



Experimental Study of Alfvén Wave Reflection from an Alfvén-speed Gradient Relevant to the Solar Coronal Holes

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Abstract

We report the first experimental detection of a reflected Alfvén wave from an Alfvén-speed gradient under conditions similar to those in coronal holes. The experiments were conducted in the Large Plasma Device at the University of California, Los Angeles. We present the experimentally measured dependence of the coefficient of reflection versus the wave inhomogeneity parameter, i.e., the ratio of the wavelength of the incident wave to the length scale of the gradient. Two-fluid simulations using the `Gkeyll` code qualitatively agree with and support the experimental findings. Our experimental results support models of wave heating that rely on wave reflection at low heights from a smooth Alfvén-speed gradient to drive turbulence.

Unified Astronomy Thesaurus concepts: The Sun (1693); Plasma physics (2089); Plasma astrophysics (1261); Alfvén waves (23); Solar corona (1483); Solar coronal holes (1484); Solar coronal heating (1989); Solar coronal waves (1995); Fast solar wind (1872)

1. Introduction

Coronal holes are low-density regions of the solar atmosphere with open magnetic field lines that extend into interplanetary space. These regions appear as dark areas resembling holes in ultraviolet and X-ray images. Spectroscopic measurements indicate that coronal holes are at 10^6 K, approximately 200 times hotter than the underlying photosphere (Fludra et al. 1999). Despite several decades of research, the physics behind the heating of coronal holes is not well understood (Cranmer 2009; Cranmer et al. 2015).

Alfvén waves are posited to play a significant role in the heating of coronal holes (Alfvén 1942; McIntosh et al. 2011; Banerjee et al. 2021). Perturbations of the footpoints of open magnetic field lines, due to the sloshing of the photospheric plasma, are thought to excite the Alfvén waves (Priest 2014). These waves predominantly travel along the magnetic field lines, transporting from the photosphere to the corona the energy necessary for heating coronal holes (Cranmer 2009).

Recent observations have found Alfvénic waves at the base of coronal holes that satisfy the energy budget needed to heat the plasma in coronal holes (McIntosh et al. 2011). The term “Alfvénic” highlights that in addition to Alfvén waves, transverse kink modes may also be present in coronal holes (Van Doorsselaere et al. 2008; Goossens et al. 2009, 2012). Furthermore, the detection of strong damping of Alfvénic waves at low heights in coronal holes suggests that wave-driven processes may be responsible for heating the plasma (Bemporad & Abbo 2012; Hahn et al. 2012; Hahn & Savin 2013; Hara 2019).

The most promising wave-based model put forward to explain the damping of wave energy in coronal holes involves

nonlinear interaction between counterpropagating waves, resulting in the development of turbulence, which leads to an irreversible cascade of wave energy to smaller scales, at which the waves are more easily damped, leading to the heating of the plasma (Moore et al. 1991a, 1991b; Matthaeus et al. 1999; Dmitruk et al. 2001; Oughton et al. 2001; Cranmer et al. 2007; Chandran & Hollweg 2009). Recent observations of counterpropagating Alfvénic waves in coronal holes support the wave-turbulence model (Morton et al. 2015). But, the mechanism responsible for the generation of counterpropagating waves is still unknown. Among the different theories put forward to explain the counterpropagating waves (Musielak et al. 1992; Del Zanna et al. 2001), a number of them invoke partial reflection of outward-propagating Alfvén waves at low heights in coronal holes due to an Alfvén-speed inhomogeneity along the ambient magnetic field lines (Moore et al. 1991a, 1992; Musielak et al. 1992; Hahn et al. 2018; Asgari-Targhi et al. 2021; Hahn et al. 2022).

Several experiments have been carried out in the past where Alfvén waves were made to propagate through an Alfvén-speed gradient produced by a magnetic field gradient. However, none of those experiments detected a reflected wave (Stix & Palladino 1958; Swanson et al. 1972; Breun et al. 1987; Yasaka et al. 1988; Roberts et al. 1989; Vincena et al. 2001; Mitchell et al. 2002; Bose et al. 2019). An experiment on Alfvén wave propagation through multiple magnetic field wells reported a possible indirect signature of wave reflection (Zhang et al. 2008), but the geometry studied is not relevant to coronal holes.

Here, we report the first direct detection of a reflected Alfvén wave in the laboratory under conditions relevant to coronal holes. The wave experiments were performed in the Large Plasma Device (LAPD; Gekelman et al. 2016; Bose et al. 2019).

The rest of this paper is organized as follows. A comparison of coronal hole and LAPD parameters relevant to Alfvén wave physics is described in Section 2. The wave experiments and



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Table 1
Dimensionless Parameters for Coronal Holes and LAPD

Parameter	Coronal Hole	LAPD
$\bar{\beta}$	3–18	5–11
$\bar{\omega}$	$\lesssim 9.4 \times 10^{-5}$	0.2–0.35
$k_{\perp}^2 \rho_i^2$	$\ll 1$	$\ll 1$
$k_{\perp}^2 \rho_s^2$	$\ll 1$	$\ll 1$
β_e	$1.5\text{--}9.6 \times 10^{-3}$	$0.7\text{--}1.5 \times 10^{-3}$
$\lambda_{\parallel}/L_{A,\min}$	$\gtrsim 4.5$	$\lesssim 7.5$
ν_{ci}/ω	2–2400	42–114
$L_{A,\min}/\lambda_{\text{mfp},e}$	~ 13	9–46
b/B_0	$\lesssim 0.02$	$\lesssim 10^{-4}$

simulations are presented and analyzed in Sections 3 and 4, respectively. In Section 5, we discuss the implication of our results in the solar context. This is followed by a summary in Section 6.

2. Alfvén Waves in Coronal Holes and LAPD

The plasma and Alfvén wave parameters in the LAPD were scaled to match those in coronal holes, to within laboratory limitations, by adopting the framework discussed by Bose et al. (2019). In the Sun, Alfvén waves excited in the photosphere (Narain & Ulmschneider 1996; Priest 2014) propagate upward through coronal holes along the ambient magnetic field lines, which are nearly straight. The geometry of the LAPD is similar to coronal holes: LAPD is a cylindrical machine, wherein we excite waves at one end of the machine, and the waves follow the magnetic field along the length of the machine.

Alfvén waves interact with electrons and ions in the plasma as the waves propagate. The response of the electrons to the wave field is characterized by the dimensionless parameter, $\bar{\beta} = 2v_{te}^2/v_A^2$. The electron thermal speed $v_{te} = \sqrt{T_e/m_e}$, where T_e is the electron temperature in energy units and m_e is the electron mass. The Alfvén speed $v_A = B_0/\sqrt{\mu_0\rho}$, where 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 is the ion number density, n_e is the electron number density, and m_i is the ion mass.

In coronal holes, $\bar{\beta} > 1$. As a result, the electrons respond adiabatically to the wave field. We matched the condition of coronal holes $\bar{\beta} > 1$ in the LAPD by tuning the parameters such as n , T_e , and B_0 (see Table 1).

The wave energy in coronal holes has a wide spectrum. However, most of the wave energy occurs at $\omega \ll \omega_{ci}$, where $\omega_{ci} = qB_0/m_i$ is the angular ion cyclotron frequency, and q is the charge of the ion. Models suggest photospheric fluctuations primarily generate waves at frequencies $f = \omega/2\pi$ between ~ 0.1 and 100 mHz (Cranmer & Van Ballegoijen 2005). The ambient magnetic field in a coronal hole is ~ 0.7 G at a height of $0.15 R_{\odot}$ (Morton et al. 2015), where $R_{\odot}$ is the solar radius. At this height, $\bar{\omega} = \omega/\omega_{ci}$ ranges from $\approx 9.4 \times 10^{-8}$ to 9.4×10^{-5} . The parameter $\bar{\omega}$ reduces the Alfvén wave speed as ω approaches ω_{ci} . This effect can be seen from the simplified Alfvén wave dispersion relation adopted from Gekelman et al. (1997, 2011):

$$\frac{\omega}{k_{\parallel}} \approx v_A \sqrt{1 - \bar{\omega}^2}, \quad (1)$$

where $\rho_s = c_s/\omega_{ci}$ is the ion sound gyroradius, $c_s = \sqrt{T_e/m_i}$ is the ion sound speed, $k_{\parallel} = 2\pi/\lambda_{\parallel}$ is the wavenumber parallel to B_0 , and $\lambda_{\parallel}$ is the wavelength along B_0 . We minimized the finite frequency correction, $1 - \bar{\omega}^2$, by limiting the wave frequency to satisfy $\bar{\omega} \lesssim 0.35$ near the antenna.

Alfvén wave dynamics can be affected by two-fluid and kinetic effects (Cross 1988; Gekelman et al. 1997; Cramer 2011). One of the parameters that affects two-fluid and kinetic physics is $k_{\perp}$, which appears in the rigorously derived Alfvén wave dispersion relation through the dimensionless terms $k_{\perp}^2 \rho_i^2$, $k_{\perp}^2 \rho_s^2$, and $k_{\perp}^2 \delta_e^2$ (Gekelman et al. 1997; Cramer 2011; Bose et al. 2019). Here, $k_{\perp} = 2\pi/\lambda_{\perp}$ is the wavenumber perpendicular to B_0 , $\lambda_{\perp}$ is the perpendicular wavelength of the Alfvén wave, $\rho_i = v_{ti}/\omega_{ci}$ is the ion Larmor radius, $v_{ti} = \sqrt{T_i/m_i}$ is the ion thermal velocity, T_i is the ion temperature, $\rho_s = c_s/\omega_{ci}$ is the ion sound gyroradius, $\delta_e = c/\omega_{pe}$ is the electron skin depth, c is the speed of light, $\omega_{pe} = \sqrt{ne^2/m_e \epsilon_0}$ is the electron plasma frequency, e is the fundamental unit of electrical charge, and ϵ_0 is the permittivity of free space.

