RESEARCH ARTICLE
10.1002/2015JA022078

Special Section:
Nature of Turbulence, Dissipation, and Heating in Space Plasmas: From Alfvén Waves to Kinetic Alfvén Waves


Key Points:
- Equatorial ionospheric HF heating experiment is simulated in a large laboratory plasma
- A field-aligned current system is established by heating pulses and advanced by shear Alfvén waves
- Shear Alfvén waves at controllable frequencies can be coherently driven by modulated heating pulses

Correspondence to:
Y. Wang, wangyuhou@gmail.com

Citation:

Received 25 OCT 2015
Accepted 9 DEC 2015
Accepted article online 12 DEC 2015

Abstract
ELF/ULF waves are powerful tools for submarine communication, geophysical mapping, and radiation belt remediation. However, due to their large wavelength (on the order of \(10^2\)–\(10^4\) km or 0.1–10 \(R_E\)) it is difficult to launch them using ground-based antennas. Alternatively, these waves can be generated by modulating the temperature of the ionosphere using ground-based HF transmitters. The paper reports a detailed laboratory study on the generation of shear Alfvén waves by repetitive electron heating. The experiments were conducted on the large plasma device at University of California, Los Angeles. In the experiment, 10 pulses of high-power microwaves (250 kW, 1 \(\mu\)s each) near the plasma frequency modulated at a variable fraction between 0.1 and 1.0 of \(f_{ci}\) are launched transverse to the background field. In addition to bulk electron heating the interaction generates a population of fast electrons in the tail of the distribution function. The field-aligned current carried by the fast electrons acts as an antenna that radiates shear Alfvén waves. It is demonstrated that a shear Alfvén wave at a controllable, arbitrary frequency \((f < f_{ci})\) can be coherently driven by the repetitive microwave pulses. The radiation pattern and power dependence of the virtual antenna are also presented. The experiments provide a novel virtual antenna concept relevant to the equatorial region where the Earth’s magnetic field is horizontal and the field-aligned plasma density gradient is small. The results are important to design of new mobile ionospheric heaters for equatorial and middle latitude locations.

1. Introduction
Electromagnetic extremely low frequency (ELF) and ultralow frequency (ULF) waves, if generated in a controlled manner, are powerful tools for communications with submarines and for underground mapping because of their ability to penetrate deep into seawater or the Earth’s crust. Upward propagating ELF/ULF waves may also have an important application in remediating the hostile environment of the Earth’s radiation belts for satellite infrastructure protection [Streltsov et al., 2005]. These waves are difficult to launch by conventional ground-based antennas due to their enormous free space wavelengths (\(10^2\)–\(10^4\) km or 0.1–10 \(R_E\)). A promising approach is the thermal modulation of the ionosphere at the ELF/ULF frequency to generate an oscillating current that acts like an ELF/ULF antenna [Barr et al., 1985; Shoucri et al., 1985]. Extensive studies of this topic performed using a number of progressively improving ionospheric high frequency (HF) heater facilities scattered around the world (notably European Incoherent Scatter in Tromso, Norway and High Frequency Active Auroral Research Program in Alaska, USA) have yielded strong evidence of the feasibility of this concept [Stubbe et al., 1982; Barr and Stubbe, 1991; Moore et al., 2007; Piddyachiy et al., 2008] and stimulated many novel techniques such as beam painting [Papadopoulos et al., 1990], geometric modulation [Cohen et al., 2008], and ionospheric current drive [Papadopoulos et al., 2011a, 2011b], to name a few. These ionospheric experiments were conducted at high latitudes where the Earth’s magnetic field is predominantly vertical and the plasma density gradient scale length is relatively short. The situation is reversed at low latitude and equatorial geometries where the magnetic field is predominantly horizontal. In the absence of ionospheric heaters at such locations presently, laboratory experiments provide unique proof of principle of theoretical concepts as well as guidance in the design requirements for equatorial and low-latitude heaters [Papadopoulos, 2015].

