. Both narrow strap helical antennas (the 19 cm and the 30 cm), yield similar ion temperatures. However, the WSH19 antenna ion temperatures are lower at all pressures. It is important to note that at the lowest pressure value of 2.2 mTorr, the visual structure of the plasma changed considerably. A hollow, diffuse core replaced the bright blue core that is indicative of the helicon mode. Therefore, it is unlikely that the source remained in the helicon mode.

For the same magnetic field of 800 G, rf frequency of 9 MHz, and a pressure of 3.6 mTorr, the downstream plasma density and perpendicular ion temperature versus rf power are shown in figure 7. For all five antennas, both the density and perpendicular ion temperature increase with increasing rf power. Again, of the three antennas with the same inductance, the NSH19 antenna yields the highest densities and ion temperatures. Of the three different m = +1 antennas, the two antennas with narrow straps yield similar densities and ion temperatures.

For the same rf frequency of 9 MHz, pressure of 3.6 mTorr, and an rf power of 500 W, the perpendicular ion temperature and downstream plasma density versus the magnetic field strength in the source are shown in figure 8. Of the three antennas with the same inductance, the NSH19 antenna still yields the highest densities and ion temperatures. Although the densities for the Nagoya III antenna are 20–30% lower than for the NSH19 antenna, the ion temperatures are 70% lower. The magnetic field scaling and rf power scaling results indicate that the plasma densities achieved with the NSH19 antenna at 500 W can be attained with the Nagoya III antenna operating at 750 W, but with perpendicular ion temperatures a factor of two lower. Therefore, if low ion temperatures are desired, supplying more power to antennas that couple less efficiently to the plasma may provide the best solution.

In contrast to reports from other groups of peaks in plasma density at particular rf frequencies [22–24], previous measurements in HELIX using a Nagoya III antenna showed clear evidence of monotonically increasing plasma density with decreasing rf frequency [25]. To re-examine the rf frequency dependence of the plasma density in HELIX, rf frequency scans such as the one shown in figure 9 were performed. For these experiments, the magnetic field was 800 G, the rf power was 500 W and the pressure was raised to 6 mTorr. Below 4–5 mTorr, the frequency dependence of density on inverse rf frequency evident in figure 9 was not observed.

### 4. Frequency and magnetic field experiments for four antennas

That the ion temperature scales so strongly with magnetic field while the plasma density reaches a plateau above which there is little change (see figure 8) suggests the mechanism responsible for ion heating is distinct from the process of plasma production. In fact, it is only during the rf power scans when the overall energy coupled into the plasma increases that both the plasma density and ion temperature increase simultaneously (see figure 7). Given the preliminary frequency-dependent density measurements shown in figure 9 and the strong dependence of ion temperature on magnetic field, additional experiments were conducted to carefully examine both the effects of magnetic field and rf frequency on the plasma density, electron temperature and ion temperature in
the combined HELIX source plus expansion chamber system. For these experiments, the cusp magnetic field configuration (figure 2) was used in the source. In the cusp configuration, a significant increase (factor of ten) in the downstream plasma density was realized. All measurements were performed at an rf power of 750 W and a neutral pressure of 3.6 mTorr. The higher rf power was chosen in order to maintain the discharge in the helicon mode over as wide a parameter range as possible.

The ion temperature in the source, downstream plasma density, and downstream electron temperature versus source magnetic field and rf frequency are shown in figure 10 for four antennas: the wide strap 19 cm \( m = +1 \) (WSH19), the narrow strap 19 cm \( m = \mp 1 \) (NSH19), the 30 cm \( m = +1 \) (NSH30), and the Nagoya III. The electron temperature is determined from the slope of the Langmuir probe \( I-V \) characteristic in the electron retardation region. There are a number of well-known difficulties associated with this method [33], particularly in plasmas containing non-Maxwellian particle distributions. However, similar electron temperature measurements in previous experiments with this Langmuir probe were consistent with electron temperatures derived from measurements of the phase velocity of electrostatic ion cyclotron waves in the source [34].

Looking at the first column of figure 10, it is clear that the maximum ion temperature for all four antennas occurs in the region of smallest rf frequency and largest magnetic field strength. Here again, the Nagoya III antenna consistently yields the smallest ion temperatures (by a factor of two or more). Evident in the four ion temperature plots is a boundary between higher and lower ion temperatures that follows a line of increasing frequency for increasing magnetic field. This trend is clearest in the NSH19 antenna measurements (second plot in first column of figure 10). Not only does the NSH19 antenna generate the highest ion temperatures, the rate of decrease in the ion temperature as the rf frequency rises or the magnetic field decreases is greater than for the other antennas, i.e. \( dT_i/df \) and \( dT_i/dB \) is largest.