In coronal holes, there is no measurement of the $k_{\perp}$ spectrum of the Alfvén waves. However, studies have measured the correlation length in the transverse direction at the base of the corona. According to these studies, Alfvén waves at the energy-containing scale may be described by ideal magnetohydrodynamics (MHD; Sharma & Morton 2023). Furthermore, most of the wave-based heating models invoke ideal MHD conditions, i.e., $k_{\perp}^2 \rho_i^2$, $k_{\perp}^2 \rho_s^2$, and $k_{\perp}^2 \delta_e^2$ are all $\ll 1$ (Gekelman et al. 1997). We used an antenna that excites a large dominant $\lambda_{\perp}$ to match this condition in the LAPD (Gigliotti et al. 2009; Karavaev et al. 2011). In our experiments, the dominant $\lambda_{\perp}$ of the incident wave is approximately 21.78 cm, ensuring that $k_{\perp}^2 \rho_i^2$, $k_{\perp}^2 \rho_s^2$, and $k_{\perp}^2 \delta_e^2$ are all $\ll 1$. This value of $\lambda_{\perp}$ is determined from the wave data using a Fourier–Bessel analysis (Churchill & Brown 1987) as illustrated by Vincena (1999).

The energy in coronal holes is in the magnetic field. The magnetic pressure dominates over thermal pressure, which is represented by the dimensionless parameter $\beta_e = 2\mu_0 n T_e / B_0^2$. The value of β_e varies between $\approx 9.6 \times 10^{-3}$ and 1.5×10^{-3} at low heights in coronal holes (Bose et al. 2019). To match this in the LAPD, we adjusted B_0 , n , and T_e to produce a value of β_e ranging from $\approx 0.7 \times 10^{-3}$ to $\approx 1.5 \times 10^{-3}$.

Alfvén waves encounter a strong v_A gradient at low heights in coronal holes. An estimate of the effect of the gradient on a wave is $\lambda_{\parallel}/L_A$, which is also referred to as the wave inhomogeneity parameter. L_A is the length scale of v_A in the gradient. This length scale is defined as v_A/v_A' , where v_A' is the first spatial derivative of v_A . If $\lambda_{\parallel}/L_A \gtrsim 1$, the gradient is strong because v_A changes significantly within a wavelength; while if $\lambda_{\parallel}/L_A < 1$, the gradient is weak because the variation of v_A within a wavelength is small. In coronal holes, L_A varies spatially at low heights, and we have used $L_{A,\min}$ for scaling purposes, where $L_{A,\min}$ is the minimum value of the length scale in the gradient region. Note that the length scale attains its minimum value at the strongest part of the gradient. The bulk of the wave energy in coronal holes satisfies the condition $\lambda_{\parallel}/L_{A,\min} \gtrsim 4.5$ (Morton et al. 2015; Bose et al. 2019). To match this regime in the LAPD, we adjusted B_0 , n , and ω to produce $\lambda_{\parallel}/L_{A,\min}$ up to 7.5.

Alfvén waves are known to damp due to Coulomb collisions (Cramer 2011). A parameter characterizing the effect of

collisions on waves is ν_{ei}/ω , where ν_{ei} is the electron-ion collision frequency. The ratio ν_{ei}/ω is a measure of the number of collisions occurring in a wave period. If $\nu_{ei}/\omega \gg 1$, the plasma is collisional for the wave; and if $\nu_{ei}/\omega \ll 1$, it is collisionless plasma. To calculate ν_{ei} , we use the conventional method from Braginskii (1965):

$$\nu_{ei} = 2.9 \times 10^{-6} n \Lambda T_e^{-3/2}, \quad (2)$$

where Λ is the Coulomb logarithm (Huba 2016), and ν_{ei} is in hertz. For coronal hole conditions of $n \sim 2 \times 10^7 \text{ cm}^{-3}$ and $T_e \sim 86 \text{ eV}$ (10^6 K) at $0.15 R_\odot$, we find $\nu_{ei} \sim 1.5 \text{ Hz}$ (Morton et al. 2015; Cranmer 2009). Therefore, for wave frequencies ranging from $f \sim 0.1$ to 100 mHz (Cranmer & Van Ballegooyen 2005), ν_{ei}/ω varies from ~ 2 to 2400 . Hence, at low heights in the v_A gradient region of coronal holes, collisions are sufficient to affect Alfvén wave physics. To match this in the laboratory, we adjusted, ω , n , and T_e (see Table 1).

Another estimate of the effect of electron-ion collisions on the Alfvén wave in the gradient region is given by the ratio of the electron mean free path, λ_{mfpe} , to $L_{A,min}$ (Bose et al. 2019). This ratio gives a measure of the number of electron mean free paths within the v_A gradient. The value of $L_{A,min}/\lambda_{mfpe}$ in coronal holes is estimated to be ~ 13 (Bose et al. 2019). We match this in the LAPD by suitably selecting the range of n , T_e , and $L_{A,min}$. See Table 1 for representative values of $L_{A,min}/\lambda_{mfpe}$ in the LAPD.

Lastly, Alfvénic waves with amplitude as high as $b/B_0 \sim 0.02$ were reported in coronal holes (McIntosh et al. 2011). In this regime, nonlinear effects may play a role. Following Bose et al. (2019), we restricted our experiment to the low-amplitude regime $b/B_0 \lesssim 10^{-4}$ to avoid known nonlinear effects associated with larger-amplitude Alfvén waves.

3. Experiments

3.1. Overview

The LAPD was used to produce an $\approx 19 \text{ m}$ long cylindrical plasma column (Gekelman et al. 2016). Electromagnets arranged coaxially along the cylindrical vacuum vessel were used to generate a background axial magnetic field, B_0 . Plasma was formed through electron impact ionization of helium by applying a discharge voltage between a mesh anode and a LaB₆ cathode located at the far end of the machine, as shown in Figure 1.

For our experiments, a two-cycle linearly polarized Alfvén wave of azimuthal mode number $m = 1$ was excited using an orthogonal ring antenna placed on the cylindrical axis of the LAPD at $x = y = z = 0$ (Gigliotti et al. 2009; Karavaev et al. 2011; Bose et al. 2019). Triaxial B-dot probes at $z_1 = 1.92 \text{ m}$, $z_2 = 3.51 \text{ m}$, $z_3 = 7.67 \text{ m}$, and $z_4 = 8.95 \text{ m}$ were used to make wave magnetic field measurements (Everson et al. 2009; Bose et al. 2018).

We studied the reflection of Alfvén waves by varying $\lambda_{||}$ and $L_{A,min}$. The wave frequency was changed to vary $\lambda_{||}$, while different B_0 gradients were employed to alter $L_{A,min}$. The four B_0 profiles used for the reflection experiments are shown in Figure 1.

A Langmuir probe was used to measure n and T_e for the gradient cases (Hershkowitz et al. 1989; Bose et al. 2017). The density measurements were calibrated using an interferometer that measured line-integrated density. For the gradient cases,

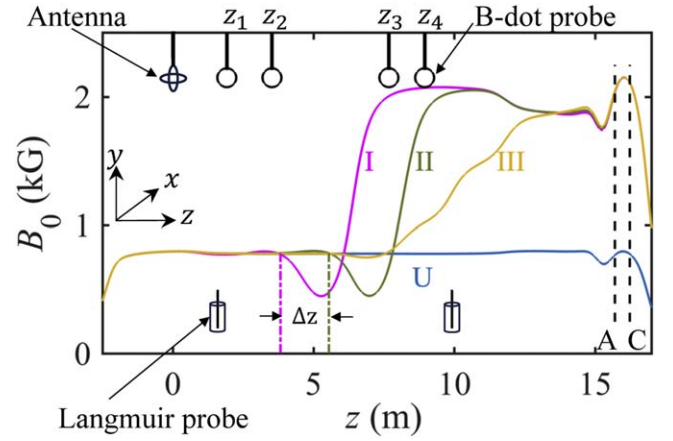


Figure 1. Schematic of the experimental arrangement. The anode (A) and the cathode (C) of the plasma source are at 15.7 and 16.23 m , respectively. The orthogonal ring antenna used to excite Alfvén waves is located at $x = y = z = 0$. The vertical ring of the antenna lies in the y - z plane, while the horizontal ring lies in the x - z plane. The four magnetic field profiles used for the wave experiment (U, I, II, and III) are indicated by different colors. The locations of the four B-dot probes are indicated at the top of the figure. A Langmuir probe was used to make measurements at two locations shown at the bottom of the figure. The quantity Δz corresponds to 1.72 m .

the estimated plasma parameters at $z = 1.6 \text{ m}$ are $n \sim 5\text{--}8 \times 10^{12} \text{ cm}^{-3}$ and $T_e \sim 3 \text{ eV}$, while at $z = 9.9 \text{ m}$ they are $n \sim 7\text{--}9 \times 10^{12} \text{ cm}^{-3}$ and $T_e \sim 10 \text{ eV}$. We do not have Langmuir probe measurements for the uniform B_0 case; the estimated n from the Alfvén wave dispersion relation is $\sim 8 \times 10^{12} \text{ cm}^{-3}$.