Laboratory experiments have for a long time complemented active space experiments including ionospheric modifications. Despite decades of success, ionospheric experiments are restricted by uncontrolled ionospheric conditions and limited diagnostics. These studies are usually based on time series measurements taken from a few (and often just one) ground-based stations or passing satellites. It is difficult to study the
physical process involved without measurements of basic quantities such as the current profile driven by the HF heating. Laboratory experiments, on the other hand, can make thorough and detailed measurements by probes in situ, and when carefully scaled, they can offer insights to ionospheric campaigns. The fascinatingly rich phenomena of the interaction between plasmas and high power waves in the plasma frequency range have attracted broad interest, and numerous laboratory experiments have been performed on this subject [Vodopianov et al., 2005; Prater, 2004; Hidaka et al., 2008]. However, very few relate directly to ELF/ULF generation by ionospheric heating modulation, perhaps because of the unusually large plasma size required since in the ionosphere the electromagnetic ELF/ULF waves correspond to the Alfvén mode, with typical wavelengths of several meters in laboratory plasmas (see critical parameters and scaling factors in Table 1).

The Large Plasma Device at University of California, Los Angeles (UCLA) produces an 18 m long, 60 cm diameter magnetized plasma well suited to such experiments. An earlier experiment [Compernolle et al., 2005; Van Compernolle et al., 2006] has observed generation of broadband shear Alfvén waves by a short high-power microwave pulse ($f_{microwave} \approx f_{pe}$). In this paper, we report the controlled excitation of a monochromatic shear Alfvén wave by injecting modulated microwave pulses.

### 2. Experiment

The experiment is performed in the Large Plasma Device (LAPD) at the University of California, Los Angeles [Gekelman et al., 1991]. The device produces a 18 m long, 60 cm diameter plasma column by a pulsed dc (direct current) discharge between a hot BaO-coated cathode and a mesh anode located at a separation of 0.5 m, positioned at one end of the vacuum chamber with (Figure 1). The vacuum chamber is filled with ∼$4 \times 10^{-3}$ Torr of either Helium or Neon gas. A typical discharge has a voltage of $V_{dis} = 40$ V and a current $I_{dis} = 4$ kA and is pulsed for a duration of 10 ms with a 1 Hz repetition rate. The experiment is conducted in the quiescent afterglow plasma after the discharge is switched off.

### Table 1. Comparison of Critical Parameters in the Ionosphere and the LAPD Plasma

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Ionosphere (100–250 km)</th>
<th>LAPD Plasma</th>
<th>Ratios</th>
<th>Ionosphere (100–250 km)</th>
<th>LAPD Plasma</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_e$</td>
<td>$10^{4}$–$10^{6}$ cm$^{-3}$</td>
<td>0.5–$2 \times 10^{12}$ cm$^{-3}$</td>
<td>$f_{pe}/f_{ce}$</td>
<td>1–$10^{3}$</td>
<td>1.6–10</td>
</tr>
<tr>
<td>$f_{pe}$</td>
<td>1–10 MHz</td>
<td>6–14 GHz</td>
<td>$f_{heating}/f_{pe}$</td>
<td>0.1–10</td>
<td>0.6–1.5</td>
</tr>
<tr>
<td>$f_{heating}$</td>
<td>2.75–10 MHz</td>
<td>9 GHz</td>
<td>$f_{modulation}/f_{ci}$</td>
<td>$10^{-4}$–$10^{3}$</td>
<td>0.1–1.2</td>
</tr>
<tr>
<td>$B_0$</td>
<td>1 mG (equator)–0.6 G (L = 6)</td>
<td>0.4–2 kG</td>
<td>$L_{plasma}/\delta_i$</td>
<td>(&gt;1) $10^{3}$–$10^{4}$</td>
<td>(&gt;1) 12–25</td>
</tr>
<tr>
<td>$f_{modulation}$</td>
<td>$10^{-3}$–$10^{6}$ Hz</td>
<td>10–100 kHz</td>
<td>$D_{plasma}/\delta_e$</td>
<td>(&gt;1) $10^{3}$–$10^{4}$</td>
<td>(&gt;1) 80–160</td>
</tr>
<tr>
<td>$n_e/\nabla n_e$</td>
<td>10 km</td>
<td>30 cm</td>
<td>$\lambda_{heating/free}/L_{Yu}$</td>
<td>(&gt;1) 100</td>
<td>(&gt;1) 10</td>
</tr>
</tbody>
</table>