The contours of constant ion temperature in the NSH19 antenna data run parallel to the curve along which the rf frequency equals the lower hybrid frequency, \( \omega_{LH} \), in the
Figure 8. Downstream plasma density (full circles) and perpendicular ion temperature in the source (open squares) versus magnetic field strength: (a) 19 cm Boswell saddle-coil antenna; (b) 19 cm Nagoya III antenna; (c) NSH19 antenna; (d) WSH19 antenna; and (e) NSH30 antenna.

The downstream density measurements (second column of figure 10) for all four antennas indicate that the shorter $m = +1$ antennas (NSH19 and WSH19) yield higher densities than the NSH30 antenna. Given that the measured parallel wavenumbers of the helicon wave in helicon sources are on the order of $\pi / L_A$, where $L_A$ is the antenna length of a half-wavelength antenna [7, 8], this result is consistent with the dispersion relationship for small aspect ratio helicon sources ($L \gg a$, where $L$ is the length of the system and $a$ is the plasma radius) [25]

$$n(r) = \frac{B_0 k_{||}}{\omega \mu_0 e a(r)}$$

where $\alpha(r)^2 = k_{\perp}^2 + k_{\parallel}^2$, $k_{\parallel}$ and $k_{\perp}$ are the parallel and perpendicular wavenumbers respectively, $k_{\perp} \gg k_{\parallel}$ because of the aspect ratio of the source and the length of the antenna, $B_0$ is the source magnetic field, $\omega$ is the driving frequency, $\mu_0$ is the free space permeability, $e$ is the electron charge and $n$ is the electron density. According to equation (4), antennas that launch shorter wavelength waves along the field (larger $k_{\perp}$) should match at higher plasma densities.

Figure 9. Downstream plasma density versus inverse rf frequency for the NSH19 antenna and a neutral pressure of 6 mTorr.

Note also that the Nagoya III yields the smallest densities, by a factor of two, of any of the four antennas. In fact, at low magnetic fields or high rf frequencies, the Nagoya III plasmas drop out of the helicon mode entirely. The dramatic drop in density for these parameters corresponds to a sharp rise in the electron temperature (see the third column of figure 10 for the Nagoya III electron temperature measurements). The edge of the region for which the Nagoya III plasmas are in the helicon mode also parallels the lower hybrid frequency curve.

Most striking in the electron density measurements is the clear peak in density for rf frequencies just above the lower hybrid frequency. Looking again at the data for the NSH19 antenna, the correlation between lower hybrid frequency and peak density production is unmistakable. The correlation does not, however, extend to the highest frequencies studied. This suggests that other experiments operating at frequencies above 13–14 MHz, will not see enhanced density production unless they operate at much higher magnetic fields than is typical. This is consistent with our previous observations of a higher power threshold for the helicon mode at higher rf frequencies [25].

indicate that at 800 G, there is only a modest variation in ion temperature with rf frequency. It is only at the greater magnetic field strengths that the correlation between ion heating and rf frequency is evident.

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The correlation between ion temperature and rf frequency was overlooked because those rf frequency experiments were performed at a magnetic field of 800 G. The ion temperature data shown in figure 10 indicate that at 800 G, there is only a modest variation in ion temperature with rf frequency. It is only at the greater magnetic field strengths that the correlation between ion heating and rf frequency is evident.

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$\omega_H = \sqrt{\omega_{ce}(r) \omega_{ci}(r)}$ for these plasma parameters, where $\omega_{ce}$ and $\omega_{ci}$ are the electron and ion cyclotron frequencies respectively. Because the bulk of the ion heating occurs for rf frequencies close to or slightly below the lower hybrid frequency and the constant temperature contours parallel the lower hybrid frequency curve, lower hybrid waves or the decay of lower hybrid waves into other waves may be responsible for the ion heating in helicon sources. It should be noted that the contours of constant ion temperature also run parallel to the curve for ion cyclotron frequency but the rf frequencies used here are hundreds of times greater than the ion cyclotron frequency.
Correlations between density production and the lower hybrid frequency have been observed since the beginning of helicon source research \[6, 22, 24, 35\]. The role of lower hybrid resonances in helicon sources has received some emphasis in recent years as resonance absorption of rf power at the lower hybrid frequency has been suggested as a possible mechanism for the efficient operation of helicon sources \[24, 36\]. The helicon wave has no resonance for typical helicon source parameters and therefore collisional damping or more exotic collisionless wave damping mechanisms are often invoked to explain the rf power absorption in helicon plasmas. However, the bounded electron cyclotron wave that appears at frequencies above the lower hybrid frequency in the cold plasma dispersion relationship when finite electron mass is included (often referred to as the 'slow' or 'Trivelpiece-Gould' wave in the helicon source literature) is believed to exist as an...
provides further evidence that collisional equilibration with the hotter electrons is not responsible for the observed ion temperatures. For the most part, the maximum electron temperatures are observed at the highest rf frequencies and the smallest magnetic fields.

