Experimental Observations of Shear Alfvèn Waves Generated by Narrow Current Channels.

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Abstract

Alfvén waves are ubiquitous in space plasmas and are the means by which information about changing currents and magnetic fields are communicated. Shear Alfvén waves radiated from sources with cross field scale size on the order of the electron inertial length, $\delta = c/\omega_{pe}$, have properties which differ considerably from planar Magneto-hydrodynamic waves. Currents of cross field size δ are common in space plasmas. A series of experiments in the **La**rge **P**lasma **D**evice at UCLA is presented which illustrate that waves generated by small scale fluctuating currents radiate across magnetic field lines and are associated with complex three dimensional currents. Waves generated by two sources are observed to constructively interfere to produce large magnetic fields in spatial regions away from source field lines. Volume data sets will be presented and discussed in the light of space plasma applications.

I. Introduction

The plasma environment that the Earth exists in is a difficult one to do experiments in. It is certainly not the best place to study basic plasma physics, but it is home for a wide variety of interesting phenomena. The principal tools in these investigations are rockets and satellites which record temporal records of field quantities at a single point. A satellite could be moving faster than the background ions, and the disturbance being recorded can rapidly sweep across the detectors, and perhaps come back for an encore.

In the past decade the quality of the instruments flown has increased enormously; there is more data flowing to the Earth than people to analyze it. Rockets and satellites cannot be used to directly measure wavenumbers, or for that matter the topology of anything. This type of experiment awaits the development of inexpensive, miniature satellites that could be flown in a flotilla.

A number of models of magnetic field geometry and current systems of the Earth's magnetopause have evolved over the past twenty years. Spacecraft data is carefully studied and cases which fit these models are identified. But every event cannot be fit into a neat category. Space plasmas are spatially non uniform, contain non-Maxwellian distribution functions and are subject to non local effects. Using paradigms which automatically equate a signal received by spacecraft with a model can be dangerous. In this paper we will present several examples of wave phenomena studied in the laboratory which are not part of the present model but could be of fundamental importance in space.

Alfvén Waves

Alfvén waves play a central role in the dynamics of many space plasmas from the solar corona to planetary ionospheres. They are low frequency waves [Alfvén,1942] (below the ion cyclotron frequency) propagating in a magnetized conducting fluid, such as the plasmas found in space. These waves not only transport electromagnetic energy but communicate information concerning changes in plasma currents and magnetic field topology.

There are two very different modes of electromagnetic propagation at low frequencies, a compressional wave in which density and field strength vary and a shear wave in which only the direction of the magnetic field changes. Here we are concerned only with the shear Alfvén wave. In the standard MHD (Magneto-Hydro-Dynamic) picture the shear Alfvén wave is particularly interesting because wave energy is transported directly along field lines. Measurements of fluctuations in the magnetic field due to the shear Alfvén wave then give a direct map of the source of the wave. This picture is modified, however, when the source radiating the wave has physical dimensions across the magnetic field on the order of the collisionless electron skin depth, $\delta = c/\omega_{pe}$ (c is the speed of light and ω_{pe} is the electron plasma frequency).

The properties of Alfvén waves have been the subject of several laboratory investigations (Bostick and Levine [1952], [Jephcott, 1959], [Sawyer, et al., 1959; Wilcox, et al., 1960],Jephcott and Stocker [1962], [Cross and Lehane, 1967a, 1967b; Lehane and Paoloni, 1971; Muller, 1973; Cross, 1988]. The first experiments on Alfvén waves were performed in pinches and arcs which produce high density plasmas, but suffer from high noise levels, large shot to shot variability and high collision rates. Recent studies of both the shear and compressional mode were done in a narrow, partially ionized column by Amagishi, et al. [1989, 1990, 1993, 1994] Wave propagation and polarization were measured but damping by neutral particles was found to significantly change the dispersion from the fully ionized case.

