



Measurement of Energy Reduction of Inertial Alfvén Waves Propagating through Parallel Gradients in the Alfvén Speed

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Abstract

We have studied the propagation of inertial Alfvén waves through parallel gradients in the Alfvén speed using the Large Plasma Device at the University of California, Los Angeles. The reflection and transmission of Alfvén waves through inhomogeneities in the background plasma are important for understanding wave propagation, turbulence, and heating in space, laboratory, and astrophysical plasmas. Here we present inertial Alfvén waves under conditions relevant to solar flares and the solar corona. We find that the transmission of the inertial Alfvén waves is reduced as the sharpness of the gradient is increased. Any reflected waves were below the detection limit of our experiment, and reflection cannot account for all of the energy not transmitted through the gradient. Our findings indicate that, for both kinetic and inertial Alfvén waves, the controlling parameter for the transmission of the waves through an Alfvén speed gradient is the ratio of the Alfvén wavelength along the gradient divided by the scale length of the gradient. Furthermore, our results suggest that an as-yet-unidentified damping process occurs in the gradient.

Unified Astronomy Thesaurus concepts: The Sun (1693); Plasma astrophysics (1261); Plasma physics (2089); Solar corona (1483); Solar flares (1496); Solar coronal heating (1989); Alfvén waves (23)

1. Introduction

One of the most perplexing problems in modern solar physics is the mechanism responsible for heating the solar corona, the outer atmosphere of the Sun. The temperature of the corona is ~ 200 times greater than the underlying photosphere. Different physical theories exist to explain the phenomenon (S. R. Cranmer 2009). One of the major theories posits that the heating is caused by Alfvén waves (S. W. McIntosh et al. 2011).

Strong damping of Alfvén waves has been observed at low heights in coronal holes, which are regions of the Sun with open magnetic field lines extending into interplanetary space. The observed damping has been found to release sufficient energy to heat the solar corona (A. Bemporad & L. Abbo 2012; M. Hahn et al. 2012; M. Hahn & D. W. Savin 2013; H. Hara 2019). The Alfvén waves are generated by the jostling of flux tube footpoints (E. R. Priest et al. 2000). These Alfvén waves propagate outward along the magnetic field lines (i.e., longitudinally). The waves are predicted to be partially reflected toward the Sun by the longitudinal gradient in the Alfvén speed along the magnetic field lines (R. L. Moore et al. 1991; W. H. Matthaeus et al. 1999; S. R. Cranmer & A. A. Van Ballegooijen 2005; B. D. G. Chandran & J. V. Hollweg 2009). The interaction of the reflected and outward propagating waves is thought to drive magnetohydrodynamic (MHD) turbulence, dissipating wave energy, and heating the solar corona (W. H. Matthaeus et al. 1999; S. R. Cranmer 2009). Hence, understanding Alfvén wave propagation in the presence of an

Alfvén speed gradient is an important step in unraveling the heating mechanism of the solar corona.

In our previous experimental work, we investigated the transmission and reflection of kinetic Alfvén waves for plasma parameters scaled to be representative of coronal holes (S. Bose et al. 2019). The kinetic Alfvén wave regime occurs when $v_A < v_{Te}$, where v_A and v_{Te} are the Alfvén speed and electron thermal speed, respectively. The Alfvén speed is given by $v_A = B_0 / \sqrt{\mu_0 \rho}$. Here, B_0 is the ambient magnetic field; μ_0 is the permeability of free space; $\rho = (n_i m_i + n_e m_e)$ is the mass density of the plasma; n_i and n_e are the number densities of ions and electrons, respectively; and m_i and m_e are the ion and electron masses, respectively. The electron thermal speed is $v_{Te} = \sqrt{T_e / m_e}$, where T_e is the electron temperature in eV and m_e is the electron mass. Our kinetic regime experiments found that the wave energy transmitted through an Alfvén speed gradient was strongly reduced as the gradient became sharper compared to the wavelength. The wave energy that is not transmitted should be reflected or absorbed. Absorption could occur, for example, if the wave encountered a resonance in the plasma. Our subsequent measurements of wave reflection in the Large Plasma Device (LAPD) found that the reflection was surprisingly insufficient (S. Bose et al. 2024).

Here, we extend our work to the inertial Alfvén wave regime, where $v_A > v_{Te}$. Our objective was to determine whether the transmission and reflection of inertial Alfvén waves differed from the previously measured kinetic Alfvén waves. In particular, since the Alfvén speed lies outside the electron energy distribution, we expected to greatly reduce the effects of Landau damping (R. L. Lysak & W. Lotko 1996; D. J. Thuecks et al. 2009).

In a solar physics context, inertial Alfvén waves are likely to be found in active regions where the strong magnetic field