3.2. Detection of an Alfvén Wave Reflected from a v_A Gradient

We performed a number of wave experiments to detect a reflected Alfvén wave from a v_A gradient and validate the findings. We first studied the wave propagation through a uniform B_0 as a control case (profile U in Figure 1). Second, we excited an Alfvén wave in the presence of a strong v_A gradient (profile I in Figure 1) and detected a reflected wave from the v_A gradient. Third, we pushed the v_A gradient further from the antenna (profile II in Figure 1) and found the phase difference between the incident and reflected waves increased, confirming that the v_A gradient is the reflector. Fourth, we weakened the v_A gradient significantly (profile III in Figure 1); we could not find a reflected wave from this gradient, proving that reflection is a gradient-driven effect. In the subsections below, we describe the results and analysis of these experiments using an $\approx 76 \text{ kHz}$ incident wave as an example.

3.2.1. Alfvén Wave in Uniform B_0

Figure 2 shows the wave magnetic field time series recorded by B-dot probes at z_1 and z_2 for gradient U. Initially, the peaks and troughs of the wave signal at z_1 leads z_2 , which is consistent with an incident wave propagating in the $+z$ direction. Some time after the incident wave in Figure 2, we see a much smaller wave in the region between the dotted lines. The signal of this smaller wave is observed at z_2 before z_1 , indicating the waveform is propagating in the $-z$ direction, toward the antenna.

Our analysis suggests that the smaller wave signal is reflected from the plasma source at the far end of the LAPD. Furthermore, reflection introduces an additional 180° phase

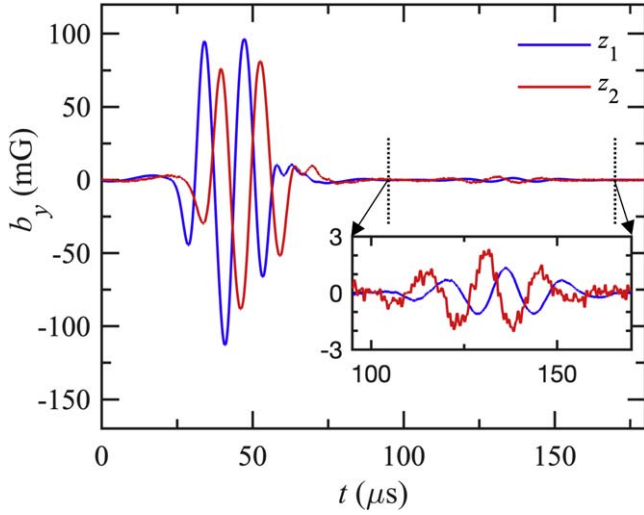


Figure 2. The time variation of the y-component of the wave magnetic field, b_y . The measurements were made on the axis of the LAPD at z_1 and z_2 for case U. Initially, the wave at z_1 (blue) occurs before the wave at z_2 (red), suggesting that the wave is propagating away from the antenna. The waveform within the dotted lines, highlighted in the inset figure, is due to reflection from the cathode and propagation toward the antenna.

difference between the reflected and incident waves; the smaller signal in Figure 2 has three peaks and two troughs, while the incident wave has two peaks and three troughs. We performed time-of-flight calculations using the logic that if the smaller wave at z_1 is reflected from the plasma source, then the time lag between the incident and the inverted smaller waves should be equal to twice the time of flight of the incident wave from z_1 to the plasma source. The time lag (t_{lag}) between the incident and the smaller waves obtained from their phase difference at z_1 is $95.3 \pm 0.4 \mu\text{s}$. The error bar represents the 1σ uncertainty obtained by calculating the standard deviation of the time lag measured at various radial locations. The time of flight ($t_{\text{tof}}^{\text{U}}$) of the incident wave from z_1 to the plasma source is determined by dividing the distance between z_1 and the cathode, 14.31 m, by the velocity of the wave. The velocity of the wave is $3 \pm 0.1 \times 10^5 \text{ m s}^{-1}$, as determined by dividing the distance between z_1 and z_2 by the time lag between the wave signals at those two locations. Therefore, $t_{\text{tof}}^{\text{U}}$ is $47.7 \pm 1.6 \mu\text{s}$. Hence, $t_{\text{lag}}^{\text{U}}$ agrees with $2t_{\text{tof}}^{\text{U}}$, indicating that the smaller wave has been reflected from the plasma source. Our findings agree with previous experiments where physical objects in the plasma, such as metal and insulator plates, were found to reflect Alfvén waves (Leneman 2007).

3.2.2. Wave Reflection from a Strong v_A Gradient

We introduced a strong v_A gradient between the antenna and the far end of the LAPD and detected a wave reflected from the v_A gradient. The minimum value of the v_A length scale within the gradient was $L_{A,\text{min}} = 0.74 \text{ m}$. The wave magnetic field data before the gradient are given in Figure 3(a). Initially, the peaks and troughs of the wave signal at z_1 leads z_2 , which is expected for an incident wave. However, in the region between the dotted lines, a small wave signal is observed at z_2 before z_1 , suggesting the wave is propagating in the $-z$ direction. This is likely due to a partial superposition of waves reflected from gradient I and the plasma source, as we explain shortly. Here, we remind the reader that since $v_A \propto B_0$, the time window for the wave reflected by the plasma source at z_1 and z_2 for the

strong v_A gradient and uniform B_0 profile will be different as the values of B_0 near the plasma source are different in the two cases.

In order to help disentangle wave reflection from the gradient from wave reflection by the plasma source, we also measured the wave magnetic field on the high-field side at z_3 and z_4 (Figure 3(b)). The first two peaks and troughs at z_3 leads z_4 , which is consistent with wave propagation in the $+z$ direction. However, the third trough of z_3 lags behind z_4 , suggesting the presence of a wave reflected from the far end in the measured signal. The amplitude of the third trough at z_4 is also more than at z_3 , suggesting constructive interference between waves traveling in the $+z$ (incident) and $-z$ (reflected from far end) directions. The presence of a far-end reflected wave is also supported by the amplitude of the third peak at z_4 , which is greater than z_3 . This observation suggests that the far-end reflected wave may have reached z_4 around $t = 68.3 \pm 3.5 \mu\text{s}$. The upper limit corresponds to the time of the third peak at z_4 , where we observe a signature of a reflected wave from the far end. The lower limit refers to the time of the second trough at z_4 where we do not observe a sign of reflection from the far end.

Building on this, we put forward two sets of analyses which imply that the first cycle of the wave propagating in the $-z$ direction at z_2 is reflected from gradient I only and does not have any contribution due to far-end reflection. First, we estimate the time at which a wave reflected from the plasma source will reach z_2 . The arrival time of the reflected wave from the source is equal to $68.3 \pm 3.5 \mu\text{s}$ plus the time of flight of the wave from z_4 to z_2 . Since the speed of Alfvén wave propagation in the $+z$ and $-z$ directions is the same, the time of flight of an Alfvén wave from z_4 to z_2 (i.e., the $-z$ direction) is determined from the phase difference of the incident wave (i.e., the $+z$ direction) between z_2 and z_4 . The inferred time of flight is $21.4 \pm 0.7 \mu\text{s}$. Therefore, the part of the waveform at z_2 beyond $t = 89.7 \pm 3.6 \mu\text{s}$ may contain a contribution from a wave reflected from the plasma source. Hence, the first cycle of the waveform in the inset graph of Figure 3(a) is not affected by reflection from the source.

Next, we show that the location of reflection of the first cycle of the wave propagating in the $-z$ direction at z_2 is within gradient I. Since gradient I is located between z_2 and z_3 , for the first cycle to be reflected from the gradient I, the time lag between the incident and reflected wave at z_2 , $t_{\text{lag}}^{\text{I}}$, must be less than twice the time of flight of the wave from z_2 to z_3 , $2t_{\text{tof}}^{\text{I}}$. We used the results of the simulations given in Section 4 to correlate the phases of the incident and gradient-reflected waves. Simulations showed that reflection from a v_A gradient introduces a 180° phase difference between the incident and the reflected waves. In addition, the simulations also suggest that the leading low-amplitude trough of the incident Alfvén wave may not produce a sufficiently strong reflected wave to be experimentally detectable. The subsequent peaks and troughs of the incident Alfvén wave, though, are predicted to produce a detectable reflected wave. Therefore, in Figure 3(a), the first peak of the incident wave should correspond to the first trough of the wave moving in the $-z$ direction if it is reflected from the v_A gradient. The time lag between the first peak of the incident wave and the first trough of the reflected wave is $t_{\text{lag}}^{\text{I}} = 36.0 \pm 0.2 \mu\text{s}$. The time of flight of the wave from z_2 to z_3 obtained by comparing the phase difference between the $+z$ propagating part of the wave at z_2 and z_3 is $t_{\text{tof}}^{\text{I}} = 20.4 \pm 0.7 \mu\text{s}$. Hence, $t_{\text{lag}}^{\text{I}} < 2t_{\text{tof}}^{\text{I}}$, indicating that the source of reflection is located within gradient

