Intense on-axis plasma production and associated relaxation oscillations in a large volume helicon source

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A helicon wave mode with a peak downstream density of greater than $10^{18}$ m$^{-3}$ in argon that exhibits bright ArII emission along the axis has been characterized. The experimental conditions are: Ar gas pressure of 1–5 mTorr, external magnetic field of 70–150 G and radio frequency (rf) power input between 2 and 4 kW a 13.56 MHz using a double half-turn antenna into a source of 9 cm inner radius and 50 cm length that opens into a diffusion chamber 45 cm radius and 200 cm length. Radial profiles of the density in the source and downstream show that plasma production is strongly concentrated on axis. B-dot probe measurements indicate that the wave phase velocity in this discharge mode is between 2 and $2.5 \times 10^6$ m/s, which has been shown previously to be the optimum velocity for resonant wave heating of electrons to increase the ionization rate. An interesting property of the high-density mode is that it is unstable on timescales of a few milliseconds and that a relaxation oscillation occurs between the high- and low-density modes. It is believed that this is driven by the depletion of neutrals in the source region due to ionization and momentum exchange with ions leaving the source. © 1999 American Institute of Physics.

I. INTRODUCTION

Helicon wave generated plasmas are well known as high-density, efficient plasma sources.\(^1\)–\(^3\) This is especially true in the low pressure, low magnetic-field regime where most processing plasmas operate.\(^4\),\(^5\) In these systems dramatic jumps in the plasma density are commonly reported as the input rf power is increased,\(^4\),\(^6\),\(^7\) and are interpreted as transitions from capacitive (E-mode) to inductive (H-mode) to wave (W-mode) coupling mechanisms,\(^8\),\(^9\) or transitions between higher radial or axial helicon wave modes.\(^10\),\(^11\) Generally the transition from capacitive to inductive coupling occurs when the perpendicular skin depth for the evanescent antenna magnetic field decreases to a length of the order of the source radius.\(^8\),\(^12\) The transition to helicon wave coupling is commonly associated with the matching of an excited helicon wavelength to the system dimensions or to an antenna length.\(^5\) However, in the present experiment the helicon wavelength is only weakly specified by the system geometry, and the wave amplitude remains large over a broad range of wavelengths as the magnetic field and plasma density are varied. Therefore, we associate the transition to helicon mode with a rapid increase in plasma density and corresponding drop in phase velocity of the helicon wave to about the threshold electron velocity for ionization (namely between 2 and $3 \times 10^7$ m/s). It has been shown previously that this regime corresponds to the optimum condition for ionization via resonant wave-particle interactions.\(^13\)

Previous experiments on the same experimental set up used in this paper\(^8\) have shown that when the experiment was run continuous wave (CW) with 2 kW input power, the argon plasma density downstream peaked at a value of $5 \times 10^{11}$ cm$^{-3}$ at a magnetic field of 50 G (and a corresponding wave phase velocity of $3 \times 10^6$ m/s). For magnetic fields lower and higher than this value the downstream density decreased significantly for the same input power. It was noted however that at magnetic fields above 50 G the density would sporadically jump to a value an order of magnitude higher than the nominal value for a fraction of a second, once or twice a minute. When this happened, a narrow column of bright blue light (ArII) was observed down the axis of the source. It was found that this high-density “blue mode” plasma could be made to occur regularly by increasing the peak rf power level and pulsing the power input. With a pulse length of up to a few tens of milliseconds and a low duty cycle, the blue mode occurred for a few milliseconds at the start of the pulse. By adjusting the antenna matching circuit to minimize the reflected power when the blue mode was operating, it was found that a relaxation oscillation resulted, with the blue mode regularly reoccurring about every five milliseconds.

Transitions between E and H modes, or between H and W modes that are characterized by discrete jumps in density are known to exhibit hysteresis with the input power and other parameters.\(^14\) This is a general indicator that the transitions are caused by unstable, positive feedback processes. When such systems are driven by a restoring force between the two points of stability (for example, between the H-mode and W-mode as in the present case) they become relaxation oscillators. Here, it is proposed that a relaxation oscillation is being driven by the depletion of neutrals in the source, caused by ionization and the momentum transfer from ions leaving the source during the high density mode. This effect

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has been demonstrated in a global numerical model of the system, presented in another paper.\textsuperscript{15}

II. EXPERIMENT SETUP

The experimental setup for WOMBAT (Waves On Magnetized Beams And Turbulence) consists of a glass source tube 50 cm long and 18 cm inner diameter, attached at one end to a large volume stainless steel diffusion chamber 200 cm long and 90 cm in diameter. As shown in Fig. 1, the other end of the source is terminated by a grounded stainless steel endplate through which various probes can be inserted. A dc axial magnetic field ($B_0$) is maintained by a set of external solenoids surrounding the source and internal solenoids in the diffusion chamber. These coils provide a direct current (dc) magnetic field of up to 150 G in the source. Generally, the magnetic field in the diffusion chamber is set to half the value in the source to ensure the field decreases monotonically from the source to the diffusion chamber.