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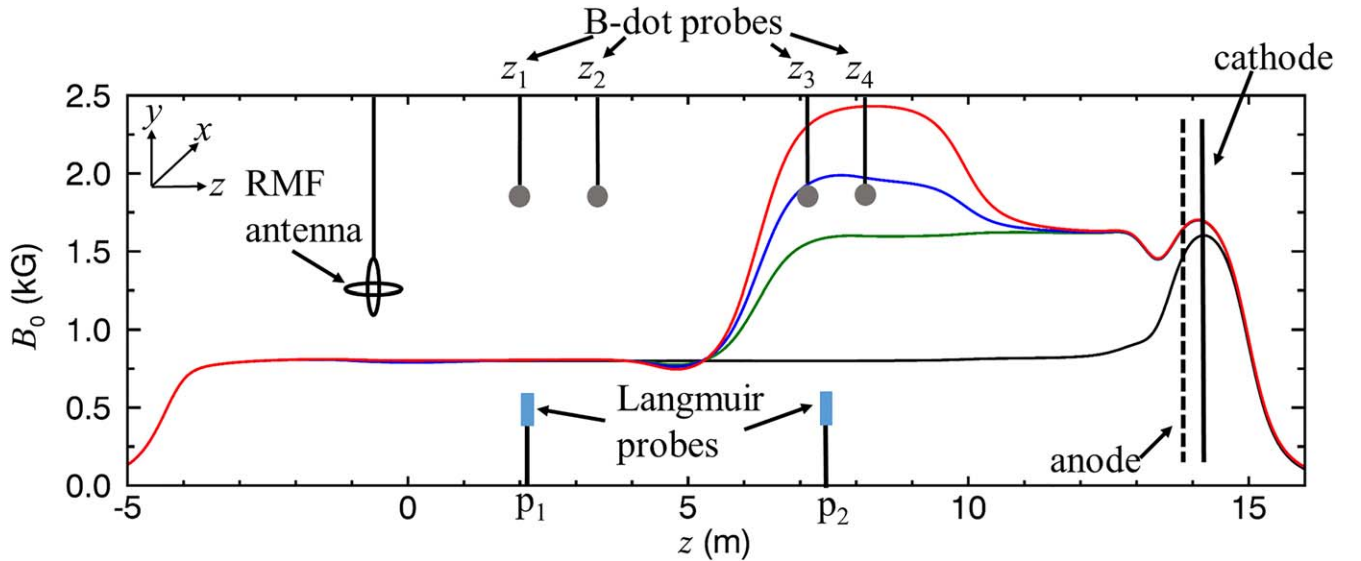


Figure 1. Schematic of the experimental setup. The various magnetic field profiles used are shown in different colors. Black represents a uniform field of $B_0 = 800$ G. Not shown is the uniform field of 1600 G. Green, blue, and red represent 800 G on the low-field side of our configuration and plateaus of 1600, 2000, and 2400 G on the high-field side. The orthogonal loop antenna is on the low-field side. Wave is launched toward the plasma source, i.e., the anode shown by the dashed line and the cathode shown by the solid line. Also noted in the figure are the locations of the two Langmuir probes used to measure the plasma density and temperature and the four B-dot probes used to measure the wave magnetic field.

causes v_A to be large. For example, Alfvén waves have been hypothesized to accelerate electrons during solar flares (L. Fletcher & H. S. Hudson 2008; K. G. McClements & L. Fletcher 2009; D. B. Jess et al. 2023). One mechanism by which they may accelerate electrons is through a turbulent cascade that occurs when downward propagating Alfvén waves reflect at the solar chromosphere. So, our measurements of the reflection and transmission of inertial Alfvén waves may have implications for understanding solar flares.

The rest of the paper is organized as follows. In Section 2, we describe the experimental configuration. Section 3 describes the experiment results. This is followed by a discussion and summary in Section 4.

2. Experiment

We conducted our experiment in LAPD at the University of California, Los Angeles (W. Gekelman et al. 2016). LAPD can generate a plasma column that is 18 m long and up to 60 cm in diameter. Our experiments were performed in a hydrogen plasma, for which the device was filled with neutral hydrogen at a pressure of $\sim 10^{-5}$ Torr.

The experimental schematic is shown in Figure 1. An LaB₆ source (Y. Qian et al. 2023) was used to generate the plasma by creating a discharge between the cathode and anode. Discharges (i.e., shots) were created every 3 s. Simultaneously with the onset of the discharge, hydrogen was puffed into the system near the plasma source for 19 ms. The discharge current ramped up to ~ 5.5 kA in about ~ 2 ms, forming the main discharge. After 22 ms, the discharge voltage was turned off. When the discharge is turned off, the most energetic electrons rapidly leave the plasma, resulting in a cooler quiescent afterglow plasma, which was suitable for the inertial Alfvén waves studies reported here.

The plasma density, n_e , and electron temperature, T_e , were measured using Langmuir probes (p_1 and p_2 in Figure 1) and taking averages along an x line through the plasma column at $y = 0$. The density for p_1 was determined using the area of the

probe tip. In the afterglow, the plasma density at p_1 was $n_e = 1.6 \pm 0.3 \times 10^{11} \text{ cm}^{-3}$. Here and throughout, unless otherwise stated, all uncertainties are quoted at a 1σ statistical confidence level. The electron temperature T_e was found by sweeping the Langmuir probes from -35 to $+110$ V, from which we found $T_e = 0.8 \pm 0.3$ eV. The density for p_2 was calibrated using a microwave interferometer. The plasma density at p_2 was $n_e = 6.0 \pm 0.6 \times 10^{11} \text{ cm}^{-3}$. The electron temperature T_e was found by sweeping the Langmuir probes from -35 to $+50$ V, from which we found $T_e = 1.0 \pm 0.3$ eV. The ion temperature is not routinely measured in LAPD, but previous studies have estimated it to be $T_i \sim 0.5$ eV (S. T. Vincena et al. 2013).

We used five axial magnetic field configurations that are along the z -direction. This included two uniform cases of $B_0 = 800$ and 1600 G and three configurations with gradients rising from $B_0 = 800$ G before the gradient and increasing to 1600, 2000, and 2400 G after the gradient, as shown by the colored curves in Figure 1. Throughout the paper, we will use the terminology “before the gradient,” which refers to the region where the antenna is located, and “after the gradient,” which refers to the region closer to the plasma source.