### Figure 1. Schematic of the experimental setup (not shown to scale). High-power microwave pulses are introduced in the radial direction near the middle section of an 18 m long magnetized plasma column. The location of the microwave launcher defines the $z = 0$ position, while $(x, y) = (0, 0)$ denotes the axis of the plasma column. The solenoidal electromagnets around the vacuum chamber that produce the axial background magnetic field are not shown in the figure.
corresponds to the O mode or the X mode in the magnetized plasma. The spatial profiles of microwave signals are rectified intensity in the plasma are measured by a short electric dipole (5 mm each arm) probe. The received intensity |E| pulses, where adjacent pulses are separated by 5 μs.

The polarization of the microwaves can be chosen so their electric axis. They are polarized to (top) O mode or (bottom) X mode. The radial locations where the microwave frequency matches some characteristic frequencies are calculated and marked on the figure, with error bars arising from shot-to-shot variation of the plasma density profile. The average density profiles are shown as purple lines.

Figure 2. Experimental measurements of the microwave intensity |E_{microwave}|² along its propagation direction at z = 0. The microwaves are broadcast from outside the plasma and propagate inward from the negative x axis. They are polarized to (top) O mode or (bottom) X mode. The radial locations where the microwave frequency matches some characteristic frequencies are calculated and marked on the figure, with error bars arising from shot-to-shot variation of the plasma density profile. The average density profiles are shown as purple lines.

The plasma is magnetized by an axial static magnetic field provided by 91 solenoidal electromagnets that encircle the device vacuum chamber over a length of 20.1 m. B₀ in this experiment is typically 400–2000 G. Under these plasma conditions the wavelength of a typical shear Alfvén wave is several meters along the background magnetic field. The large size of the plasma column is necessary to support free propagation of these waves. Moveable probes inserted radially into the device at several different axial locations provide localized diagnostics. The high repeatability of the experiment allows data collection over a set of spatial locations by moving only one probe with a computer-controlled data acquisition system.

High-power microwaves are injected in the plasma from a pyramidal horn antenna located outside the vacuum chamber. A microwave lens focuses the microwaves before they enter the vacuum chamber through a Pyrex window (Figure 1). The microwaves travel radially inward, into a plasma density gradient (Figure 2). The antenna is axially located near the middle of the plasma column (about 10 m away from the cathode). Its axial location is defined as z = 0 in this experiment. The origin of the x and y coordinates is the machine axis. The microwaves are generated by a 9 GHz magnetron with a 250 kW peak power. The magnetron is energized by a high-power modulator. The output microwaves typically take the form of a train of 10 1 μs pulses, where adjacent pulses are separated by 5 μs ≤ Δt_{mod} ≤ 100 μs. Although, strictly speaking, the full sinusoidal modulation of the microwave power is not applicable in this experiment, in this article we define the microwave modulation frequency as f_{mod} = 1/Δt_{mod}.

The polarization of the microwaves can be chosen so their electric field is either in z or in y direction, which corresponds to the O mode or the X mode in the magnetized plasma. The spatial profiles of microwave intensity in the plasma are measured by a short electric dipole (5 mm each arm) probe. The received microwave signals are rectified by a detector diode, which outputs a signal proportional to the microwave intensity |E_{microwave}|². Figure 2 shows measurements along its propagation direction for both polarizations. In this case the background magnetic field is 650 G, uniform across the radial direction. The radial plasma density profiles are measured separately by a Langmuir probe in absence of the microwave pulses and are calibrated using a 65 GHz microwave interferometer. The locations where the microwave frequency matches the critical frequencies associated with O mode and X mode, i.e., ω_{pe} (electron plasma frequency ω_{pe} = (4πne²/m_e)⁴), ω_R (R cutoff frequency ω_R = (ω_{ce} + (4ω_{pe}² + ω_{ce}²)²)²), ω_{uh} (upper hybrid frequency ω_{uh} = (ω_{pe}² + ω_{ce}²)¹/²), and ω_L (L cutoff frequency ω_L = (−ω_{ce} + (4ω_{pe}² + ω_{ce}²)²)²), are calculated using independent measurements of n_e and B₀ and are marked in Figure 2. With both polarizations, the measured microwave intensity profile peaks just before the first encountered cutoff layer (at the matching point of ω_{pe} for O mode and ω_R for X mode), where the wave is reflected. This is consistent with both classical wave theories [Ginzburg, 1970] and previous experimental [Van Compernolle et al., 2005, 2006] and simulation [Tsung et al., 2007] studies with similar setups. The majority of this experiment is conducted using O mode polarization. Unless mentioned otherwise, data presented below are measured with O mode microwave pulses. In the case of X mode, no tunneling to the upper hybrid resonance through the right-hand cutoff has been observed in the experiment, presumably due to the rather gentle plasma density gradient investigated (the ratio between the microwave free space wavelength to the perpendicular plasma density gradient scale length λ_{heating} free /L_{pe} ∼ 10 is similar to that of the ionospheric conditions).
It is also worth noting that due to the gentle density gradient, a small change in plasma density can translate into a large change in the location of microwave power deposition. The shot-to-shot plasma density variation in this experiment is well controlled (within ±5%), resulting in a variation of the matching layer location smaller than 3 cm.