In this experiment a base pressure of 10\textsuperscript{-6} Torr is maintained by a turbo pump (with a pumping speed of 330 L/s) located at the end of the diffusion chamber opposite the source. An operating Argon gas pressure from 1–5 milliTorr measured by a capacitance manometer in the diffusion chamber is set by adjusting the flow rate (where 3 milliTorr corresponds to a flow rate of 20 sccm). The entry for the gas feed line is located at a side port in the diffusion chamber roughly 50 cm axially from the turbo pump end.

Up to 4 kW radio frequency (rf) power is provided at 13.56 MHz, via a $\pi$ matching network to a double half-turn antenna axially aligned around the source, 7 cm from the end plate. The power is pulsed at a 10\% duty cycle, with individual rf pulses between 1 and 40 ms in length. Forward and reflected power measurements are made as a function of time by a directional coupler between the matching network and the rf generator, and the antenna current is monitored by a calibrated current transformer.

III. DIAGNOSTICS

A. Plasma density measurements: Langmuir probe

Two langmuir probes, an axially inserted dog-leg probe in the source and a radial probe in the diffusion chamber were used in this experiment. The radial langmuir probe has a cylindrical tungsten probe tip 3 mm in length and 0.5 mm in radius. The probe wire fits into a small bore ceramic tube with an exposed length of 0.15 m, the end of which fits into a 6 mm diameter grounded stainless steel tube that is inserted through a vacuum seal at the diffusion chamber wall. The probe is inserted horizontally across a diameter at an axial position of 1.05 m from the source endplate, and has a radial length of travel from 0.3 m on one side of the axis to 0.18 m on the other side. The Langmuir probe used in the source during this experiment is a “dog leg” design with a radial arm 8 cm long, and an axial shaft 60 cm long inserted into the source endplate through a port at a radius of 8 cm (farthest away from the high voltage side of the antenna) to enable measurements axially along the center of the source and along the arc defined by rotating the axial probe shaft. The probe consists of a flat stainless steel circular disk of 0.5 cm diameter oriented perpendicular to the machine axis and facing the source end of the experiment. The probe disk is mounted onto a small ceramic tube of the same outer diameter as the disk and about 1 cm long, so that the plasma only makes contact with one face of the disk. The other side of the ceramic tube is connected at right angles to the radial arm. This arrangement minimizes any perturbing effect of the probe shaft on measurements by removing the probe disk as far a practicable (1 cm) from the radial arm of the probe shaft.

These probes are used in ion saturation (biased at $\approx$80 V) to give measurements of the plasma density, where the density ($n_e$) is estimated from the ion flux to the probe surface according to

$$I_{\text{sat}} = 0.6 A n_e e v_B.$$  \hspace{1cm} (1)

Here $A$ is the probe area, $e$ the charge of an electron, and $v_B$ is the ion Bohm velocity given by

$$v_B = \sqrt{\frac{kT_i}{m_i}},$$  \hspace{1cm} (2)

where $kT_i$ is the electron temperature in eV and $m_i$ is the ion mass. Previous measurements in WOMBAT indicate an electron temperature of 3 eV, yielding a Bohm velocity of $2.8 \times 10^5$ ms\textsuperscript{-1}. A 35 GHz microwave interferometer that makes line integrated density measurements across a diameter in the source has been used to calibrate the ion saturation measurements from the source langmuir probe and shows good agreement when the radial density profile is taken into account.
B. Wave magnetic-field measurements: The B-dot probe