Alfvén waves were launched by an orthogonal loop antenna with frequencies that we varied from $(0.32\text{--}0.52)\omega_{ci}$, where the ion cyclotron frequency is defined as $\omega_{ci} = qB_0/m_i$ and q is the ion charge. Here and throughout, ω_{ci} refers to the frequency for H^+ .

We launched left-hand circularly polarized shear Alfvén waves of five sinusoidal cycles using a rotating magnetic field (RMF) antenna (A. Gigliotti et al. 2009). The RMF antenna consists of two rings, each with three turns of 0.25 cm diameter solid copper wire. The horizontal ring couples to the y -axis and is ~ 8 cm diameter. The vertical ring couples to the x -axis and is ~ 9 cm diameter. The rings were driven out of phase with each other by $\pi/2$. The antenna size determines the characteristic initial perpendicular wavelength of $\lambda_\perp \sim 9$ cm. However, the wavelength grows to ~ 27 cm as it propagates to the vicinity of the gradient at probe location z_2 (see Section 3.3), which we attribute to the changing plasma

Table 1

Dimensionless Plasma Parameters for Inertial Alfvén Waves in LAPD, Coronal Holes, and Solar Flares

Parameters	LAPD	Coronal Holes	Solar Flares
b/B_0	10^{-5}	10^{-2}	10^{-1}
$k_{\perp}^2 \delta_e^2$	$\ll 1$	$\ll 1$	$\ll 1$
$k_{\perp}^2 \rho_i^2$	$\ll 1$	$\ll 1$	$\ll 1$
λ/L_A	0–4	≥ 4.5	≥ 20
ω/ω_{ci}	0.15–0.52	$\ll 10^{-5}$	10^{-9}
β	10^{-5} – 10^{-4}	$\approx 10^{-3}$	$\lesssim 10^{-2}$

Note. Flare parameters are for Alfvén waves at the corona/chromosphere boundary and based on the estimates of L. Fletcher & H. S. Hudson (2008).

properties along the device. The largest measured Alfvén wavelength along the magnetic field (i.e., parallel or longitudinal) was $\lambda_{\parallel} \approx 6$ m, so that at least three wavelengths could be accommodated in a device.

Starting at 4.3 ms after the onset of the discharge and continuing until 24.3 ms, every millisecond we launched a sequence of six wave trains. Each wave train was separated by $\sim 100 \mu\text{s}$ and was at a different frequency. Here, we used six frequencies: $f = 390, 439, 488, 536, 585$, and 634 kHz.

The Alfvén wave magnetic field b was measured using B-dot probes at four axial locations. Each probe consists of three axes to measure the b_x , b_y , and b_z wave components. The probes were mounted on linear translators that stepped through the LAPD cross section to obtain plane measurements. Wave field data were collected for planes at z_1 and z_3 , covering 49×36 spatial locations. Line measurements along x , for $y = 0$, were collected at $z_1 = 223.65$ cm, $z_2 = 383.4$ cm, $z_3 = 743.85$ cm, and $z_4 = 830.7$ cm. The shot-to-shot variation in LAPD is very low, and the signal was averaged over eight shots and digitized using a 16-bit data acquisition system. The probe remained stationary during data collection and then was moved to another position for the next measurement. This process was repeated throughout the plane.

The motivation of our work is to understand the propagation of inertial Alfvén waves through a parallel v_A -gradient. To that end, we adjusted the dimensionless plasma parameters in LAPD to match those in the Sun as closely as was experimentally feasible. Table 1 compares the relevant parameters in LAPD to both coronal holes and the low corona near the chromosphere of a solar flare. A detailed discussion comparing LAPD with coronal hole conditions has been given by S. Bose et al. (2019). Here, we briefly review some specific parameters relevant to the present results.

The wave amplitude b relative to the background magnetic field B_0 was $\leq 10^{-5}$ in LAPD but is about $b/B_0 \approx 10^{-2}$ in coronal holes and $b/B_0 \approx 10^{-1}$ in an active region during a solar flare. We chose to work with such a low value of b/B_0 to avoid nonlinear plasma effects.

We have excited Alfvén waves with low frequency such that the parallel phase velocity of the wave is approximately equal to the Alfvén speed, $\omega/k_{\parallel} \approx v_A$, as in the solar atmosphere. Here, ω is the angular frequency of the wave and $k_{\parallel}$ is the parallel wavenumber along the magnetic field lines. Our experiments, described below, verify that for $\omega/\omega_{ci} \leq 0.5$, the Alfvén waves follow the dispersion relation for inertial waves.

The perpendicular wavenumber $k_{\perp}$ in the solar corona has large uncertainties, but it is assumed that ideal MHD holds and both $k_{\perp}^2 \delta_e^2$ and $k_{\perp}^2 \rho_i^2$ are $\ll 1$, as is supported by recent

observations at the base of the corona (R. Sharma & R. J. Morton 2023). This condition also holds in the the experiment. The value of $k_{\perp}$ is calculated using the Fourier–Bessel analysis discussed in Section 3.3. Here, $\delta_e = c/\omega_{pe}$ is the collisionless electron skin depth, c is the speed of light, and $\omega_{pe} = \sqrt{n_e e^2 / m_e \epsilon_0}$ is the electron plasma frequency, where e is the fundamental unit of electrical charge and ϵ_0 is the permittivity of free space. The ion gyroradius is $\rho_i = v_{ti}/\omega_{ci}$, where $v_{ti} = \sqrt{T_i/m_i}$ is the ion thermal speed.