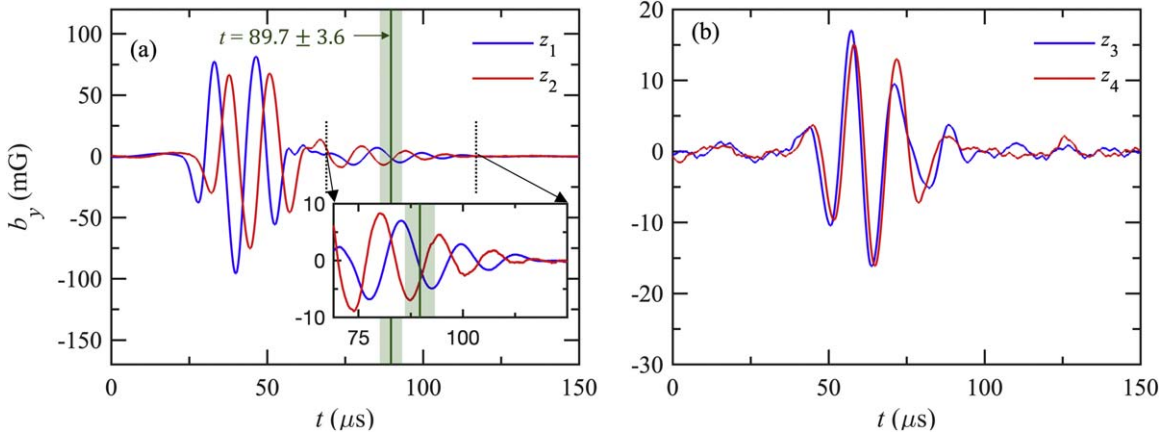


Figure 3. The b_y time series for gradient I as measured on the axis of the LAPD (a) on the low-field side at z_1 and z_2 , and (b) on the high-field side at z_3 and z_4 . The inset figure in (a) shows the waveform propagating toward the antenna on the low-field side. The green line and shaded region in (a) represent the expected time for a wave reflected from the cathode to arrive at z_2 .

I. This experimental finding is supported by our simulations, described in Section 4.

3.2.3. Wave Reflection Experiment by Changing the Location of a Strong v_A Gradient

To further confirm experimentally that gradient I is indeed reflecting an Alfvén wave, we moved the gradient further away from the antenna and checked if the time lag between the incident and reflected waves increased accordingly. We refer to this shifted gradient as gradient II. A comparison of the wave signal at z_2 for gradients I and II is presented in Figure 4.

We performed further analysis to quantitatively show that the phase difference between the reflected wave from gradients I and II agrees with the extra distance traversed by the wave to reach gradient II and return. The investigation was done using the first wave cycle propagating in the $-z$ direction for both gradients. This is because an analysis for gradient II following the methodology in Section 3.2.2 that was used for gradient I showed that the reflector for the first cycle is located within the gradient II region. The time lag between waves reflected from gradients I and II is $t_{\text{lag}}^{I,II} \approx 2\Delta z/v_{\text{ph},\parallel}$, where $\Delta z = 1.72$ m is the distance between I and II (Figure 1), and $v_{\text{ph},\parallel}$ is the phase velocity of the Alfvén wave parallel to B_0 in the low-field side. We find $v_{\text{ph},\parallel} = 3.3 \pm 0.1 \times 10^5$ m s $^{-1}$, as determined by dividing the distance between z_1 and z_2 by the phase difference of the incident wave at z_1 and z_2 . This gives, $t_{\text{lag}}^{I,II} \approx 10.4 \pm 0.3$ μ s. The phase difference between the reflected wave from gradients I and II is $\Delta t_{I,II}^{\text{ref}} \approx 11.0 \pm 0.2$ μ s. In Figure 4, we find a minor phase offset between the incident waves for cases I and II, possibly due to a small difference in density. This minor phase offset adds to the phase difference between the reflected waves from the two gradients. Correcting for the phase difference between incident waves, we find $\Delta t_{I,II}^{\text{ref}} \approx 10.0 \pm 0.3$ μ s. Thus, $t_{\text{lag}}^{I,II}$ closely agrees with $\Delta t_{I,II}^{\text{ref}}$, further confirming that the gradient is reflecting Alfvén waves. This experimental finding is supported by our simulations, discussed in Section 4.

3.2.4. Alfvén Wave Incident on a Weak v_A Gradient

As a further test to prove that the first cycle of the reflected wave in Figure 3(a) is a gradient-driven effect, we weakened the v_A gradient and repeated the experiment. The $L_{A,\text{min}}$ within the gradient was 3.24 m. The wave magnetic field data at z_1 and

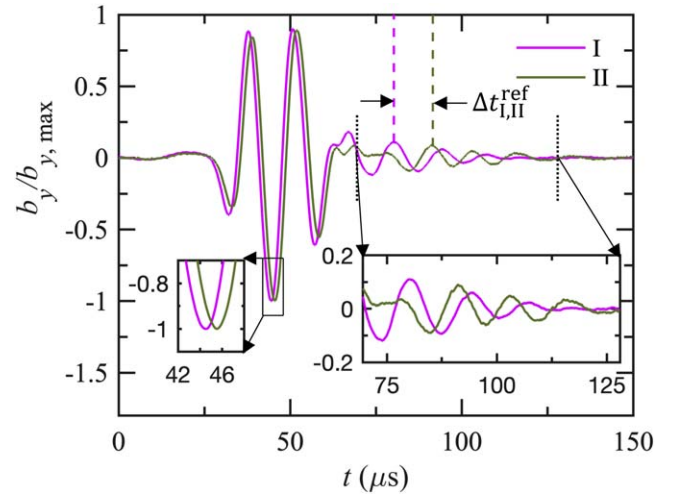


Figure 4. Comparison of the normalized b_y time series measured at z_2 on the axis of the LAPD before (magenta) and after (green) moving the gradient away from the antenna. The inset figure on the right highlights the significant phase difference observed between the reflected waves due to moving the gradient away from the antenna. The inset figure on the left shows that there is a minor phase difference between the incident waves of the two cases.

z_2 for gradient III is shown in Figure 5. Initially, the troughs and peaks of the wave signal at z_1 leads z_2 , which is consistent for a wave propagating in the $+z$ direction. However, some time after the incident wave in Figure 5, we see a much smaller wave in the region between the dotted lines. This small wave is propagating in the $-z$ direction, as the peaks and troughs of the small wave at z_2 leads z_1 .

Analysis shows that the small wave is reflected from the plasma source of the LAPD and that there is no signature of the wave being reflected from the gradient. For the small wave to be reflected from the source, the time lag ($t_{\text{lag}}^{\text{III}}$) between the incident and small wave at z_1 should be equal to twice the time of flight ($t_{\text{tof}}^{\text{III}}$) of the wave from the z_1 to the plasma source. The $t_{\text{lag}}^{\text{III}}$ measured by cross-correlating the incident and small waves after accounting for the 180° phase shift caused by reflection is 67.2 ± 1.5 μ s. The time of flight calculated using $t_{\text{tof}}^{\text{III}} = \int_{z=z_1}^{z=16.3} dz / \int_{z=z_1}^{z=16.3} v_A dz$ is 35.7 ± 1.9 μ s. Here, the z dependence of B_0 primarily causes an axial variation of v_A as $v_A \propto B_0$, while a minor variation in n does not affect v_A much

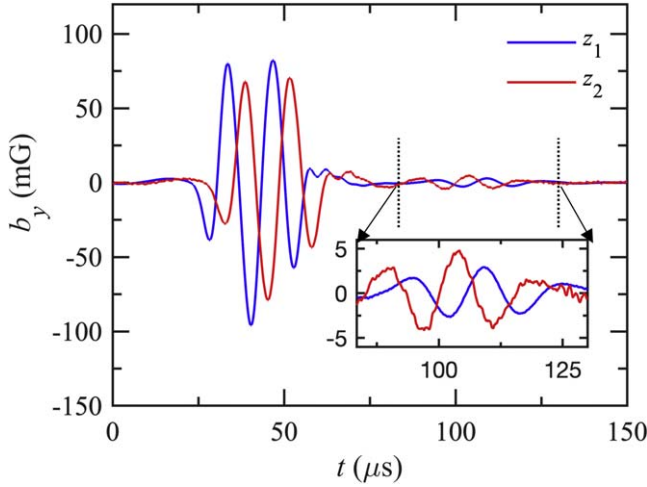


Figure 5. The time variation of b_y for gradient III measured on the axis of the LAPD at z_1 and z_2 . Initially, the peaks and troughs of the wave signal at z_1 leads z_2 , which is consistent for a wave propagating in the $+z$ direction. However, some time after the incident wave, the smaller wave reflected from the far end is seen propagating in the $-z$ direction.

as $v_A \propto 1/\sqrt{n}$. Therefore, $t_{\text{lag}}^{\text{III}}$ agrees with $2t_{\text{tof}}^{\text{III}}$ to within the measurement uncertainty, proving that the small wave is reflected from the plasma source. Since we do not observe any other wave between the incident wave and the small source-reflected wave in Figure 5, we conclude that gradient III does not reflect Alfvén waves. This experimental finding is supported by our simulations, which show that gradient III does not reflect (see Section 4).