Radio frequency (rf) magnetic fields (b) are measured in situ in this experiment using a small inductive loop, in which rf changes in the magnetic-field component normal to the plane of the loop induce an rf voltage across the loop (hence the name b-dot, since the time derivative of b is measured). The probe consists of a pair of 0.5 cm diameter, 5 turn windings of thin, insulated copper wire separated by 2 cm on the end of a 70 cm long fiber glass tube, with the normal of the loops oriented in the axial direction, hence this probe measures the z-component of b at two closely spaced positions. This tube is inserted axially into the source from the endplate at a radius of 4 cm, 90 degrees from the high voltage side of the antenna (the top), inside a long glass tube that is closed at the end. The glass tube separates the probe from the plasma, however, the tube does not exclude time varying magnetic fields, allowing their measurement. The glass tube has a small perturbing effect on the plasma, simply because it presents an additional loss surface to the plasma species. Generally it was found that roughly a 10% increase in input power was required to achieve the same density levels with the glass tube inserted. However, moving the b-dot probe inside the glass tube does not perturb the plasma. Therefore, the perturbation of the glass tube on the plasma was made a constant of the experiment by leaving the tube inside the source for all measurements. The signals from the b-dot probes are each carried by a twisted pair inside the fibreglass tube. Each signal includes the differential signal from magnetic induction across the probe coil as well as a common signal with respect to ground caused by electrostatic pickup along the probe wires. These signals are separated with a rejection ratio of 100:1 using a hybrid combiner circuit.

The magnetic-field (differential) signal from the hybrid combiner is input to an rf amplitude and phase detector, with the phase referenced to the antenna current signal. Generally a smooth increase in phase and a monotonically decreasing amplitude as the probe is inserted further into the source (away from the antenna) indicate that the rf magnetic field propagates away from the antenna as a wave with a finite phase velocity. The wave phase velocity is given by the rate of change of phase \( \phi \) with axial position z according to

\[
v_{\phi} = \omega \left( \frac{d \phi}{dz} \right)^{-1}.
\]

Reflections from the endplate produce standing waves between the antenna and the endplate, which are characterized by abrupt changes in phase of \( \pm \pi \) and spatial modulations in the wave amplitude corresponding to half a wavelength.

In this experiment the amplitude and phase of the axial magnetic-field component was recorded as a function of time for various magnetic-field settings. Using a b-dot probe with a single pickup coil, the amplitude and phase variation as a function of time were mapped at 2 cm intervals in the axial direction, with each measurement taken from a different shot. This data showed that, when the high-density plasma mode was operating, large amplitude travelling waves propagated at least 40 cm downstream from the antenna. The differential of the phase along z could be calculated from this data and the phase velocity obtained, however, this measurement is susceptible to errors in the probe position (which was moved manually) and small variations in the plasma from shot to shot. Using a b-dot probe with two pick up coils alleviates this problem because the differential can be calculated from a single shot, and the distance between the coils is fixed.

The \( b_z \) wave phase velocity was therefore measured using this probe for magnetic fields between 80 and 140 G, at an axial position 16 cm from the endplate (the mean position between the two coils). A two point measurement such as this is, however, susceptible to error in estimating the phase velocity if any wave reflections in the axial direction exist, the resulting standing wave component would be misinterpreted as a dramatic increase in the phase velocity.

IV. RESULTS AND DISCUSSION

Section IV A gives an account of the initial observations of the high-density mode and the relaxation oscillation behavior. The following two sections report the characterization of the high- and low-density modes and diagnosis of the plasma production mechanisms through wave field measurements (Sec. IV B), and plasma density measurements (Sec. IV C). Section IV D details an investigation of the relaxation oscillation behavior by carrying out parameter scans in rf power input, pressure, and magnetic field, in order to identify the cause of the instability and the driving parameter that gives rise to the oscillation.

A. High density plasma operation

During CW operation at an input power of 2 kW, an argon filling pressure of 3 milliTorr and magnetic-field settings between 70 and 150 G, a high-density helicon plasma mode was observed to occur sporadically for a fraction of a second once or twice a minute. The mode was distinguished by the sudden appearance of a bright blue column of emission (identified as Ar II emission using a monochrometer) down the axis of the source with a radial width of about a centimeter.

It was initially thought that the mode should become stable under the appropriate matching conditions (that is, when the reflected power while this mode operated was minimized). However, searching for these matching conditions meant moving away from the already established match for the pre-existing cw plasma. It is easy to show that, generally, matching to a higher-density mode requires the load capacitance in a \( \pi \) matching circuit to decrease. In this case it was found that the load capacitance required was beyond the range of the variable capacitance (the parallel connection of a fixed 1200 pF capacitor and a 10–1000 pF variable vacuum capacitor) used in the matching network to achieve a match for the nominal (lower density) conditions, therefore, moving from one plasma mode to the other by changing the matching conditions would prove to be difficult. The range of the load capacitance in the matching circuit was lowered to allow matching to the high-density mode by replacing the
fixed 1200 pF capacitor with a 600 pF capacitor.

In order to avoid the risk of causing damage to the rf generator when searching for a match to the high-density mode (with the range of the load capacitance appropriately adjusted) the rf input power was pulsed with a low duty cycle of 10%. The pulse length was chosen to be 5 ms to allow ample time for the plasma to come to equilibrium within each pulse. It was expected that once a good match was found, the pulse length could be extended indefinitely.