At the gradient, the Alfvén speed can change significantly. This is described using an inhomogeneity parameter, which is defined by $\lambda_{\parallel}/L_A$, where L_A is the gradient scale length. The gradient scale length in the experiment and the coronal hole are similar. Here, $L_A = v_A/v'_A$ and $v'_A = dv_A/dz$ is the spatial derivative of v_A with respect to z . The plasma medium is considered as uniform when $\lambda_{\parallel}/L_A \ll 1$ and as nonuniform when $\lambda_{\parallel}/L_A \geq 1$.

The interplay between magnetic field pressure and thermal pressure is represented by the plasma beta parameter, $\beta = 2\mu_0 n_e T_e / B_0^2$. In the solar corona the magnetic pressure is generally much larger than the thermal pressure and $\beta \approx 10^{-3}$. The situation for solar flare is similar with $\beta \lesssim 10^{-2}$. In LAPD, this value varies from $(10^{-4} - 10^{-5})$.

3. Results

3.1. Inertial Alfvén Wave

In order to confirm that we are in the inertial Alfvén wave regime, we have calculated v_A and v_{Te} . For this we have used the n_e and T_e from the Langmuir probe measurements. These are shown in Figure 2 for the $B_0 = 800$ G flat-field case and the $B_0 = 800$ – 2400 G gradient case. Both v_A and v_{Te} were determined by averaging along x between -10 and $+10$ cm, which is where most of the wave energy is concentrated, as can be seen in Figure 3.

For the flat-field case, before the gradient, $v_A = 1.7 \pm 0.2 \times 10^8 \text{ cm s}^{-1}$ and $v_{Te} = 4.9 \pm 0.7 \times 10^7 \text{ cm s}^{-1}$, giving $v_{Te}/v_A = 0.29$. After the gradient, $v_A = 1.2 \pm 0.8 \times 10^8 \text{ cm s}^{-1}$ and $v_{Te} = 5.9 \pm 0.5 \times 10^7 \text{ cm s}^{-1}$, giving $v_{Te}/v_A = 0.5$. For the 800 – 2400 G gradient, before the gradient, $v_A = 2.2 \pm 0.2 \times 10^8 \text{ cm s}^{-1}$ and $v_{Te} = 3.6 \pm 0.5 \times 10^7 \text{ cm s}^{-1}$, giving $v_{Te}/v_A = 0.16$. After the gradient, $v_A = 3.2 \pm 0.4 \times 10^8 \text{ cm s}^{-1}$ and $v_{Te} = 4.3 \pm 0.4 \times 10^7 \text{ cm s}^{-1}$, giving $v_{Te}/v_A = 0.13$. These ratios demonstrate that our experiments satisfy the inertial Alfvén wave criterion of $v_A > v_{Te}$.

3.2. Wave Structure

We have mapped the Alfvén wave structure in two xy cross sections of LAPD: one before the gradient at z_1 and the other after the gradient at z_3 . The wave temporal profile and spatial structure perpendicular to the ambient magnetic field are shown in Figure 3 for the $B_0 = 800$ – 2000 G gradient. The top two panels in the figure, (a) and (b), show the b_x component of the wave magnetic field as a function of time at $x = y = 0$ for a wave with $\omega = 0.36\omega_{ci}$. Similar data were obtained in xy cross sections of LAPD at 49×35 locations. The data in each cross-section plane were collected with a 1 cm step size. At each location, the data were averaged over eight shots. The bottom two panels in Figure 3, (c) and (d), show the perpendicular components of the wave magnetic field vector, $b_{\perp} = \sqrt{b_x^2 + b_y^2}$. These two panels correspond to the time of

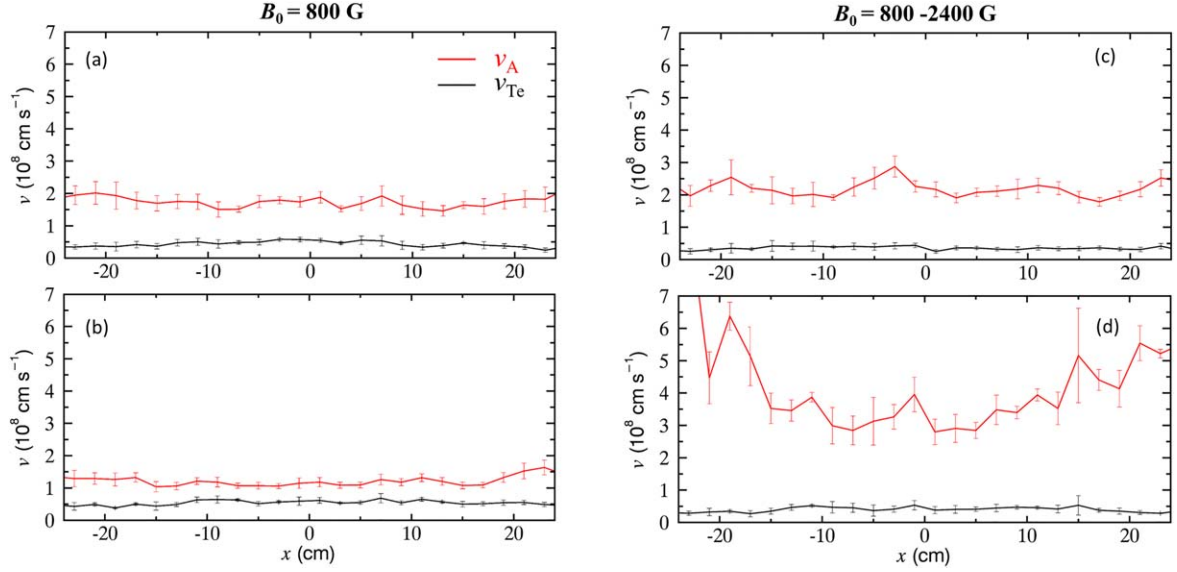


Figure 2. Alfvén speed (v_A in red) and electron thermal speed (v_{Te} in black) in (a) and (b) for the flat-field case at p_1 and p_2 , respectively, and in (c) and (d) for the gradient case at p_1 and p_2 , respectively.