3.3. Dependence of Reflected Alfvén Wave Energy on the v_A Inhomogeneity

We determined the coefficient of reflection, $\mathcal{R}$, to quantify the effectiveness of a v_A gradient in reflecting Alfvén waves. As a first step for determining $\mathcal{R}$, we calculate the energy of the incident wave and of the wave reflected from the v_A gradient. The energy, $\mathcal{E}$, of an Alfvén wave is obtained by integrating the Poynting vector of the wave, and $\mathcal{E}$ is given by

$$\mathcal{E} = \int \left(\iint S_{\parallel} dx dy \right) dt, \quad (3)$$

where $S_{\parallel} \approx \frac{1}{4\pi} b^2 v_{\text{ph},\parallel}$ is the energy flux along $\mathbf{B}_0$ (Bose et al. 2019). The spatial integration is carried out over the xy cross section of the LAPD, and the integration in time, t , is carried out over the duration of the wave train.

$\mathcal{R}$ is obtained from $\mathcal{E}$ using

$$\mathcal{R} = \frac{\Gamma_r}{\Gamma_i} = \frac{\mathcal{E}_r/t_{\text{dur},r}}{\mathcal{E}_i/t_{\text{dur},i}} = \frac{\left[\int \left(\iint b_r^2 dx dy \right) dt \right] / t_{\text{dur},r}}{\left[\int \left(\iint b_i^2 dx dy \right) dt \right] / t_{\text{dur},i}}, \quad (4)$$

where Γ is the wave power, t_{dur} is the time duration of the wave train, and the subscripts “i” and “r” refer to the incident and reflected waves, respectively. The quantity $t_{\text{dur},i}$ consists of the initial ramp-up period and the first full cycle of the incident wave, while $t_{\text{dur},r}$ is the period of the first cycle of the reflected wave. The definition of $t_{\text{dur},i/r}$ is motivated by the simulation results given in Figure 8(d), where a single cycle of the reflected wave is produced by an incident wave comprising of an initial ramp-up followed by a full cycle.

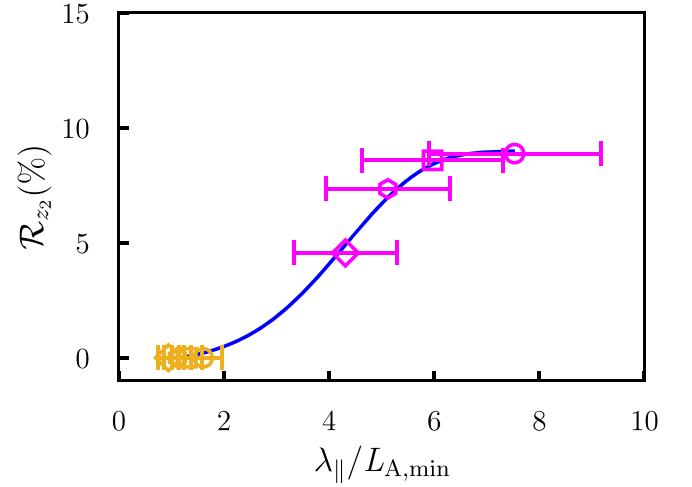


Figure 6. The variation of the coefficient of reflection of an Alfvén wave measured at z_2 vs. $\lambda_{\parallel}/L_{A,\text{min}}$. The vertical error bars are smaller than the symbol size. The value of $\lambda_{\parallel}$ was changed by altering the wave frequency. The different wave frequencies are represented by various symbols: circle = 61 kHz, square = 76 kHz, hexagon = 89 kHz, and diamond = 104 kHz. $L_{A,\text{min}}$ was varied by changing the B_0 gradient. The magenta and yellow colors correspond to gradients I and III, respectively. The continuous blue line is the most probable function that connects the data points as per GPR.

3.3.1. Measurement of the Coefficient of Reflection at z_2

The values of $\mathcal{R}$ calculated by taking the ratio of the reflected to incident wave power at z_2 is given by color-filled symbols in Figure 6, where the magenta- and yellow-colored data points represent measurements for gradients I and III, respectively. $\mathcal{R}$ is presented as a percentage by multiplying Equation (4) by 100. For convenience, we have referred to $\mathcal{R}$ measured at z_2 as $\mathcal{R}_{z_2}$.

The $\mathcal{R}_{z_2}$ data points for gradient I show that longer-wavelength waves are reflected more strongly from a v_A gradient than shorter wavelengths. The wavelengths were changed by varying the wave frequency. For the longest wavelength, $\lambda_{\parallel} = 5.6 \pm 1.2$ m ($\lambda_{\parallel}/L_{A,\text{min}} = 7.5 \pm 1.6$), and $\mathcal{R}_{z_2}$ is $\approx 9\%$. For the shortest wavelength, $\lambda_{\parallel} = 3.2 \pm 0.7$ m ($\lambda_{\parallel}/L_{A,\text{min}} = 4.3 \pm 1$ m), and $\mathcal{R}_{z_2}$ is 4.6%. Note, the error bar of $\lambda_{\parallel}$ is due to uncertainty in frequency measurement, which in turn is due to the finite temporal length of the incident wave. We estimated the frequency uncertainty using the full width at half maximum of the frequency peak in the Fourier spectrum of the incident wave.

A comparison of $\mathcal{R}_{z_2}$ data points for gradients I and III suggests that the length scale of the v_A gradient affects wave reflection. $\mathcal{R}_{z_2}$ is zero for gradient III, as measurement of the wave magnetic field along the x -axis spanning the width of the plasma column at $y=0$ did not reveal any signature of a reflected wave from the v_A gradient. However, $\mathcal{R}_{z_2}$ is nonzero for gradient I. The key difference between gradients I and III are their values of $L_{A,\text{min}}$ because $\lambda_{\parallel}$ for both gradients lie in the same range. The $L_{A,\text{min}}$ values for gradients I and III are 0.74 m and 3.24 m, respectively. Note that $L_{A,\text{min}}$ signifies the degree of inhomogeneity of a v_A gradient and a small $L_{A,\text{min}}$ indicates a strong gradient.

The blue curve in Figure 6 shows the variation of $\mathcal{R}_{z_2}$ versus $\lambda_{\parallel}/L_{A,\text{min}}$ as predicted by Gaussian process regression (GPR), a class of machine-learning algorithms (Rasmussen 2005). GPR is a Bayesian nonparametric regression technique that predicts

a probability distribution over possible functions that fit a set of discrete data points. The blue curve in Figure 6 gives the mean of the probability distribution, i.e., the most probable characterization of the data (Pedregosa et al. 2011; Bose et al. 2024).

3.3.2. Estimating the Coefficient of Reflection in the Gradient

The values of $\mathcal{R}_{z_2}$ in Figure 6 are the lower limit of the coefficient of reflection. This is because the incident Alfvén wave damps as it propagates from z_2 to the location of the reflector in the gradient, causing the incident wave energy to be smaller at the location of the reflector than at z_2 . Similarly, the reflected wave damps as it propagates from the site of the reflector in the gradient, causing the reflected wave energy to be smaller at z_2 . As a result, the incident wave energy is overestimated, while the reflected wave energy is underestimated at z_2 compared to the corresponding energies at the site of the reflector in the gradient.

We have used a simple model to estimate the incident and reflected wave energy at the site of the wave reflector to make a zeroth-order correction to the directly measured values of $\mathcal{R}_{z_2}$. In the model, the incident wave energy at z_2 ($\mathcal{E}_i$) is related to the incident wave energy at the site of the wave reflector ($\mathcal{E}_{i,0}$) by

$$\mathcal{E}_{i,0} \approx \mathcal{E}_i \exp(-2\Delta z/d), \quad (5)$$

where Δz is the distance between z_2 and the location of the reflector, and d is the collisional damping length of the Alfvén wave, i.e., the length over which the Alfvén wave amplitude decreases to $1/e$ of its initial value. Note, the factor 2 appears in the exponential term of Equation (5) because $\mathcal{E} \propto b^2$ and the damped amplitude of $b \propto \exp(-\Delta z/d)$. Similarly, the reflected wave energy at the reflector ($\mathcal{E}_{r,0}$) and at z_2 ($\mathcal{E}_r$) are related by

$$\mathcal{E}_r \approx \mathcal{E}_{r,0} \exp(-2\Delta z/d). \quad (6)$$

Therefore, the coefficient of reflection at the site of the reflector ($\mathcal{R}_0$) is given by

$$\mathcal{R}_0 \approx \frac{\mathcal{E}_{r,0}/t_{\text{dur},r}}{\mathcal{E}_{i,0}/t_{\text{dur},i}} \approx \mathcal{R}_{z_2} \exp(4\Delta z/d). \quad (7)$$

The collisional damping length is estimated using the two-fluid dispersion relation of Alfvén waves for uniform plasma in the $\bar{\beta} \gg 1$ limit (Vranjes et al. 2006; Gigliotti et al. 2009; Bose et al. 2019):

$$\omega^2 - k_{\parallel}^2 v_A^2 (1 - \bar{\omega}^2 + k_{\perp}^2 \rho_s^2) + i\omega k_{\perp}^2 \delta_e^2 \nu_e = 0. \quad (8)$$