When pulsing the plasma, it was found that the high-density mode could be made to occur consistently during the first 3 to 4 milliseconds of the pulse, however, after this initial period the plasma density would quickly decay by about a factor of ten. Matching to the high-density part of the pulse slightly decreased the duration of the mode, and increased the density. As the high-density plasma decayed the matching became poor, with about half the input power reflected.

It was found that as the pulse length was increased, the high-density mode could be made to reoccur after about 3–6 milliseconds by adjusting the matching. Again the mode would last for only a few additional milliseconds, however, further increases in the pulse length showed that an oscillation between the high- and low-density modes would continue indefinitely. The oscillations were found to be regular from pulse to pulse to within a few hundred microseconds, enabling the time evolution of the plasma parameters during a pulse to be recorded using a digital oscilloscope triggered by the pulse generator. Typical examples of the time evolution of the forward and reflected power, antenna current and plasma density in the source (from the Langmuir probe at z = 20 cm along the axis) are shown in Fig. 2.

**B. Helicon wave structure and dispersion**

Measurements of the rf axial magnetic field ($B_z$) were made as a function of time during a series of rf pulses (for a magnetic field of 100 G, and pressure of 3 mTorr) at 2 cm intervals in the axial direction along the length of the source, at a radius of 4 cm. The amplitude and phase as a function of axial position and time are shown as filled contour plots in Figs. 3(a) and 3(b), respectively, with Fig. 3(c) giving individual examples of the phase variation along z during the high density mode (solid line) and subsequent low-density mode (dashed line).

The high- and low-density modes are easily distinguishable from the amplitude and phase variations shown in these diagrams. In Fig. 3(b), the high-density mode, which occurs over the first 4.5 ms, is clearly characterized by a smooth increase in the wave phase with position (ignoring the abrupt

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**FIG. 2. Time evolution of plasma parameters during a pulse. The source magnetic field is 140 G, Argon pressure is 3 mTorr. (a) Forward power and reflected power; (b) Antenna current; (c) Plasma density.**

**FIG. 3. Plots showing the spatio-temporal evolution of $b_z$ wave parameters measured using the $b$-dot probe during the initial occurrence of the blue mode. (a) Greyscales of $b$-dot amplitude; (b) Greyscales of $b$-dot phase with respect to antenna current; (c) Wave phase verses z at t = 1 ms (high-density mode) and t = 6 ms (low-density mode).**
phase changes of $2\pi$ every wavelength) indicating the existence of traveling helicon waves with a definite phase velocity. The wavelength clearly increases with time during the high-density mode, and increases very rapidly as the transition to the low-density mode is approached. Figure 3(a) shows that the wave amplitude during the high-density mode has a sharp peak at the antenna position, and another maximum at $z = 25$ cm that attenuates as $z$ is further increased. The low-density mode, occurring from about 4.5–9 ms, is characterized in Fig. 3(b) by two flat regions of phase separated by an abrupt change of $\pi$ radians, indicating that a standing wave field exists, and a single peak in amplitude occurring at $z = 10$ cm in Fig. 3(a) (in front of the antenna).

The measured phase delay between a pair of b-dot probes axially separated by 2 cm was used to estimate the local wave phase velocity as a function of time according to Eq. (3) for a range of magnetic-field settings between 80 and 140 G in the source, at constant axial position of $z = 16$ cm. Three examples of the results are shown in Fig. 4 [triangle data points, for: (a) 80, (b) 110, and (c) 140 G]. The peak density on axis was also measured using the Langmuir probe as a function of time for each case, and was used to estimate the phase velocity expected for helicon waves according to the simple plane wave dispersion relation

$$v_{\phi} = \left( \frac{\omega B_0}{\mu_0 n_e} \right)^{1/2},$$

where $\mu_0$ is the permeability of free space, and $n_e$ is the average density (estimated as half the measured peak density).

The phase velocity measurements show quite good agreement with the above dispersion relation while in the high-density mode, however, the measurements clearly do not agree during the low-density mode. The disagreement is an artifact of the two point measurement of phase that is used to give the phase velocity, since this technique is susceptible to misinterpretation when wave interference is significant, such as is the case during the low-density mode. The phase variation in Fig. 3(c) indicates a wavelength of about 40 cm during the low-density mode, which corresponds to a phase velocity of about $5.5 \times 10^6$ m/s, which is roughly consistent with the dispersion relation. Another erroneous feature in these plots is the apparent misalignment in time of the data and the theory in some cases. This misalignment is caused by small changes in the observed oscillation period (in the order of 100 $\mu$s) from pulse to pulse. Unfortunately the limited number of data acquisition channels prevented the phase and the density measurements from being made simultaneously.