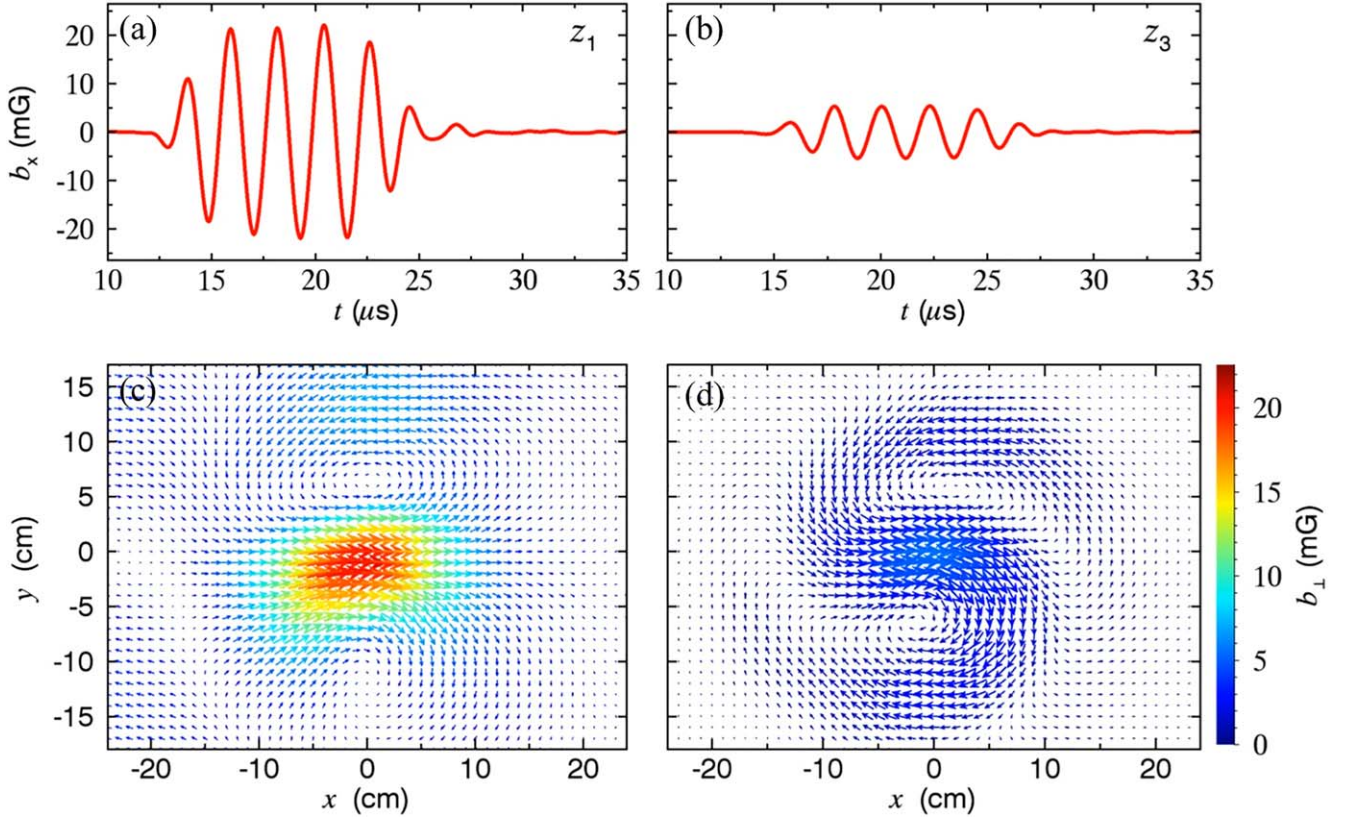


Figure 3. Alfvén wave structure at two z locations for the 800–2000 G gradient case for $x = y = 0$. Panels (a) and (b) show the temporal profile of the b_x component at z_1 and z_3 , respectively. Panel (c) shows the wave spatial structure in an xy cross section at z_1 at the time of the second peak in the temporal profile of the b_x component in (a). Panel (d) shows the same but for z_3 . See the text for more details.

the second peak in the time series data shown in panels (a) and (b). The direction of each arrow represents the orientation of the wave magnetic field at that location. The color of each arrow represents the magnitude of $b_{\perp}$. The wave structure forms an $m = 1$ mode, where m is the azimuthal mode number. The wave structure has two current channels ~ 18 cm apart at

z_1 on the low-field side and on the high-field side ~ 10 cm apart at z_3 .