This quadratic equation can be solved algebraically, and the imaginary root, $k_{\text{Im},\parallel}$, gives the damping length:

$$d = \frac{1}{k_{\text{Im},\parallel}} = \frac{\sqrt{2} v_A}{\omega} \left[\frac{\sqrt{1 + k_{\perp}^4 \delta_e^4 (\nu_e/\omega)^2} - 1}{1 - \bar{\omega}^2 + k_{\perp}^2 \rho_s^2} \right]^{-1/2}. \quad (9)$$

The dominant perpendicular wavelength of the incident wave is $\lambda_{\perp} = 21.78$ cm. The average value of the plasma parameters between z_2 and the reflector are employed for estimating d using Equation (9). The site of the reflector is taken to be the location of the strongest part of the v_A gradient, which is at $z = 6.2$ m; therefore, $\Delta z = 2.7$ m. The average B_0

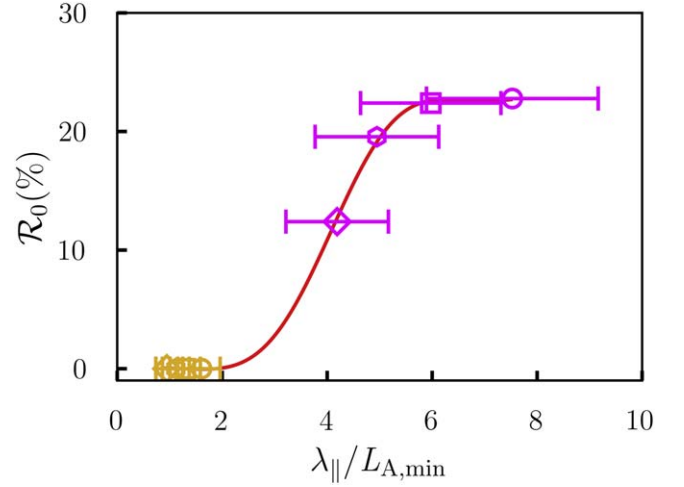


Figure 7. The variation of the coefficient of reflection of an Alfvén wave estimated at the site of the reflector in the gradient, $\mathcal{R}_0$, vs. $\lambda_{\parallel}/L_{A,\text{min}}$. The vertical error bars are smaller than the symbol size. The continuous red line is the most probable function that connects the data points as per GPR.

between z_2 and $z = 6.2$ m is 623 G. The values of d for 61, 76, 89, and 104 kHz waves are 11.4, 11.2, 11, and 10.6 m, respectively.

The resulting value of $\mathcal{R}_0$ has a monotonic variation with respect to $\lambda_{\parallel}/L_{A,\text{min}}$, as shown in Figure 7. The data points are shown by symbols, while the red curve is the most probable characterization of the data points as per GPR. The $\mathcal{R}_0$ versus $\lambda_{\parallel}/L_{A,\text{min}}$ curve shows that as the inhomogeneity increases, so does the reflection of Alfvén waves.

The values of $\mathcal{R}_0$ are approximate quantities as we estimated the d of the Alfvén wave in the gradient using the dispersion relation for a uniform plasma. A comprehensive analysis to accurately determine d in a strong non-WKB gradient relevant to our experiments is beyond the scope of this paper. However, past experiments of Bose et al. (2019) do provide an insight on the damping of Alfvén waves in a strong non-WKB gradient. They found the energy reduction of an Alfvén wave in a strong non-WKB gradient to be more than in an almost uniform plasma. Furthermore, the wave damping was found to increase on enhancing the inhomogeneity parameter in the strong non-WKB regime. This implies that the values of d used to calculate $\mathcal{R}_0$ overestimate the damping length in the gradient, and the overestimation is more for stronger gradients. Thus, the model underestimates $\mathcal{R}_0$, and the underestimation is more for stronger gradients. Therefore, $\mathcal{R}_0$ in Figure 7 is likely to be a lower bound on the coefficient of reflection after a simple correction for collisional damping. Furthermore, the appearance of saturation of $\mathcal{R}_0$ at $\lambda_{\parallel}/L_{A,\text{min}} \gtrsim 6$ may be an artifact of the greater underestimation of $\mathcal{R}_0$ at strong gradients.

Figure 7 may also serve as a useful tool for comparing the $\mathcal{R}_0$ predicted by Alfvén wave heating models that invoke wave reflection to experimental data. However, the comparison should be limited to $\lambda_{\parallel}/L_{A,\text{min}} \leq 7.5$, for which the experimental data exist; and one should bear in mind that the $\mathcal{R}_0$ values are likely the lower limit of the Alfvén wave reflection coefficient. Extrapolating the laboratory data to predict $\mathcal{R}_0$ in the transition region of the Sun, where density changes almost discontinuously, may not be appropriate. $\mathcal{R}_0$ is expected to be greater than 23% for inhomogeneities stronger than attained in the laboratory. However, it is not possible to comment on the upper limit of $\mathcal{R}_0$ from the available experimental data; further

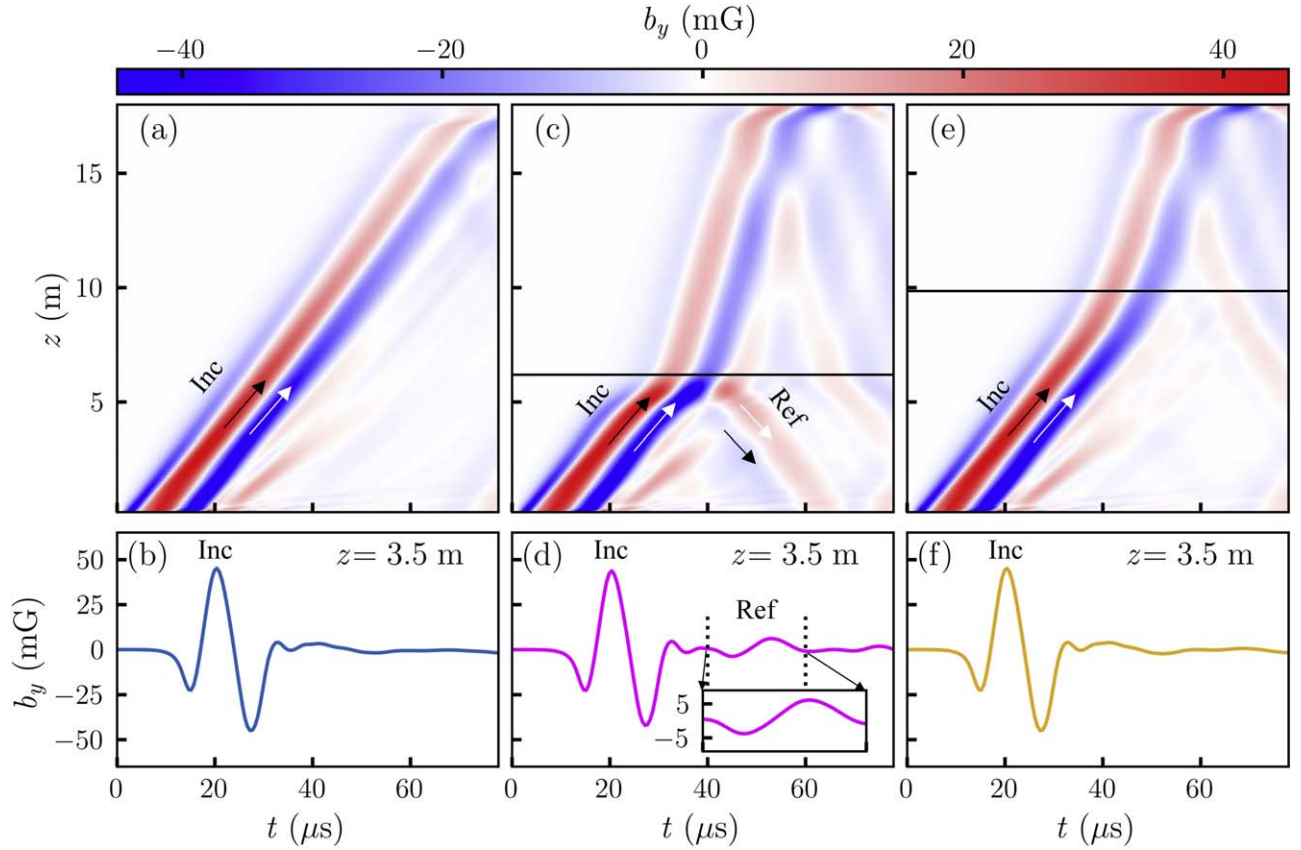


Figure 8. Top row: two-dimensional color plots of $b_y(x = y = 0)$ displaying the propagation of the incident (“Inc”) Alfvén wave and its reflection (“Ref”) in the t - z plane for gradients (a) U, (c) I, and (e) III. The z -axis extends from 0.2 to 18 m, while the t -axis ranges from 0 to 78 μ s. The deep red color implies that the oscillating b_y is at its maximum positive value of the wave peak, while the deep blue indicates b_y is at the minimum of the wave trough. The arrows trace the phase of the wave. The black horizontal line in panels (c) and (e) show the z location of $L_{A,\min}$ in the v_A gradient. Bottom row: the time variation of b_y obtained by taking a horizontal cut at $z = 3.5$ m for gradients (b) U, (d) I, and (f) III. The inset figure in panel (d) shows b_y vs. t between 40 and 60 μ s.

analysis and new experiments will be needed to make an accurate prediction.