While these experiments establish the validity of the standard MHD picture of Alfvén waves, they do not address Alfvén wave radiation by small sources. A series of experiments on the propagation of the shear Alfvén wave launched by a small disk exciter has recently been reported by Gekelman, et al. [1994]. Related experiments using localized sources, but performed in plasmas with high electron-neutral collisionality were performed by Cross in a linear machine [Cross, 1983] and Borg and Cross [1987] in a small Tokamak. The experimental results reported here establish two important new characteristics associated with Alfvén wave radiation from small sources. The first property is the spreading of radiation across magnetic field lines along trajectories called Alfvén wave cones. The second feature is a magnetic field-aligned electric field which leads to wave dissipation through resonant wave-particle interactions.

II. Properties of the Shear Alfvén Wave

The shear Alfvén wave propagates with the wave magnetic field vector perpendicular to the background field. In the shear Alfvén wave the current along the magnetic field is carried by electrons while the current across the magnetic field is carried by ions. The dispersion relation for this wave can be obtained by combining the two Maxwell equations for the curl of the electric and magnetic field. The dispersion relation can be written as [Gekelman et al. 1997]

$$Z'(\zeta)\,(s^2(1-\varpi^2)-\zeta^2) \;=\; k_\perp^2\,\delta^2 \qquad (1)$$

where $s= v_A/a$ is the ratio of the Alfvén velocity ($v_A = \sqrt{B^2/(4\pi n m_+)}$ to the electron thermal speed, and ϖ is the normalized angular frequency ($\varpi= \omega/\Omega_+$). The subscripts $\parallel$ and $\perp$ refer to components of quantities along and across the background magnetic field respectively. Here ω_{p+} and Ω_+ are the ion plasma frequency and gyrofrequency, and $\zeta= \omega/k_\parallel a$ and $\lambda_+ = (k_\perp a_+/\Omega_+)^2$. The electron thermal speed is denoted by $a = (2T_e/m_e)^{1/2}$ with T_e

the electron temperature, measured in ergs, and m_e the electron mass. The ion thermal velocity a_+ is defined similarly with T_+ and M_+ denoting the ion temperature and mass. $Z'(\zeta)$ is the derivative of the plasma dispersion function with respect to ζ.

The form of the dispersion relation for the shear Alfvén differs in two regimes which we will designate as the inertial and kinetic regimes. The parameter s^2 is related to the electron plasma beta, $\beta_e = \left(\frac{8\pi nkT}{B^2}\right)$, as:

$$s^2 = \frac{v_A^2}{a^2} = \frac{m_e}{M_+}\frac{1}{\beta_e} \qquad (2)$$

In our experiments the parameter s^2 is small ($v_A{}^2 << a^2$), the plasma electron beta is larger than the mass ratio and the Alfvén speed is much slower than the electron thermal speed and the dispersion relation (1) simplifies to

$$\frac{\omega^2}{k_\parallel^2} = v_A^2\,(1 - \varpi^2 + k_\perp^2 \rho_s^2) \qquad (v_A^2 << a^2) \qquad (3)$$

where ρ_s is the ion sound gyroradius, $\rho_s = c_s/\Omega_+$, with $c_s = (T_e/M_+)^{1/2}$ the ion sound speed. The standard MHD dispersion relation is recovered in the case $k_\perp = 0$, and $\varpi \approx 0$. The kinetic Alfvén wave has a field aligned component of the electric field. For $k_\perp\rho_s$ large the parallel electric field is $E_\parallel = -(k_A\rho_s)E_\perp/(1-\varpi^2)$, where $k_a = \omega/V_A$.

III. Experimental Arrangement

Experiments on Alfvén wave propagation were conducted in the LAPD (**LA**rge **P**lasma **D**evice) [Gekelman, et al. ,1991] at UCLA (University of California, Los Angeles). The LAPD is a large cylindrical stainless steel chamber one meter in diameter, ten meters long, surrounded by 68 pancake magnets. The machine is ideal for studying Alfvén waves because of its large physical size, dense plasma and substantial magnetic field. The LAPD plasma column is 50 cm in diameter and 9.4 meters in length. The experiments reported here were performed in a He plasma with a uniform 1.1-1.32 kG magnetic field at a densities of up to 2.6 x 10^{12} cm^{-3}. Plasma densities are measured using both Langmuir probes and a 70 GHz microwave interferometer.