Electron heating due to the energy deposition of the high-power pulses has been observed in this experiment. Figure 3 shows the time evolution of electron temperature measured by a Langmuir probe located at \( z = 64 \text{ cm} \), at the same radial position as the hot spot of the microwave power density. Instead of the classical operation of sweeping the Langmuir probe bias with a sawtooth voltage ramp that is fast enough the plasma does not change during the ramp time, the probe is biased at a constant voltage throughout 10 plasma shots, and the probe current recorded and averaged over all shots. Then the bias is raised by a small step (0.2–1 V), and the process repeats. A fine time resolution (40 ns) is achieved by this measurement. The electron temperature rises quickly upon introduction of the microwave pulse and peaks around 1 \( \mu \text{s} \) after the pulse shuts off, which is consistent with the parallel electron thermal transit time from the source region to the probe location. After the initial increase, the electron temperature decays on a time scale of tens of microseconds, consistent with a 20 \( \mu \text{s} \) decay time due to parallel heat diffusion. As shown in Figure 3b, the electron temperature is effectively modulated by the repetitive high-power heating pulses. In the case where a background parallel electric field is present (such as in the experiments of ionosphere heating in a preexisting electrojet region [Barr et al., 1985; Shoucri et al., 1985]), a large oscillating current would be driven due to the modulation in the plasma conductivity. This effect is negligible in the nearly current-free plasma in this experiment.

In addition to electron heating, a small population (1–2 %) of fast electrons (\( E > 10 \text{ eV} \)) streaming away from the source region is generated by the microwave pulses. Figure 4a shows the parallel electron energy...
distribution function measured by a double-sided planar Langmuir probe located at $z = 64\text{ cm}$ downstream from the hot spot of microwave power density. In this figure the distribution function is shown as a set of equal value contours one e-folding value apart. In this case a single microwave pulse with a pulse length of $1\mu\text{s}$ was turned on at $t = 0$. The contours clearly show the presence of a fast electron tail in the direction moving away from the microwave incidence region. In fact other measurements suggest the fast tail extends to more than $100\text{ eV}$. Figure 4b shows the ion saturation current collected with a probe (area = $1.5\text{ mm}^2$) biased negatively to repel electrons with energy less than $175\text{ eV}$. The rapid drop appears during the microwave pulse indicates presence of fast electrons that overcome this potential barrier. Detection of lower hybrid waves and whistler waves, as shown in Figure 5, also suggests generation of fast electrons of hundreds of eV, according to a widely accepted theory of resonant amplification of these waves by fast electrons matching the Cerenkov condition $v_{||} = \omega_c / k_{||}$, where $v_{||}$ is the parallel velocity of the emitting electrons and $\omega_c / k_{||}$ is the parallel phase velocity of the whistler/lower hybrid wave [Maggs, 1976; Vincena et al., 2008]. In general, whistler waves can also be excited through cyclotron resonance $\omega - v_{||}k_{||} = n_o\omega_c$. But this requires electron energies at keV levels in this case and is not likely to be the wave generation mechanism here.