C. Axial plasma production and electron heating

Spatial variations of the density were mapped as a function of time using the "dog-leg" Langmuir probe in the source, (for a magnetic field of 100 G and pressure of 3 mTorr), by setting the probe position and taking a plasma pulse to obtain the time evolution at that position. The filled contour plots in Figs. 5(a)–5(d) show the distribution of density in the source at times of 0.05, 0.1, 0.2, and 0.4 ms after
the beginning of the pulse, during which time the high-density mode is initiated. The radial Langmuir probe in the diffusion chamber \((z = 1.05 \text{ m})\) was used to take profiles of the plasma density at various times (from 0.2 to 4.3 ms) during the high- and low-density phases of the oscillation, as shown in Figs. 6(a) and 6(b). A box-car integrator (with a gate width of 100 \(\mu\text{s}\)) was used to specify the time during each pulse of the measurement. Figure 6(a) shows the initial 2.0 ms of pulse at intervals of 0.2 and 0.3 ms during which time the plasma density is increasing, and Fig. 6(b) shows profiles of the remainder of the pulse during which time the plasma density is generally decreasing.

A number of features are notable in these plots. Figure 5(a), taken at \(t = 0.05 \text{ ms}\), shows that the density is highest (about \(3 \times 10^{17} \text{ m}^{-3}\)) near the edge of the source near the antenna (positioned at \(z = 7 \text{ cm}\)) and has a local minimum in the center (\(1 \times 10^{17} \text{ m}^{-3}\), at \(z = 25 \text{ cm}\)). Profiles in WOMBAT in this density range have been associated with inductive coupling, where the higher density at the edges is a result of heated electrons that are energized by the antenna near field and travel along magnetic-field lines to preferentially increase the ionization rate in this region. Figure 5(b), taken at \(t = 0.1 \text{ ms}\), shows the onset of plasma production in the center of the source, indicating a transition in the coupling mechanism from the edge heating mechanism of Fig. 5(a). The peak density in this figure is about \(2 \times 10^{18} \text{ m}^{-3}\) occurring on the axis under the antenna. Figures 5(c) and 5(d), taken at \(t = 0.2\) and 0.4 ms, respectively, show a very strongly peaked plasma on axis that is expanding downstream from the source. The location of the maximum density is also seen to move downstream from the antenna, occurring at \(z = 15 \text{ cm}\) and \(z = 20 \text{ cm}\) in Figs. 5(c) and 5(d), respectively (about \(5 \times 10^{18} \text{ m}^{-3}\) in both cases). These measurements and the coinciding measurements of large amplitude helicon waves downstream from the antenna are characteristic features of a helicon wave coupled plasma, or ‘W-mode’.

Figure 5(c) shows that as the distance from the antenna increases from about \(z = 40\) to 60 cm, the central density peak becomes more strongly localized along the axis (although the radial maximum decreases). This is a typical feature of the density distribution in the source during the early stage of the discharge that occurs further downstream as the time is increased above 0.1 ms. The radial profiles in Fig. 6(a) taken at \(z = 1.05 \text{ m}\) show similar behavior, namely that the density initially begins to increase as a localized peak on axis, the radial width of the peak (i.e., the full width-half maximum) increasing as the central maximum increases. While it is obvious from these figures that the high-density mode is the result of on-axis ionization in the source, it less clear whether the region of ionization along the axis extends downstream into the diffusion chamber, or whether it is confined to the source near the antenna. The localized central peaks described above in Figs. 5(c) and 6(a) support the hypothesis that local ionization is occurring on axis to produce the peak which then diffuses radially. Figure 6(a) is consistent with the evolution of the density profile towards a \(n = n_0 \log(a/r)\) steady state that is expected for an axially constant line source in a cylindrical geometry. However, the finite speed with which the high-density plasma extends through the source, (between 1 and \(2 \times 10^3 \text{ m/s}\), which roughly corresponds to the ion sound speed) indicates that axial diffusion, at least within the source, is also significant. The most consistent interpretation of this data is that the plasma is initially created by local ionization along the axis throughout the source and well into the diffusion chamber, however, the ionization rate is peaked between 10 and 30 cm downstream from the antenna, and decreases further downstream. Therefore, at locations further downstream in the source, the central plasma density initially increases due to local ionization, however, axial diffusion from higher densities generated closer to the antenna also becomes significant as time progresses.