4. Simulations

4.1. Overview

We employ the five-moment, two-fluid model (Hakim et al. 2006; Wang et al. 2015, 2020) within the Gkeyll simulation framework to model Alfvén wave reflection in the LAPD. The five-moment model evolves equations for density, momentum, and isotropic pressure for each species, which are coupled through Maxwell’s equations, and includes the displacement current. We model the full LAPD domain in Cartesian coordinates with reflecting boundary conditions in each dimension, $-0.6 \text{ m} \leq x, y \leq 0.6 \text{ m}$, and $-10 \text{ m} \leq z \leq 18 \text{ m}$, and employ $n_x = n_y = 64$ and $n_z = 700$ cells. We initialize a helium plasma, $m_i = 4m_p$, with $m_p = 1.67 \times 10^{-24} \text{ g}$ and a reduced mass ratio, $m_i/m_e = 100$, uniform temperatures and densities based on fiducial values from the experiments, $T_e = 7 \text{ eV}$, $T_e/T_i = 5$, and $n = n_e = n_i = 7 \times 10^{12} \text{ cm}^{-3}$. The speed of light for simulations is taken to be $c \simeq 9.5 \times 10^6 \text{ m s}^{-1}$. Three background, axial magnetic field profiles are employed corresponding to field profiles U, I, and III in Figure 1. We drive the plasma with a model of the Arbitrary Spatial Waveform (ASW) antenna placed at $z = 0 \text{ m}$ (Thuecks et al. 2009; Drake et al. 2013). The antenna parameters are $J = 10 \text{ kA m}^{-3}$, $f_{\text{ant}} = 76.4 \text{ kHz}$, and $\lambda_{\perp \text{ant}} = 21.78 \text{ cm}$, which drives an Alfvén wave with $\lambda_{\parallel} \simeq 4.4 \text{ m}$. The antenna is driven for a time $t_{\text{drive}} = 1.5/f_{\text{ant}}$. This includes ramping up and down

periods, each of length $t_{\text{ramp}} = 0.25/f_{\text{ant}}$. We note that we both extend the LAPD-model domain to $z = -10 \text{ m}$ and flatten the background magnetic field gradient in this region to reduce spurious reflections from behind the antenna.

4.2. Results

4.2.1. Alfvén Wave through Uniform B_0

Figure 8(a) shows the wave propagation along the cylindrical axis of the LAPD in the t - z plane for gradient U. The color gives the y -component of the wave magnetic field, which in turn also indicates the phase of the wave. The slope of the band traced by the phase of the wave indicates the propagation direction of the wave; positive and negative slopes correspond to the $+z$ and $-z$ directions, respectively. In Figure 8(a), the slope of the band traced by the phase of the wave is positive, consistent for an incident wave propagating away from the antenna. Figure 8(b) shows the time variation of the incident wave at $z = 3.5 \text{ m}$. Unlike the experiment, we do not see a wave reflected from the far end in the time-series data because the simulation was carried out up to $\approx 78 \mu\text{s}$, and the wave reflected from the far end requires a longer time to reach $z = 3.5 \text{ m}$.

4.2.2. Alfvén Wave Reflection from a Strong v_A Gradient

Figure 8(c) shows the wave propagation in the t - z plane for gradient I, where we observe experimentally wave reflection

from the v_A gradient. Initially, from $t=0$ to $\lesssim 40 \mu\text{s}$ and $z \lesssim 5$ m, the wave propagates in the $+z$ direction as expected for an incident wave. Upon reaching the gradient region, where $L_A \approx L_{A,\min}$, a portion of the incident wave is reflected. The negatively sloped arrows trace the phases of the wave reflected from the v_A gradient.

We observe that reflection from a v_A gradient introduces a 180° phase difference between the wave magnetic field of the incident and the reflected waves. In Figure 8(c), the deep blue band of the incident wave, marked by the positively sloped white arrow, correlates to the negatively sloped red band (reflected wave), marked by the negatively sloped white arrow. Similarly, the positively sloped deep red band of the incident wave corresponds to the negatively sloped blue band of the reflected wave, as shown by the black arrows in Figure 8(c). The change in the color between the corresponding phases of the incident and the reflected waves represents a 180° phase difference. We performed a second test to check the phase difference. Simulations using an incident wave having only a strong negative b_y (i.e., no strong positive b_y) gave rise to a reflected wave with only a positive b_y , further demonstrating a 180° phase difference between the incident and reflected waves due to reflection. See Appendix for the additional details on this second test.

The time variation of b_y before the gradient at $z = 3.5$ m in Figures 8(c) and (d) show that the first low-amplitude trough of the incident wave does not produce a strong detectable reflected wave. The reasons for this observation may be related to the process associated with Alfvén wave reflection at the boundary, such as establishing currents at the boundary to support a reflected Alfvén wave. A discussion on the interaction of the Alfvén wave with the v_A gradient boundary is beyond the scope of this paper and will be discussed elsewhere.

4.2.3. Alfvén Wave Incident on a Weak v_A Gradient

Figure 8(e) shows the wave propagation in the t - z plane for case III, i.e., the B_0 profile with gradient III. We do not observe any wave reflection from the v_A gradient, but the transmitted wave is reflected from the far end of the simulation domain. The b_y time-series data in Figure 8(f) only show a well-formed incident wave and do not exhibit any signature of a reflected wave from the v_A gradient.

5. Discussion

Our experimental results have implications regarding the heating of coronal holes. A significant temperature increase of coronal hole plasma occurs at low heights (Ko et al. 1997; Landi 2008), a region where v_A is highly nonuniform. The spatial variation of v_A is shown by the red curve in Figure 9(a). We used approximate fits of density and magnetic field given by Cranmer & Van Ballegoijen (2005) to calculate v_A .

A comparison of the wave inhomogeneity parameter ($\lambda_{\parallel}/L_A$) for a coronal hole with that of the laboratory suggests that $\mathcal{R}$ can be greater than 23% at low heights. The spatial variation of v_A and L_A in a coronal hole are given by the red and blue curves, respectively, in Figure 9(a). The $\lambda_{\parallel}$ at different heights in a coronal hole for various wave frequencies, f , can be estimated using $\lambda_{\parallel} = v_A/f$. The values of f vary from 0.2 to 10 mHz (Morton et al. 2015). The resulting values of $\lambda_{\parallel}/L_A$ were used to obtain estimates of $\mathcal{R}$ for a coronal hole by comparing the $\lambda_{\parallel}/L_A$ of a coronal hole with the $\lambda_{\parallel}/L_{A,\min}$ of the

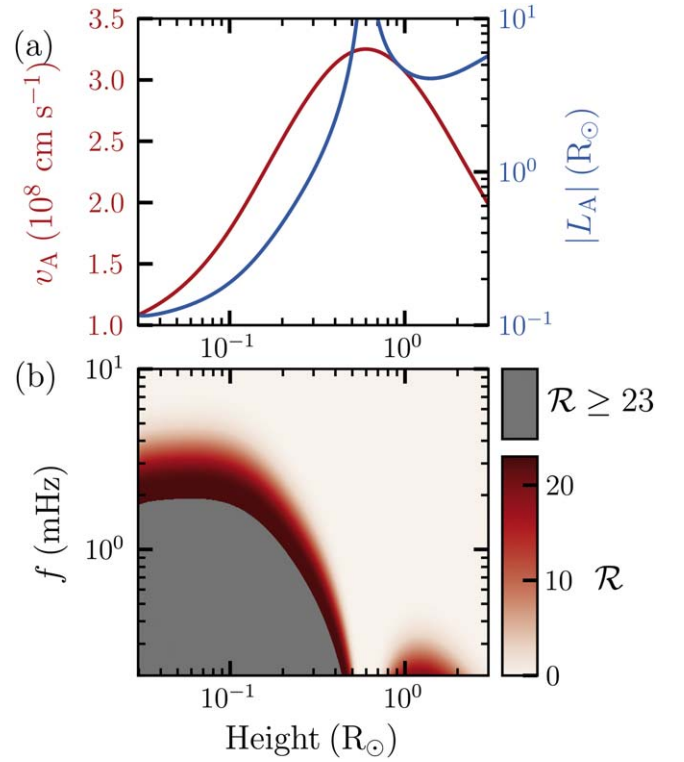


Figure 9. (a) The variation of Alfvén speed, v_A , and length scale of the v_A gradient in a coronal hole vs. height from the surface of the Sun. (b) A color map showing the estimated coefficient of reflection, $\mathcal{R}$ (%), for different wave frequencies (0.2–10 mHz) at different heights above the surface of the Sun in a coronal hole. Note that Alfvén waves are reflected strongly at low heights ($\lesssim 0.13 R_\odot$) where the v_A gradient is strong (see main text). The phrase “strong reflection” in this context implies wave reflection that may be enough to generate sufficient heating of the plasma via the wave-turbulence mechanism.

laboratory (red curve in Figure 7). Figure 9(b) shows $\mathcal{R}$ for different values of f at various heights above the surface of the Sun. The different shades of red show the values of $\mathcal{R}$ from 0% to 23%, while the gray indicates $\mathcal{R} \geq 23$. The reason for using the gray color is that in a portion of the frequency–height plane the coronal hole values of $\lambda_{\parallel}/L_A$ are greater than the maximum value of $\lambda_{\parallel}/L_{A,\min} = 7.5$ attained in the laboratory. Since the coefficient of reflection has a monotonic dependence on $\lambda_{\parallel}/L_{A,\min}$ in the laboratory with a maximum value of 23%, we assumed that $\mathcal{R}$ is $\geq 23\%$ in a coronal hole for $\lambda_{\parallel}/L_A > 7.5$.