These fast electrons inject a parallel current in the plasma. In response the plasma sets up a compensating return current, likely in the form of a net drift of the bulk electron population in the direction opposite to the motion of the fast tail electrons. Due the high density of the bulk electron population,
such return current can be generated by a very slight drift velocity (the drift velocity for a $10^{12}$ cm$^{-3}$ density bulk electron population to generate a current density of 10 mA/cm$^2$ is only $6.3 \times 10^4$ cm/s or $2 \times 10^{-6}$ eV), which is much less than the resolution of the Langmuir probe diagnostic employed. Instead of the Langmuir probe measurements the total current density derived from $\mathbf{J} = \frac{c}{4\pi} \mathbf{\nabla} \times \mathbf{B}$ can reveal the return current system. Figure 6 shows parallel current density calculated using magnetic field measurements from a three-axis $dB/dt$ probe at $z = 128$ cm. The negative peak at the earlier time (solid line) corresponds to the current carried by the fast electrons streaming in the positive $z$ direction. In this case the $\omega_{pe}$ matching layer for the microwave pulse is also near $x = -8$ cm. A return current (positive $J_z$) is clearly visible on the two sides of the peak. The current density profile reverses sign at later times (as shown in dotted line) and continues to oscillate as time goes on. This oscillating current system is essentially carried by broadband shear Alfvén waves. If the injected current is modulated at a chosen frequency by multiple microwave pulses, a monochromatic shear Alfvén wave can be launched, as we will show next in this paper.

Figure 7 shows representative magnetic oscillations measured by a three-axis $dB/dt$ probe at an axial distance $z = 384$ cm away and at a transverse location where the oscillation amplitude peaks. In this case ten 1 $\mu$s microwave pulses modulated at 60 kHz or 100 kHz ($f_{ci} = 122$ kHz) are delivered to the Neon plasma column at $z = 0$ starting from $t = 0$. The measured $B$ field signals oscillate near the modulation frequencies (Figure 7a) and are nearly sinusoidal, indicating a narrow frequency band. Spectral analysis shows that the peak frequency is the same as the modulation frequency (Figure 7b). The direction of these magnetic oscillations is dominantly perpendicular to the background magnetic field (Figure 7c),

$\omega_{pe}$ matching layer for the microwave pulse is also near $x = -8$ cm. A return current (positive $J_z$) is clearly visible on the two sides of the peak. The current density profile reverses sign at later times (as shown in dotted line) and continues to oscillate as time goes on. This oscillating current system is essentially carried by broadband shear Alfvén waves. If the injected current is modulated at a chosen frequency by multiple microwave pulses, a monochromatic shear Alfvén wave can be launched, as we will show next in this paper.

Figure 7 shows representative magnetic oscillations measured by a three-axis $dB/dt$ probe at an axial distance $z = 384$ cm away and at a transverse location where the oscillation amplitude peaks. In this case ten 1 $\mu$s microwave pulses modulated at 60 kHz or 100 kHz ($f_{ci} = 122$ kHz) are delivered to the Neon plasma column at $z = 0$ starting from $t = 0$. The measured $B$ field signals oscillate near the modulation frequencies (Figure 7a) and are nearly sinusoidal, indicating a narrow frequency band. Spectral analysis shows that the peak frequency is the same as the modulation frequency (Figure 7b). The direction of these magnetic oscillations is dominantly perpendicular to the background magnetic field (Figure 7c),

Figure 7. (a) Representative $B_y$ signal measured at an axial distance of 384 cm away, with one or ten modulated microwave pulses. The signals are phase-locked shot-to-shot and are averaged over an ensemble of 10 shots. Their spectra are shown in (b). In this case $f_{ci} = 122$ kHz $B_0 = 1600$ G. (c) Vector components of the 100 kHz modulation case, showing oscillating $B$ field is dominantly in the perpendicular direction.