Figure 6(c) shows the variation in the downstream radial density profile during the latter half of the high-density mode, and the transition to the low-density mode. This is indicated by the change in profile from the centrally peaked profile characteristic of the high-density helicon wave mode to the slightly hollow profile with weak maxima at radial positions that map along field lines to the periphery of the source. This profile, coinciding with the appearance of highly localized standing wave fields near the antenna, is characteristic of an inductively coupled plasma, or “H-mode” discharge in WOMBAT.\(^5\)

The high ionization rate (indicated by the density profile measurements) and the observed excitation of ArII along the axis between 10 and 20 cm downstream from the antenna implies that a large amount of power is being deposited to heat electrons within this region. The concurrent measurement of large amplitude helicon waves that attenuate over this region strongly implies that the waves are providing this power to the electrons. It is difficult, however, to explain why the plasma production and ArII excitation are so
strongly localized on axis, especially in view of detailed wave field measurements that were made previously on WOMBAT under similar conditions (although the high-density mode reported here was not observed) that showed an \( m = \pm 1 \) mode structure (where \( m \) is the azimuthal mode number).\(^9\) A possible explanation for a highly peaked axial profile is that the helicon wave fields are self-focusing as they propagate through the source.\(^17\) This is caused by the concentration of radial wave field profiles, and therefore power deposition, towards the axis as the radial density profile narrows.\(^18\) If this occurs and the power deposition causes an increase in the ionization rate, then a positive feedback will ensue between an increasingly sharp plasma density peak and the deposited power. It has been reported in a highly magnetized discharge that two and even four closely spaced, highly concentrated plasma columns with strong peaks in ArII emission occur off axis (occurring at \( r = 2 \) cm in a source of inner radius \( a = 5 \) cm) due to localized power deposition from \( m = \pm 1 \) and \( \pm 2 \) modes, respectively.\(^19\) The radial positions of the peaks in emission (at \( r/a = 0.4 \)) corresponded to locations where, according to theory, power deposition from the helicon wave-field was maximum. These experiments were carried out with an axial magnetic field of 700 G. The much higher cross-field diffusion of ions because of the lower axial magnetic field in the present experiment may prevent two closely spaced off axis peaks in the power deposition from being resolved in our experiment.

The mechanism by which electrons are accelerated is considered to be the collisionless electron trapping, or Landau damping interaction with the electrostatic component of the helicon wave fields, which is a phase velocity dependent effect. This is characterized by the acceleration of electrons by the wave field from velocities within a specific velocity range below the phase velocity to velocities greater than the phase velocity, producing a nonthermal “bump” in the electron distribution function above the phase velocity. The effect of this type of resonant acceleration of electrons on the excitation of ArII emission has been directly measured previously by Ellingboe et al.\(^20\) The effect on the ionization rate has also been studied previously,\(^13\) and it has been found that the greatest effect on the ionization rate occurs when the phase velocity approaches the threshold velocity for ionization, \( v_{zc} = 2.35 \times 10^{6} \text{ m/s} \). The measured axial phase velocities shown in Fig. 4 all show that the phase velocity during the high-density mode is between 2 and \( 2.5 \times 10^{6} \text{ m/s} \), very close to the optimum value.

D. Relaxation oscillations

The variation of the plasma density in Fig. 2(c) shows a very rapid jump in density followed by a slow decrease, then a rapid fall in density followed by a slow increase, and can be identified as a relaxation oscillation.\(^21\) In general such oscillations are characterized by a slowly varying quantity that drives the system between two quasi-stable equilibrium states which are separated in phase space by a region of “negative impedance.” The time scale for the oscillation strongly suggests that the instability is caused by the depletion of the neutral species in the source, and the most likely source of negative impedance is the change in the power coupling mechanism from \( H \)-mode to \( W \)-mode. Direct experimental verification of this hypothesis would require localized, time resolved measurements of the neutral density \( (n_g) \) to be made \textit{in situ} within the source, which was not possible given the equipment at hand, however, behaviors consistent with this hypothesis were found by making parameter scans in the pressure, rf power input, and magnetic field. Also, a global dynamical model has been developed that includes neutral depletion, and has been found to reproduce the experimental results.\(^15\) Below we briefly summarize the main points of this model. Abrupt transitions from \( H \)-mode to \( W \)-mode have been reported in the literature, and are easily observed on WOMBAT as a dramatic increase in density (for magnetic fields above 50 G). This indicates that a positive feedback occurs between the plasma density and the ionization rate to cause the transition once a threshold density has been reached in the \( H \)-mode \( (n_H) \). The results of the last section indicate that the most important effect on the ionization rate coefficient \( K \) in \( W \)-mode is the acceleration of electrons with velocities near the wave phase velocity \( (v_{\phi}) \) by electron trapping. This mechanism causes a strong peak in \( K \) when \( v_{\phi} \) approaches the threshold velocity for ionization \( (v_{zc}) \), which translates to a peak in \( K \) with density \( (n_i = n_{go}) \) for a given magnetic field setting, according to the dispersion relation in Eq. (4), to give

\[
\frac{n_w}{\mu_0 e v_{zc}^2} = \frac{\omega B}{\mu_0 e v_{zc}^2}.
\]