Figure 11 shows the same data as figure 10, but with an x-axis corresponding to the ratio of the lower hybrid frequency to the rf frequency. The colour bars of each plot in figure 11 have also been adjusted to provide maximum contrast. A dotted white line running through the downstream density plots marks where the rf frequency equals the lower hybrid edge mode in helicon sources [37] and does have a resonance at the lower hybrid frequency [24]. These observations support the conclusion that, although the helicon wave may play some role in density production in helicon sources, the lower hybrid resonance dominates the rf power absorption in helicon plasmas operating at low rf frequencies.

Except for the 30 cm m = +1 antenna, none of the electron temperature measurements shows any significant increase in the region of highest ion temperatures. That neither the electron density nor the electron temperature is enhanced at the same parameters where the ion temperatures are greatest,
As can be seen in the figure, the normalized rf frequency at which the peak electron density occurs increases with increasing magnetic field. The majority of the highest density values lie in the range \(0.5\omega_{LH} < \omega < \omega_{LH}\). The constant ion temperature contours (looking at the NSH19 antenna data) form vertical bars aligned with the dotted white line at \(1.5\omega_{LH}\). Until we can extend the operating range of the source to higher magnetic fields or lower rf frequencies, we cannot say whether the ion temperature continues to increase as frequency ratio increases. The enhanced contrast of the individual plots for the \(m = +1\) antennas also brings out a correlation between electron temperature and electron density that was not obvious in figure 11. Here again, however, there is no evidence of increased electron temperature at the parameters for which the ion temperatures are greatest. On close examination, the trend of increasing electron temperature for a constant relationship between magnetic field strength and rf frequency (the peaks running from the bottom left to upper right of the temperature plots of figure 11) can be seen in figure 10 as patterns of enhanced electron temperature running from the lower right to upper left in the electron temperature plots. This trend is particularly clear in the NSH19 antenna plots in figure 10 and figure 11. At this time, we do not have a physical explanation for this aspect of the electron temperature measurements.

5. Summary

These experiments have demonstrated a clear correlation between the lower hybrid resonance, electron density production and ion temperature in helicon sources. The data also strongly support the conclusion that collisional equilibration with electrons is not responsible for the ion heating observed in helicon sources. Fortunately, the parameters for maximum electron density and maximum ion temperature are distinctly different. By operating a helicon source at frequencies slightly above the lower hybrid frequency, maximum densities can be achieved at moderate ion temperatures. To further reduce the perpendicular ion temperature, the helicon source can be operated at higher frequencies, lower magnetic fields or with an antenna that is less effective at coupling energy into the ions, e.g. a Nagoya III antenna. The penalty will be a reduced plasma density. The data also indicate that narrow strap antennas couple energy into ions and electrons more cleanly, i.e. the regions of peak density production and peak ion heating are well defined and more uniform. We hypothesize that this is due to the narrower spectrum of modes in the radiation pattern of a narrower strap antenna. The coupling of rf energy into a narrower spectrum of modes in the plasma may explain why the NSH19 antenna remains in the helicon mode except for the very highest rf frequencies and lowest magnetic field strengths examined (see the density plot for this antenna in figure 10).

We have not, in this paper, attempted to explain the origin of the ion heating in our helicon source. For many years, experimentalists attempting to heat plasmas have launched waves at frequencies slightly above or below the lower hybrid frequency [38]. Those experiments rely on either direct absorption mechanisms to couple energy into ions or electrons or parametric decay processes to generate lower frequency waves that can directly heat ions [39]. For strong direct damping of lower hybrid waves on ions (electrons), the perpendicular (parallel) wave phase velocity must be comparable to the ion (electron) thermal speed [40]. Near the lower hybrid resonance, the perpendicular wavenumber becomes large. Thus, it is not inconceivable that the rf waves could directly damp on ions in a helicon source near the lower hybrid frequency. Such pictures of ion heating are consistent with our observations of strongly anisotropic ion temperatures (figure 4) in our helicon source [13,41]. For driving frequencies slightly less than the lower hybrid frequency (where the ion heating is strongest), the radial density profile may create a region near the plasma edge where the driving frequency matches the local lower hybrid frequency. In the plasma core, where the density is on the order of \(10^{13} \text{ cm}^{-3}\), the plasma density has little effect on the lower hybrid frequency. If the density near the plasma edge is on the order of \(10^{11} \text{ cm}^{-3}\), the edge lower hybrid frequency is as much as 30% lower than the on-axis lower hybrid frequency. Therefore, the observed enhanced ion heating at frequencies lower than the on-axis lower hybrid frequency may result from off-axis ion heating at the lower hybrid resonance. We have begun to measure the spectrum of electromagnetic fluctuations in the helicon source to determine if lower hybrid waves are being excited or if there is evidence of parametric decay processes that could explain the observed ion heating. Additional experiments are investigating the radial and axial dependence of density and ion temperature. The results of those experiments will be reported in a future paper.

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