Figure 8. (a) Background magnetic field profiles showing the microwave launcher and the probe locations. (b) Oscillating $B_y$ signals measured with the two $B_0$ profiles; (c) their spectra are displayed. Note the $f_{ci}$ used to scale the frequency axis in Figure 8c, is the ion cyclotron frequency at the probe location.
which is a signature of shear Alfvén waves. As a comparison, the time trace of the measured magnetic oscillation at the same location in response to a single microwave pulse is also shown in Figure 7a and its Fourier spectrum in Figure 7b. The short impulse generated broadband oscillations with a distinct cutoff in frequency at \( f_{ci} \), which is expected for shear Alfvén waves. In fact, the oscillations \( \leq f_{ci} \) due to the single pulse have been rigorously proven to be shear Alfvén waves in Van Compernolle et al. [2005] and Van Compernolle et al. [2006]. The measurement with multiple pulses implies that the shear Alfvén wave component at the modulation frequency is coherently driven by the repetitive pulses, while other components are phase mixed and become less prominent.

In addition to the current modulation at frequency \( f_{\text{mod}} \), harmonics of \( f_{\text{mod}} \) are also generated due to the nonsinusoidal impulses. If the frequency of a particular harmonic is less than \( f_{ci} \), shear Alfvén wave at that harmonic can also be driven. Because shear Alfvén waves can only propagate below \( f_{ci} \), lowering the background magnetic field can filter out these harmonic waves. This is demonstrated with measurements shown in Figure 8 with two different background magnetic field configurations. One configuration is a flat background field as with the data presented in the rest of the paper; the other has a 50% dip near the microwave incidence region (Figure 8a). In the flat profile case, both \( f_{\text{mod}} (=55 \text{ kHz}) \) and \( 2 \times f_{\text{mod}} (=110 \text{ kHz}) \) are below \( f_{ci} (=122 \text{ kHz}) \) throughout the entire plasma column. The signal detected from a B-dot probe at \( z=480 \text{ cm} \) shows a mixture of the two frequencies (Figures 8b and 8c). In the dip profile the fundamental \( f_{\text{mod}} \) is below \( f_{ci} \) everywhere, and the second harmonic still lies below the local \( f_{ci} \) at the probe location (122 kHz) but is above the local \( f_{ci} \) near the microwave launcher (59 kHz). With this arrangement the signal detected far away shows only the fundamental frequency. This observation proves that (i) the virtual antenna (modulated current directly driven by the microwave pulses) is highly localized near the microwave launcher and (ii) the second harmonic oscillations recorded at remote locations are carried by propagating shear Alfvén waves.

To further confirm that the observed magnetic oscillations driven by the modulated microwave pulses are shear Alfvén waves, we compare the measured parallel phase velocity to theory for various pulse modulation frequencies between 10 kHz and 70 kHz while keeping \( f_{ci} \) fixed at 76 kHz. The measurement is performed with two B-dot probes placed on the same \( B_0 \) field line at two axial locations separated by \( \Delta z = 255 \text{ cm} \) apart. For each modulation frequency, the acquired signals are Gaussian filtered \( (\Delta f = 20 \text{ kHz}) \) at that frequency to isolate the fundamental frequency component from any harmonics. Figure 9a shows three examples of the filtered \( B_0 \) time trace. The figure shows clear phase delays between the two locations, and the wave appears to be dispersive with slower parallel propagation at higher frequencies. Figure 9b shows the measured wave dispersion relation. The parallel phase velocity \( v_{||} \) is obtained by measuring the phase delay time \( \Delta t \) that it takes the wave to travel the distance of separation between the two probes \( \Delta z (v_{||} = \Delta z/\Delta t) \). For each modulation frequency, 20 plasma shots are recorded. The vertical error bars in Figure 9b represent the shot-to-shot differences, while the horizontal error bars are the FWHM of the spectrum peak.
The theoretical dispersion relation of shear Alfvén wave with finite perpendicular wavelength in the cold plasma approximation [Gekelman et al., 1994; Morales et al., 1994] is calculated and plotted in Figure 9b. The perpendicular wave number used in the calculation is obtained from a radial cut through the transverse wave pattern as shown in Figure 10, which gives a best fit value of $k_\perp = 0.39$ rad/cm. Also shown in Figure 9b are the cold plasma dispersion relations with ±20% density variation (note the wave is propagating on a transverse density gradient). Since the electron temperature in this case is about 2 eV and the electron thermal speed ($v_{Te} = 8.4 \times 10^7$ cm/s) is higher than the Alfvén speed ($V_A = 4.9 \times 10^7$ cm/s), the wave is categorized as a kinetic Alfvén wave [Gekelman et al., 1997; Wu, 2012]. To quantitatively assess the kinetic effects, we calculate the dispersion relation with a kinetic plasma model ($T_e = 2$ eV, $T_i = 1$ eV, and $k_{\perp} \rho_s = 0.25$, where $\rho_s = c_s/\omega_{ci}$ is the ion sound gyroradius) using a numerical method described in Vincena et al. [2001] and compare it to the measured data in Figure 9b. The kinetic model roughly agrees with the cold plasma model at low frequencies away from $f_{ci}$ with a small increase in parallel phase velocity. Significant deviation from the cold plasma model appears near the ion cyclotron frequency and the dispersion curve continues through $f_{ci}$ when a finite ion temperature is included. The collisionless damping measured as $\text{Im}(k_{\|})/\text{Re}(k_{\|})$ is color