The LAPD plasma is produced by a DC (direct current) discharge using an oxide (BaO) coated nickel cathode. The chamber is filled with helium neutrals at a pressure of 2. x 10^{-4} Torr. Plasma is produced by pulsing the cathode negative (≈66 V) with respect to a wire mesh anode located 60 cm from the cathode. The discharge pulse is repeated at a rate of 1 Hz to allow for efficient signal averaging and data processing. The discharge pulse typically lasts 5-10 ms after which it is terminated. The experiments reported here were done in the active discharge. Plasma electron temperatures of about 10 eV are achieved during the discharge.

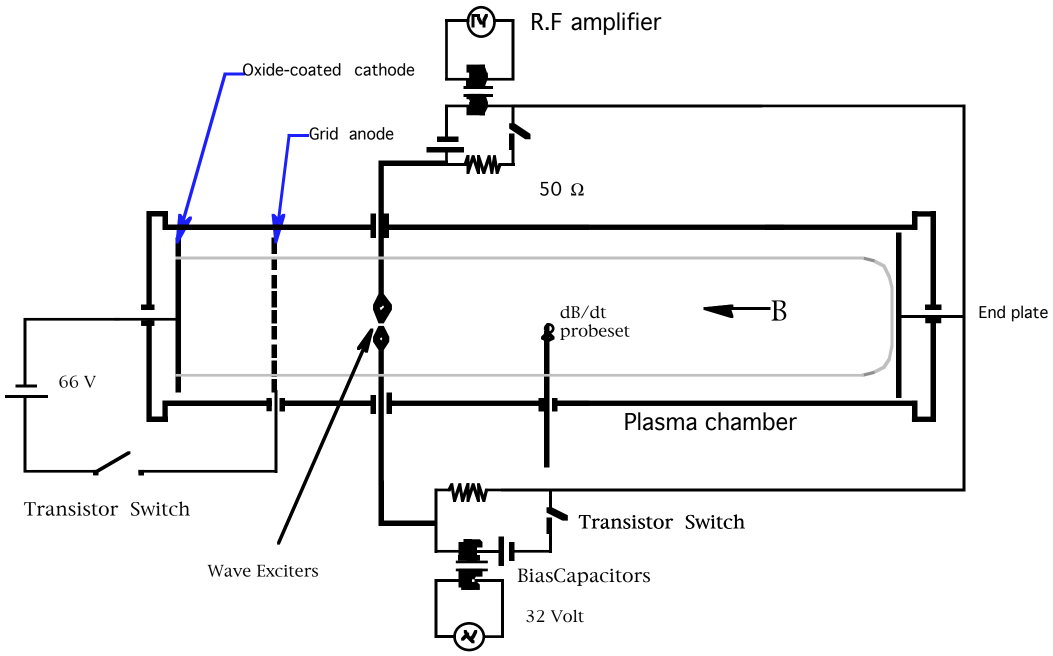

Figure 1) Schematic of the experimental set-up showing cathode, at distance δz = 60 cm from a gridded anode and the floating end plate of the machine (δ z = 10 m). In this view a single disk exciter for the shear wave is fed via a transformer. The disk may be biased with a capacitor in series with

a transistor switch. Data is acquired by a three-axis induction coil, magnetic probe which may be inserted at a number of locations along z. In the wave interference experiments two identical wave launchers are employed.

Figure 1 shows the experimental setup for launching and detecting the shear Alfvén wave from twin exciters. The radially movable antennas are circular disks of wire mesh (transparency ≈ 50%) attached to the inner conductor of a coaxial cable. The outer conductor is isolated from the plasma and the support is made of glass. The antennas are mounted on a bellows to allow for freedom in positioning. The radiated wave magnetic field is measured in planes perpendicular to the background magnetic field at various axial positions away from the antenna using a triaxial induction loop probe. The magnetic probe consists of three orthogonally oriented, 8 mm diameter, 3 mm thick, 58 turn, differential current loops. The magnetic probe was calibrated by measuring, in air, the magnetic field surrounding a long straight wire modulated at 300 kHz.