3.3. Alfvén Wave Dispersion Relation

We launched Alfvén waves of frequencies ω from $(0.32\text{--}0.52)\omega_{ci}$ and measured the wave signal along an x line

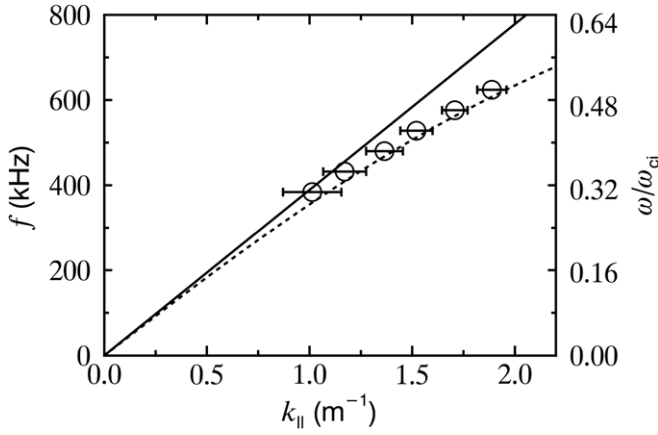


Figure 4. Alfvén wave dispersion relation for the uniform $B_0 = 800$ G measured before the gradient. The symbols represent the experimental data, while the solid line shows the ideal dispersion relation for Alfvén waves and the dashed line the dispersion relation for inertial Alfvén waves. The ratio of the angular frequency to the ion cyclotron frequency is given on the right-hand axis.

for $y = 0$ at each of the four axial z locations. Using a cross-correlation method, we calculated the time lag Δt of the wave as it traveled from z_1 to z_2 before the gradient and from z_3 to z_4 after the gradient. Since the distance between the probes is known, the phase velocity is given by $v_{\text{ph},\parallel} = \Delta z / \Delta t$, which we then use to calculate $k_{\parallel} = \omega / v_{\text{ph},\parallel}$. We have determined $v_{\text{ph},\parallel}$ for all magnetic field configurations considered here, both before and after the gradient.

Using these results, we can determine the dispersion relation. We show this in Figure 4 for the uniform field $B_0 = 800$ G case before the gradient, using the b_y component averaged over x from -6 to $+6$ cm to avoid any artifacts from the current channels. Also shown in this figure is the ideal dispersion relation for Alfvén waves, $\omega/k_{\parallel} = v_A$, and for inertial Alfvén waves, which is given by (K. Stasiewicz et al. 2000; W. Gekelman et al. 2011)

$$v_{\text{ph},\parallel} \equiv \frac{\omega}{k_{\parallel}} = v_A \frac{\sqrt{(1 - \omega^2/\omega_{ci}^2)}}{\sqrt{1 + k_{\perp}^2 \delta_e^2}}. \quad (1)$$

The perpendicular wavenumber, $k_{\perp}$, calculated using a Fourier-Bessel analysis (R. Churchill & J. Brown 1987; S. Vincena 1999), is $\approx 0.23 \text{ cm}^{-1}$. The data points follow the inertial Alfvén wave dispersion relation. In general, the measured $v_{\text{ph},\parallel}$ for all magnetic field configurations both before and after the gradient fell between v_A and the value given by Equation (1).

3.4. Wave Energy and Power

3.4.1. Two-dimensional Measurements

The total wave energy at a point (x, y, z) and time t can be calculated using the Poynting vector, which is given by A. V. Karavaev et al. (2011) as

$$S(x, y, z, t) = \frac{1}{\mu_0} b^2 v_{g,\parallel} \approx \frac{1}{\mu_0} b^2 v_{\text{ph},\parallel}, \quad (2)$$

where $b = \sqrt{b_x^2 + b_y^2 + b_z^2}$ and $v_{g,\parallel} = \partial \omega / \partial k_{\parallel}$ is the parallel group velocity. We have made the approximation that $v_{g,\parallel}$ is approximately equal to the measured $v_{\text{ph},\parallel}$.

The total wave energy in a cross section of LAPD at z can be expressed as

$$\mathcal{E}(z) = \iiint S \, dx \, dy \, dt = \frac{v_{\text{ph},\parallel}}{\mu_0} \iiint b^2 \, dx \, dy \, dt. \quad (3)$$

The wave power Γ is related to the total energy in the wave pulse by

$$\Gamma(z) = \frac{\mathcal{E}}{t_{\text{dur}}}, \quad (4)$$

where t_{dur} is the duration of the wave pulse.

3.4.2. One-dimensional Measurements

We were able to study five magnetic field configurations within the limited machine time available using one-dimensional (1D) measurements of the wave magnetic field. We used a version of Equation (3) modified for line measurements from $x = -30$ to $+30$ cm:

$$\mathcal{E}(z) = \iint S \, dx \, dt = \frac{v_{\text{ph},\parallel}}{\mu_0} \iint b^2 \, dx \, dt. \quad (5)$$

We verified the accuracy of this approach by using our two-dimensional (2D) data (e.g., Figure 3) and extracting an x -line measurement at $y = 0$. We then compared the transmittance from z_1 to z_3 for both the 2D and 1D cases. The 2D transmission ratio is given by

$$T_{31}^{2D} = \frac{\Gamma_3^{2D}}{\Gamma_1^{2D}}. \quad (6)$$

The 1D transmission ratio is derived from Equations (4) and (5), giving

$$T_{31}^{1D} = \frac{\Gamma_3^{1D}}{\Gamma_1^{1D}}. \quad (7)$$

We compared the results for a uniform 1600 G case and an 800–2000 G gradient case and found good agreement between T_{31}^{2D} and T_{31}^{1D} . We then performed experiments that only measured a line and compared those results to the 2D measurements. Again, we found good agreement for both cases.