Figure 10. (a) $\mathbf{B}$ vectors measured on a transverse plane $z = 128$ cm. The color map denotes the parallel current density derived from $j = (c/4\pi) \times \mathbf{B}$. A coaxial return current shown in gray is clearly visible. $B_0 = 1000$ G. The wave pattern shows striking similarities to that of a shear Alfvén wave launched by a small disk exciter immersed in the plasma. [Gekelman et al., 1997] (b) $B_y$ and $j_z$ on a line cut at $y = 0$. A perpendicular wavenumber ($k_\perp = 0.39$ rad/cm) is obtained from a Bessel fit to the line cut. (The origin of the $J_0$ fit is shifted 0.8 cm from that of the $J_1$ fit, which is close to the 0.5 cm probe resolution).
Figure 11. Measurements of shear Alfvén wave peak amplitude as a function of input microwave peak power. The wave measurements are made at $z = 608$ cm.

A series of experiments is performed to study the dependence of the Alfvén wave amplitude on the power of microwave pulses. In this series of experiments the microwave pulses are introduced to the plasma column through a vacuum-sealed waveguide with a small horn antenna attached to the end, so that the antenna is now inside the vacuum chamber but outside the plasma column. This arrangement eliminates power loss when the microwave beam enters the vacuum chamber through a narrow window and boosts the microwave power density delivered to the plasma column edge by a factor of 3.5 determined by measurements in air. At each power level the B-dot probe is moved on a transverse plane ($z = 608$ cm) to the point of maximum $B_y$ signal received, and a 50-shots ensemble at that location is recorded. A directional coupler is included in the microwave transmission assembly between the magnetron and the launcher to monitor the forward power delivered to the plasma. A $\sim 30$ dB signal tapped off from the forward propagating microwaves is further attenuated by $\sim 60$ dB before being rectified by a detector diode to output the power amplitude. The diode was calibrated using a 300 kHz–20 GHz network analyzer (Agilent N5230C). Figure 11 shows the measured Alfvén wave amplitude as a function of peak microwave power. The result is linear over the range of 2 kW–100 kW that is examined in this experiment. Since the power in the Alfvén wave is proportional to the square of its electromagnetic field amplitude (assuming the radiation pattern remains the same), this suggests the power of the radiated Alfvén wave scales as square of the power of the injected microwave, $P_{\text{Alfvén}} \sim P_{\text{mw}}^2$. The scaling law highlights the secondary nature of the Alfvén wave generation. Using the first-order approximation $v_{\parallel} = v_A$, it is estimated that $P_{\text{Alfvén}} = (6 \times 10^{-8} \text{ kW}^{-1}) \times P_{\text{mw}}^2$. At an input power of 1 MW typical for ionospheric heaters, the wave launching efficiency $\eta = P_{\text{Alfvén}}/P_{\text{mw}} = 6 \times 10^{-5}$ is close to results from several ionospheric experiments [Moore et al., 2007; Cohen et al., 2008], which suggests that a similar virtual antenna process can operate at similar ionospheric magnetic configurations.