The low-density side of this peak (i.e., \( n_H < n_i < n_w \)) is a region where an increase in \( n_i \) causes an increase in \( K \), and hence, leads to a positive feedback. The variation of \( K \) within this range of density constitutes the region of negative impedance required to support the relaxation oscillation.

The neutral density is depleted by ionization and the collisional transfer of momentum from faster moving ions directed out of the source during the \( W \)-mode discharge. This drives a transition to \( H \)-mode by reducing the ionization rate, and thereby reducing \( n_i \) below \( n_w \). The neutral density in the diffusion chamber \( (n_{go}) \) is unaffected by changes in \( n_g \) in the source because it has a volume 80 times that of the source, therefore, a large difference in neutral density builds up between the source and the diffusion chamber as \( n_g \) in the source decreases. During \( H \)-mode, the ionization rate and ion density are much lower, therefore, the neutral depletion rate in the source is much less than the refilling rate from the diffusion chamber from the gradient in \( n_g \). The gradual increase in ionization rate as \( n_g \) increases in the source causes a corresponding increase in \( n_i \) until it exceeds \( n_H \) and a transition back to \( W \)-mode occurs, and the whole process repeats.

The time scales for the neutral depletion and refilling processes in the source are roughly estimated by some simple calculations. Figure 5 shows that the central density in the source increases to about \( 5 \times 10^{18} \text{ m}^{-3} \) in about 0.5 ms. Assuming this density increase is entirely due to local ionization gives an estimate of peak ionization rate \( Q = n_i n_g K \approx 10^{22} \text{ m}^{-3} \text{ s}^{-1} \). The timescale for ionization (alone) to re-
move neutrals from the source (i.e., decrease \( n_g \)) by a factor of \( e^{-1} \) is given by \( \tau_{\text{ion}} = (n_i/k)^{-1} \approx 10 \text{ ms} \) (assuming \( n_g = 10^{20} \text{ m}^{-3} \) initially). The time scale for momentum transfer from ions (alone) to remove neutrals from the source is given by \( \tau_{\text{px}} = (\sigma_{\text{px}} v_x)^{-1} \), where \( \sigma_{\text{px}} = 2.3 \times 10^{-19} \text{ m}^2 \). Assuming the ions leave the source at the Bohm speed gives an estimate of \( \tau_{\text{px}} \) between 1 and 10 ms. The refilling rate of neutrals back into the source depends on the neutral density gradient and is maximum when \( n_g \) in the source is a minimum. Taking a simple molecular flow approximation, the time scale of refilling is given by \( \tau_{\text{refill}} \approx 4L/v_g \), where \( L \) is a length scale in the order of the source length (0.5 m) and \( v_g \) is the neutral thermal speed (300 m/s), which gives an estimate of \( \tau_{\text{refill}} \) between 5 and 10 ms. These order of magnitude estimates are consistent with the observed timescales of the \( H \) and \( W \)-modes in the experiment.

Parameter scans in pressure, rf power input and the magnetic-field setting were carried out to characterize the relaxation oscillation behavior. The pressure was scanned by changing the flow rate of Ar into the diffusion chamber, and was measured using a capacitance manometer (with the rf power off). As variations in the neutral density are expected in the source, this parameter is considered to represent the neutral density in the diffusion chamber \( (n_p) \). The net rf power is shown to vary as a function of time during the pulse in Figs. 2(a) and 2(b), however, in all cases the plasma was well matched during the \( W \)-mode, hence power measurements during this parameter scan represent power input during the \( W \)-mode.