A comparison of the data in Figure 9(b) with solar observations and solar simulations suggests that wave reflection from a smooth v_A gradient may be sufficient to significantly heat the plasma at low heights up to $0.13 R_\odot$ in coronal holes via the wave-turbulence model. Solar observations suggest that waves have sufficient energy to heat a coronal hole (McIntosh et al. 2011). Furthermore, measurement of the wave-frequency spectrum by Morton et al. (2015) indicates that the bulk of the wave energy occurs at frequencies below ~ 3 mHz in a coronal hole. Simulations of Asgari-Targhi et al. (2021) suggest that a reflection coefficient of $\sim 10\%$ may be sufficient to heat the plasma at heights below $3 R_\odot$ in coronal holes. They invoked density fluctuations to reflect $\sim 10\%$ of the wave power. However, our laboratory results suggest that a smooth v_A gradient relevant to low heights in coronal holes can reflect more than 10% of wave power. In Figure 9(b), $\mathcal{R}$ is greater than 10% for $f \leq 3$ mHz for a height up to $0.13 R_\odot$. Therefore, wave turbulence driven by nonlinear

interaction between outward-propagating waves from the Sun's surface and inward reflected waves may heat a coronal hole plasma enough to sustain 10^6 K temperature in the lower corona up to a height of $0.13 R_\odot$.

Although $\mathcal{R}$ tends to decrease above $0.13 R_\odot$, reflection may still continue to play a role in heating the plasma at heights up to $\approx 0.5 R_\odot$. The frequency spectrum of Alfvénic waves measured by Morton et al. (2015) suggests the wave energy is concentrated in frequencies at the lower end of the spectrum. In their measurement, the wave energy peaked at ~ 0.2 mHz, which was the lowest frequency in their data set. In Figure 9(b), waves of 0.2 mHz frequency have $\mathcal{R} \geq 10\%$ up to a height of $\approx 0.5 R_\odot$. The value of $\mathcal{R}$ for wave frequencies above 0.2 mHz progressively decreases from $0.13 R_\odot$ to $\approx 0.5 R_\odot$. These two features of Figure 9(b) suggest that wave reflection from the smooth v_A gradient will play a partial role in heating the plasma via a wave-turbulence mechanism but that the role of reflection is expected to progressively decrease with height from $0.13 R_\odot$ to $\approx 0.5 R_\odot$. At heights above $\approx 0.5 R_\odot$, reflection from the smooth v_A gradient is rather weak, and the reflected wave may not be of consequence in heating the plasma.

6. Summary

In this paper, we report the first experimental detection of a reflected Alfvén wave from a strong v_A gradient using a series of experiments in solar-like plasmas. Our results show that a strong v_A gradient is necessary to reflect Alfvén waves, and that the reflected wave energy increases for incident waves with longer wavelengths. The trend in the laboratory wave reflection data agrees with the solar observations of Morton et al. (2015), where they showed that the ratio of the outward-propagating wave power to the inward-propagating wave power increases for longer-wavelength waves, i.e., smaller wave frequencies. This indicates that the counterpropagating waves observed by Morton et al. (2015) may be due to wave reflection, supporting their hypothesis.

Two-fluid simulations using the `Gkeyll` code qualitatively agree with and support the experimental detection of a reflected Alfvén wave. In the simulations, we excited Alfvén waves using a model of the ASW antenna. We traced the propagation of Alfvén waves along the plasma column through a uniform B_0 profile, as well as strong and weak v_A gradients. Like the experiments, the simulations show that a strong v_A gradient reflects, while a weak v_A gradient does not. In the future, we will make quantitative comparison after developing a model of an orthogonal ring antenna for simulations similar to the one used in experiment.

We experimentally measured $\mathcal{R}$ for different values of $\lambda_{\parallel}/L_{A,\min}$, and presented two sets of values of $\mathcal{R}$, i.e., $\mathcal{R}_{z_2}$ and $\mathcal{R}_0$. $\mathcal{R}_{z_2}$ is determined by dividing the measured reflected wave power just after the wave exits from the gradient region by the incident wave power that enters the gradient region. The gradient region is of finite spatial extent, and since simulations showed that a wave reflects from the vicinity of the strongest part of the gradient, we estimated the coefficient of reflection near the strongest part, $\mathcal{R}_0$, using $\mathcal{R}_{z_2}$ and a model to take into account collisional damping between the edge of the gradient region and the center of the gradient region. The values of $\mathcal{R}_{z_2}$ and $\mathcal{R}_0$ were found to increase with increasing $\lambda_{\parallel}/L_{A,\min}$.

A comparison of the laboratory results and solar parameters suggests that Alfvén waves will be reflected by the smooth v_A gradient at heights up to $0.5 R_\odot$ in coronal holes. Furthermore, solar models suggest that the coefficient of reflection may be sufficient to generate enough inward-propagating waves at low heights in a coronal hole ($\lesssim 0.13 R_\odot$) to turbulently heat the plasma at these heights. The role of wave reflection from the smooth v_A gradient in heating the plasma is expected to progressively diminish from a height of ≈ 0.13 – $0.5 R_\odot$. In addition, at heights of $\approx 0.5 R_\odot$ or above, reflection from this gradient may not be adequate to generate enough plasma heating via the wave-turbulence mechanism, requiring other processes like density fluctuation to enhance wave reflection (Shoda et al. 2019; Asgari-Targhi et al. 2021).

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Data Availability

The data that supports the findings of this study are made available using Princeton Data Commons Discovery at doi:10.34770/a9h3-r161. `Gkeyll` is open source and can be installed by following the instructions on the `Gkeyll` website (<http://gkeyll.readthedocs.io>). The input and LAPD gradient files for the `Gkeyll` simulations presented here are available in the GitHub repository at <https://github.com/ammahakim/gkyl-paper-inp>.

Appendix

Phase Relationship between Incident and Reflected Wave

We performed additional simulations to test the phase relationship between the incident and reflected waves. Profile I was used for the simulations, where the Alfvén wave propagated from a region of low to high velocity. An incident wave having a strong negative b_y was found to produce a reflected wave with a positive b_y , as shown in Figure 10(a). The direction of the propagation of the wave was confirmed by

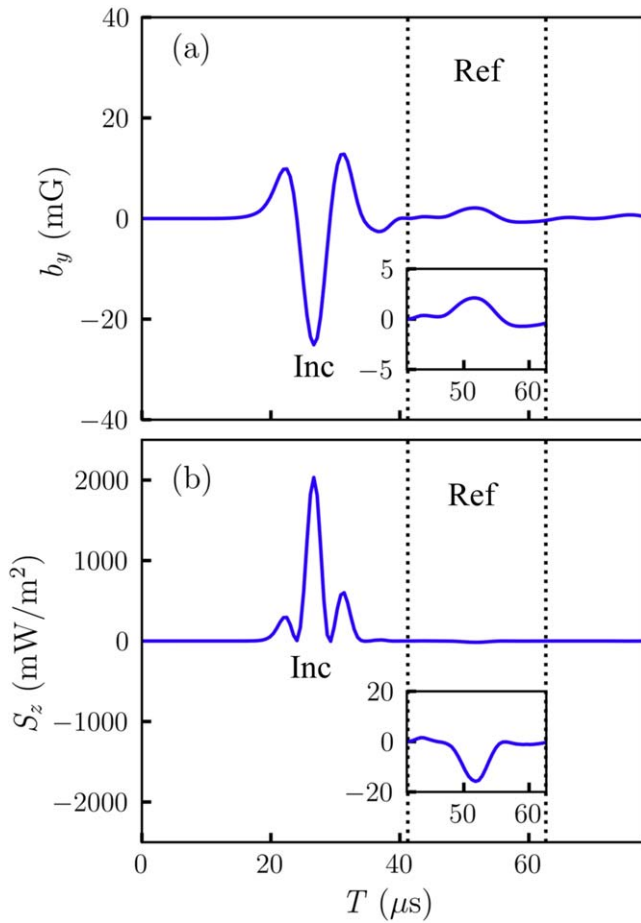


Figure 10. Time variation of (a) b_y and (b) S_z for profile I at $x = y = 0$ and $z = 3.5$ m showing the incident wave, referred to as “Inc,” and the reflected wave, denoted by “Ref.”

calculating the z -component of the Poynting vector, S , given in Figure 10(b). A positive value of S_z signifies propagation in the $+z$ direction, which is consistent for an incident wave. A reflected wave propagating in the $-z$ direction has a negative S_z value. Therefore, Figures 10(a) and (b) demonstrate that Alfvén wave reflection from gradient I introduces a 180° phase difference between the incident and reflected waves.

The results of the Alfvén wave reflection simulations agree with the predictions of theory of the reflection of light (Griffiths 2015), according to which the phase of the magnetic field of a light wave incident on a gradient from the low-velocity side is inverted by 180° upon reflection. The reason for the similarity between Alfvén and light waves may be because both are electromagnetic waves.

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