Figure 12. (a) Microwave intensity for 10 consecutive pulses along the microwave propagation direction at $z = 0$ measured with an electric dipole probe. Changes in the microwave reflection point indicate profile modification by the high power pulses. The pulses are modulated at 210 kHz. (b) Peak locations of the microwave intensity of the 10 consecutive pulses.
Acknowledgments
This work is supported by an AFOSR Multidisciplinary University Research Initiatives (MURI) award and conducted at the Basic Plasma Science Facility at UCLA funded by the DOE and NSF. The authors would like to thank Z. Lucky, M. Drandell, and T. Ly for their valuable technical help, and S. Vincena, S. Tripathi, and B. Eliasson for many helpful discussions. The data necessary to reproduce the experiments are available from the authors upon request (wangyuhou@gmail.com).

References

3. Discussion and Conclusions
Launching a shear Alfven wave using a virtual antenna has been conclusively demonstrated. Control over the Alfven wave frequency is an important step toward fully controlled wave launching using this remote technique. As for the case of a physical antenna, the next step would be controlling the wave structure by setting a perpendicular (or parallel) wavelength. This requires control of the ambient plasma density profile or tuning of the microwave frequency (or propagation mode) to match the desired heating layer. In addition, the plasma profile can be modified by the high-power pulses themselves, if the microwave energy density $|E_{mw}|^2/4\pi$ is comparable to the plasma thermal energy density $nkT_e$. Using typical values ($P_{mic} = 100$ kW, $n_e = 10^{12}$ cm$^{-3}$, $T_e = 0.5$–5 eV), we estimate $|E_{mw}|^2/(4\pi nkT_e)$ ranges from 0.2 to 2 in this experiment, where the lower figure corresponds to the plasma discharge and the higher figure is obtained during the afterglow plasma, after $T_e$ drops but the density is nearly the same. The wave pressure nonlinearity is observed in the afterglow plasma and is shown in Figure 12. As discussed the microwaves are reflected at the $\alpha_{pe}$ layer. In absence of the microwaves, the plasma density decay of the afterglow plasma is negligible ($<1\%$) for the duration of the 10 pulses (44 $\mu$s total). Each of the 10 microwave pulses expels the plasma mainly in the axial direction through a combination of ponderomotive force $\left(\alpha_{pe}^2/16\pi \alpha_{pe}^2 \cdot V_e \left( |E_{mw}|^2 \right) \right)$ and possibly heating. In this case it is estimated that $V_{osc}/V_{th} \approx 1.4$, where $V_{osc} = eE_{mw}/m \omega_{pe}$ is the velocity of the electron oscillatory motion in the microwave electric field and $V_{th}$ is the electron thermal velocity. Line integrated interferometer measurements also show a decrease in density near the source and an increase at an axial distance (dz = 320 cm). This decrease in local density moves the $\alpha_{pe}$ resonance layer inwards, so that the next pulse penetrates further into the plasma column. This is illustrated in Figure 12.

In conclusion, coherent shear Alfven waves at controllable arbitrary frequencies ($f < f_i$) are generated in a large laboratory plasma by repetitive high-power microwave pulses injected transverse to background magnetic field. It is found that electron temperature is modulated by the microwave pulses on a time scale shorter than the ion gyroparticle. Field-aligned current is detected, which is attributed to fast tail electrons streaming out of the microwave-heated region. It is shown that the current system established by the microwaves is carried along the magnetic field by shear Alfven waves. The spatiotemporal patterns of the radiated shear Alfven wave are found to be similar to that launched by physical antennas immersed in a plasma. The power of the Alfven wave is found to scale with the square of the incident microwave pulse power, which confirms the secondary nature of the Alfven wave generation mechanism. Nonlinear ponderomotive effects are observed for $|E_{mw}|^2/(4\pi nkT_e) > 1$. A comprehensive theoretical analysis of the applicability of the concept at low and equatorial latitudes is currently under development.


Van Compernolle, B., W. Gekelman, and P. Pribyl (2006), Generation of suprathermal electrons and Alfvén waves by a high power pulse at the electron plasma frequency, Phys. Plasmas, 13(9), 092112.

Vincena, S., W. Gekelman, and J. Maggs (2001), Shear Alfvén waves in a magnetic beach and the roles of electron and ion damping, Phys. Plasmas, 8(9), 3884–3896.