The results from a scan in the rf power input for a given nominal pressure setting and magnetic field (4.5 mTorr and 120 G, respectively) are shown as a filled contour plot in Fig. 7(a), with time as the \( x \) axis, rf power as the \( y \) axis and greylevels representing plasma density. This figure shows that the discharge dynamics can be divided into four categories as the power is varied, which are illustrated in Fig. 7(b). In order of decreasing input power, these are: 1) A stable \( W \)-mode (+); 2) Relaxation oscillations between \( H \)-mode and \( W \)-mode (*) for; 3) A transient \( W \)-mode that makes a transition to a stable \( H \)-mode (○); and 4) a stable \( H \)-mode (△). Figure 7(a) shows that the time spent in the low-density mode decreases as the rf power level is increased. This suggests that the minimum neutral density required to cause a transition to \( W \)-mode decreases with power, causing the time taken to refill the source sufficiently to cause the transition to decrease. This also explains how the transient \( W \)-mode that makes a single transition to a stable \( H \)-mode occurs: Initially the neutral density (and hence the ionization rate) is sufficient to allow a transition to \( W \)-mode, the neutrals are depleted and a transition to \( H \)-mode occurs, however, the (much smaller but still finite) ionization rate in this mode ensures that the neutrals are never refilled sufficiently to cause a transition back to the \( W \)-mode at this power level. As the power is increased the threshold neutral density for the \( H \) to \( W \) transition is lowered until it becomes accessible in \( H \)-mode, resulting in continuous oscillations. The time spent in \( W \)-mode also clearly increases with the rf power. This may indicate that the minimum neutral density required to sustain the \( W \)-mode decreases with the rf power, causing the time spent in \( W \)-mode before the neutrals are sufficiently depleted to lengthen.

The results from a scan in the nominal pressure while holding rf power input and the magnetic field constant are...
shown as a shaded contour plot in Fig. 8, with time as the x axis and pressure as the y axis. The most dominant feature in this figure is the increase in lifetime of the initial W-mode with the pressure setting. This is caused by the simple increase in the initial number of neutrals that need to be removed to cause the transition to H-mode. The lifetime of the H-mode becomes slightly shorter as the pressure setting is increased, and is consistent with an increase in the refilling rate due to an increase in the neutral gradient between the source and diffusion chamber.

Figure 9 shows the domain in the pressure-power parameter space in which each of the above states occur, for a constant magnetic field of 120 G. The domains are segregated by noting the maximum density that occurs for each power and pressure setting after the initial transient behavior has passed (i.e., after about 5 ms), which is shown as filled contours in the plot. The H-mode and the transient W-mode are segregated by noting the maximum density during the initial 5 ms. This figure generally shows that the relaxation oscillation and the continuous W-mode become more accessible as the pressure is increased, which is consistent with the arguments made in the previous paragraphs. It is expected that as the pressure is increased further, collisional effects in the W-mode coupling mechanism should become more important, and the range in power over which the oscillations occur should decrease.

The density was measured by the radial probe downstream from the source as the magnetic field was varied in order to compare with cw measurements taken previously which exhibited a peak in the downstream density at 50 G. This stable peak was attributed to the same ionization mechanism thought responsible for the plasma production in W-mode in this experiment. Measurements of the cw helicon mode (Δ) and the peak to peak variation of the relaxation oscillation (*) are shown in Fig. 10. Relaxation oscillations were not observed for magnetic fields below 80 G. The figure shows that the range of the peak-to-peak variation of the density during the relaxation oscillation decreases smoothly as the magnetic field is decreased, and that a linear relationship can be extrapolated to the peak in the cw density measurements. This is consistent with Eq. (5), which shows that the density at which the ionization rate by electron trapping is optimised should increase linearly with the magnetic field. The reason for the increased stability of the W-mode at lower magnetic fields is also explainable in terms of the coupling mechanism. As the magnetic field decreases, the peak in the ionization rate caused by helicon waves occurs at lower densities [Eq. (5)], where the ionization rate from inductive coupling becomes increasingly significant. Ultimately the peaks in ionization rate from inductive and helicon coupling merge into a single peak, and the region of negative impedance, or instability between the two vanishes.

V. CONCLUSION

The experimental investigation of a transient, high-density helicon plasma reveals behavior characteristic of a relaxation oscillation between the H-mode and the W-mode. Wave magnetic field and plasma density measurements show that the high-density mode is due to increased plasma production along the axis of the source from helicon waves coupling power to electrons, consistent with the wave trapping mechanism. The strongly peaked radial density profile also suggests that the helicon waves may be self focusing, where increased plasma production at locations where the wave amplitude is large tends to concentrate the propagating wave field, causing a positive feedback which sharpens the plasma profile. The driving mechanism responsible for the relaxation oscillation is believed to be the depletion of neutrals in the source by ionization and the momentum transfer from ions leaving the source during the high-density mode. Parameter scans in the power input, magnetic field and the nominal pressure show behavior that is consistent with this hypothesis.

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