3.5. Transmission

We measured the wave transmission from z_2 to z_3 , Γ_3/Γ_2 , for uniform fields of $B_0 = 800$ and 1600 G, as shown in Figure 5. The 1D transmission measurements are plotted as a function of ω/ω_{ci} . Past LAPD studies have shown that the Alfvén waves launched can be reflected from the plasma source (D. Leneman 2007). In order to avoid any potential effects of such reflection, we calculated the travel time of the reflected waves and only used the portion of the incident wave that occurred before the calculated arrival of the reflected wave. The data shown in Figure 5 were calculated using only the first two wave periods for each frequency and field case. This integration time was set by the uniform 1600 G case, for which v_A was faster than the 800 G case.

Figure 5 shows that the wave energy is significantly damped above $\omega \approx 0.36\omega_{ci}$. We remind the reader that we are using the ω_{ci} for a pure H^+ plasma, for which we would expect to see the onset of ion cyclotron damping above about $0.95\omega_{ci}$

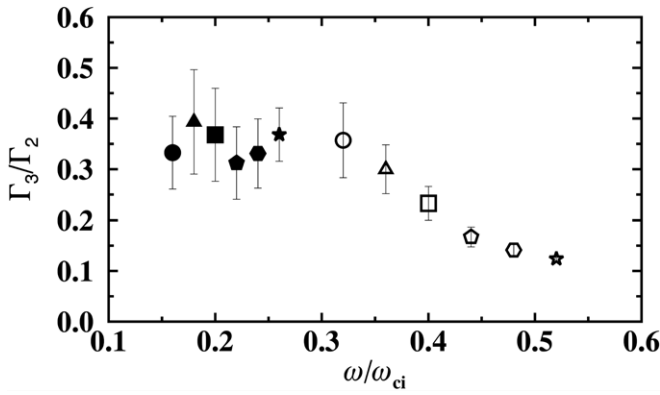


Figure 5. The 1D measurements of the wave transmission from z_2 to z_3 for a uniform magnetic field. The open symbols are for $B_0 = 800$ G and the filled symbols for 1600 G. The symbol shapes of circle, triangle, square, pentagon, hexagon, and star correspond to frequencies of 390, 439, 488, 536, 585, and 634 kHz, respectively.

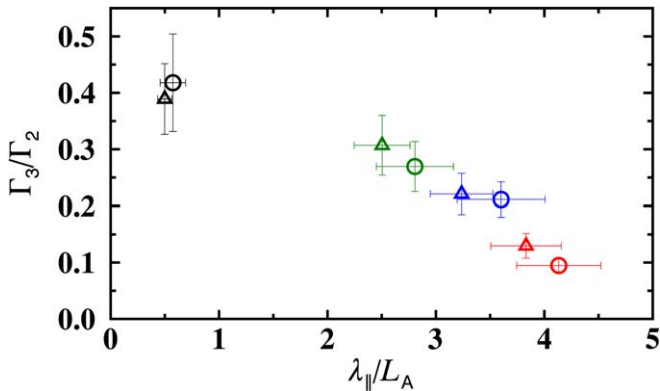


Figure 6. Measured 1D wave transmission for a uniform magnetic field $B_0 = 800$ G (black) and the three gradient cases of $B_0 = 800$ –1600 G (green), $B_0 = 800$ –2000 G (blue), and $B_0 = 800$ –2400 G (red). The symbols are defined in Figure 5.

(S. Vincena et al. 2001). As the frequency continues to increase, the measured transmission falls further and further below the theoretical prediction, primarily due to the collisional damping (G. J. Morales et al. 1994; C. A. Kletzing et al. 2010). This strongly suggests that there are additional ion species in the plasma producing damping. Possible species include H_2^+ , of which there is likely a significant population in the discharge due to electron impact ionization of the parent H_2 gas, and H_3^+ , which is rapidly formed by the reaction $H_2^+ + H_2 \rightarrow H_3^+ + H$ (I. Savić et al. 2020). The ion cyclotron frequencies for H_2^+ and H_3^+ are, respectively, half and a third of that for H^+ . In order to study the damping due solely to the gradient, we have limited our analysis to waves with frequencies $\omega \leq 0.36\omega_{ci}$.

In Figure 6, we show our measured wave transmission for the uniform $B_0 = 800$ G case and the three gradient cases. The transmission through the gradient is plotted as a function of $\lambda_{||}/L_A$. The data are shown for each axial magnetic field configuration using the minimum of L_A for that profile. Here, we were able to integrate over five wave periods, due to the reflected wave traveling slower in these four cases as compared to the uniform 1600 G case. Our results show a reduction in the wave energy even in the uniform magnetic field case. We attribute this to collisional damping. The transmission

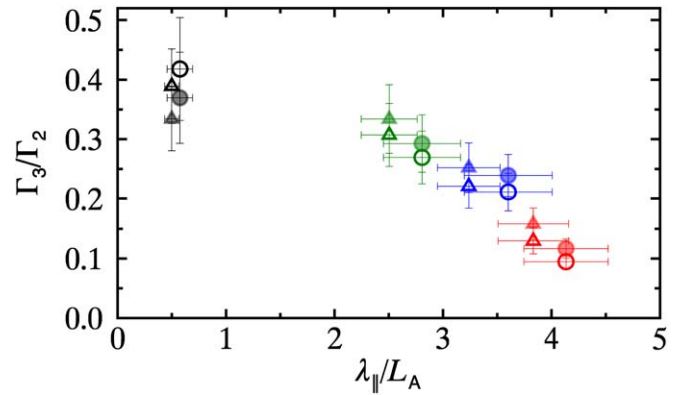


Figure 7. Measured 1D wave transmission over the full range (unfilled symbols) and over the smaller range from $x = -5$ to $+5$ cm (filled symbols). The symbols are defined in Figure 5 and the colors in Figure 6.

continues to decrease as the gradient becomes steeper. Note that the difference in the values of the $B_0 = 800$ G data in Figures 5 and 6 is due to the selection of wave period for the energy calculations.

The effect of phase mixing is ruled out by comparing and calculating wave transmission only within the region where v_A is uniform ($x = -5$ to $+5$ cm) to that over the entire measured line. Removing any effect of phase mixing would significantly increase the transmission. Figure 7 shows that the calculated transmission in the narrower range changes the transmission of the measurement by an amount ($\sim 10\%$) that is within the error bars of the respective measurements.

4. Discussion and Summary

We have performed an experiment to study the propagation of inertial Alfvén waves through a longitudinal gradient in the Alfvén speed. We launched Alfvén waves of six different frequencies from $0.32\omega_{ci}$ to $0.52\omega_{ci}$. Our gradient transmission measurements are limited to the lowest two frequencies of $0.32\omega_{ci}$ and $0.36\omega_{ci}$.

The waves with $\omega \gtrsim 0.36\omega_{ci}$ have additional damping, which we attribute to ion cyclotron resonance damping. This is likely due to resonance with H_2^+ and H_3^+ ions, whose cyclotron frequencies are, respectively, half and a third that of the H^+ cyclotron frequency. Ion cyclotron damping also plays a role in coronal heating (S. R. Cranmer 2000). However, in our hydrogen plasma the presence of H_2^+ and H_3^+ was unintentional, and the ion fractions are unknown. Future work could study the characteristics of ion cyclotron damping in a mixed species plasma using known fractions of heavy ions.

Returning to the lowest frequencies that were unaffected by the resonant damping, we found that the inertial Alfvén wave transmission scales with $\lambda_{||}/L_A$, just as was found for kinetic Alfvén waves (S. Bose et al. 2019). Furthermore, our experiments demonstrate that Alfvén speed gradients reduce the transmission of inertial Alfvén wave energy. Figure 8 compares our present inertial Alfvén wave results with the kinetic Alfvén wave transmittances measured by S. Bose et al. (2019). Comparing these results shows that the transmittances match not only in terms of the scaling but also in magnitude. That is, the amount of energy lost by both kinetic and inertial Alfvén waves when passing through a given Alfvén speed gradient is about the same. The transmittance of Alfvén waves through a gradient appears to be largely independent of

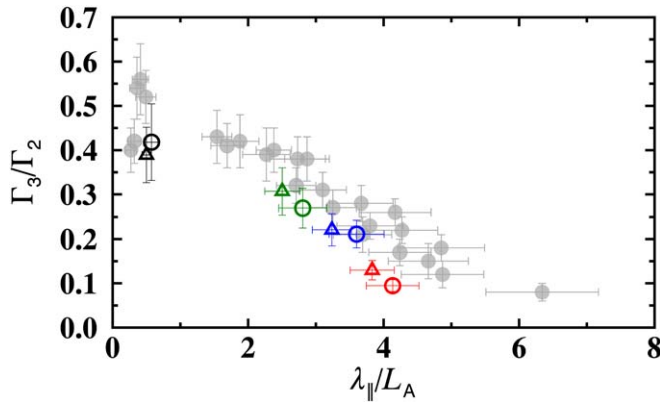


Figure 8. Comparison of our inertial Alfvén wave transmission data to the kinetic Alfvén wave results of S. Bose et al. (2019), which are shown in gray. The inertial Alfvén wave symbols are defined in Figure 6.

whether the waves are in the kinetic or inertial regime, at least for frequencies well below ω_{ci} .

For these inertial regime experiments, we expected Landau damping to be negligible. However, collisional damping continues to play a significant role. The enhanced collisional damping associated with the lower T_e for this experiment likely mitigated the reduced Landau damping, resulting in similar damping to what was observed in the kinetic regime by S. Bose et al. (2019).

These results may find implications in solar physics wherever inertial Alfvén waves encounter gradients in the Alfvén speed. One example is that Alfvén waves generated in solar flares may propagate downward, reflect off the chromosphere, and thereby produce turbulence by accelerating electrons (L. Fletcher & H. S. Hudson 2008). The gradient length scales at the chromosphere imply that $\lambda_{\parallel}/L_A$ is larger than in our experimental configurations. Nevertheless, our results show that even at moderate values of the inhomogeneity parameter, the wave transmission is dramatically reduced by the gradient. This suggests that the majority of the coronal Alfvén wave energy is not transmitted but likely undergoes reflection or mode conversion instead. Coronal Alfvén wave energy could be absorbed by the plasma, resulting in heating and/or particle acceleration, in addition to being transmitted, reflected, or mode converted.

Any reflected wave energy was below the detection limits for our probes. This implies that the inertial Alfvén waves are damped at the gradient. The wave energy may get absorbed near the gradient due to mode conversion (T. H. Stix 1992). We would expect wave damping to eventually deposit energy into the plasma, leading to heating. However, for the small amplitudes used here, the expected change in the electron temperature would be too small to measure (S. Bose et al. 2019). In future work, we plan to excite larger amplitude waves such that $b/B_0 \sim 0.01$ – 0.1 , so that we can quantify the reflected wave energy. Such large-amplitude waves are expected to also result in significant plasma heating, measurements of which would help us to better understand the wave dissipation processes in the gradient region. Moreover, larger amplitudes will be more similar to solar Alfvén waves. In future studies, we plan to conduct detailed wave and plasma measurements within the gradient region to uncover the physical processes

and the unidentified damping mechanism responsible for the wave losing most of its energy.

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