To excite the waves, a phase locked RF (Radio Frequency) tone burst is fed to one or two disk exciters through a broadband amplifier and isolation transformer. As shown in Figure 1, the signal ground is referenced with respect to an electrically floating Cu plate terminating the plasma column. The modulated grid potential drives a field aligned RF current which excites Alfvén waves. Current must flow in and out of the disk antenna. If the disc is at floating potential the current consists of electrons on one half cycle and ions on the next. Modulation of an electrically floating grid limits the amplitude of waves because the amount of ion current that can be drawn from the plasma is limited. Large amplitude waves can be launched by positively biasing the antenna, drawing electron saturation current, and then modulating that current ($V_{bias} > V_{peak\text{-}rf}$). Since a biased exciter draws a current which results in depletion of the density along the flux tube threading the antenna, the bias is applied with a pulsed transistor switch only during the time the RF is present.

A wide range of values for the background magnetic field strength, density and electron temperature are achievable in the plasmas produced with the LAPD. Therefore experiments are possible over a considerable range of electron beta values around the mass ratio. This flexibility allows us to investigate the properties of the Alfvén wave between the inertial and kinetic Alfvén wave limits. Electron beta values which have been explored in the LAPD range from 0.25 to 4 times the mass ratio.

An effect which must be considered in dealing with low frequency waves is the collisionality of the plasma. Collisions become important when $k_{||}\lambda_{mfp}$ is of order unity or less (λ_{mfp} is the mean free path). This criteria depends upon the wave frequency, plasma temperature and the type of collision process considered. In the LAPD, collisions of electrons with Helium neutrals is negligible because the plasma is highly ionized [Maggs, et al., 1991]. Electron-ion Coulomb collisions, on the other hand, are an important effect because the LAPD plasmas are dense and not very hot (due to the limited energy confinement time in a linear device). In the typical discharge plasma the electron-ion collision frequency is about $1. \times 10^6$ sec^{-1}.

IV. Experimental Results

1. Expected Behavior

The shear Alfvén wave transports energy directly along the magnetic field (no perpendicular group velocity) if $k_\perp$ is zero. For non-zero $k_\perp$ magnetic energy is transported across the magnetic field. The amplitude of radiation generated at a particular $k_\perp$ depends upon the size of the source radiating the wave. Small sources radiate more energy across the magnetic field than large sources. A large source is one with a physical size in the direction across the magnetic field much larger than the electron skin depth, δ , while a small source is one with physical size on the order of δ. A large source produces wave energy at small values of $k_\perp$ ($k_\perp\delta <<$ 1), while a small source radiates waves at large values of $k_\perp$ ($k_\perp\delta \approx 1$).

In the experiments reported here, Alfvén waves were radiated using small sources consisting of semi-transparent wire mesh disks with radii on the order of δ. Assuming azimuthal symmetry, the magnetic field radiated from these wire mesh antennas has only a component in the azimuthal direction, $\vec{B} = B_\theta(r,z)\,\hat{e}_\theta$. The spatial dependence of the radiated magnetic field is given by an integral expression involving the first order Bessel function J_1 [Morales, et al.,1994],

$$B_\theta(r,z) = \frac{2I_0}{cr_d}\int_0^\infty dk_\perp \, \frac{\sin(k_\perp r_d)}{k_\perp} \, J_1(k_\perp r)\exp\left(i\,k_\parallel(k_\perp)z\right) \qquad (4)$$

where I_0 is the oscillating current to the disk antenna and the disk radius is denoted by r_d. The dependence of parallel wave number on perpendicular wave number (i.e., $k_\parallel(k_\perp)$) is found by solving the dispersion relation given in Eq. 1.

According to Eq. 4, at any fixed axial position away from the disk exciter, the expected radial profile of the magnitude of the wave magnetic field has three characteristic features. First, the field is always zero at the disk center. Second, it increases with radial distance away from the disk center and reaches a peak value. The radial location of the peak value increases with axial distance away from the exciter. Third there exists a radial position, r_{edge} (the location of the outer Alfvén cone) beyond which the field decreases as 1/r. The 1/r decrease outside r_{edge} indicates that the oscillating wave currents are confined to $r < r_{edge}$. At a fixed radius larger than r_{edge} (i.e., outside the Alfvén cone) the magnetic field has the same value at all axial locations. In reporting our observations we compare the measured magnetic field profiles to the theoretically predicted profiles as given by Eq. 4.

2. Results

We now present our observations of the radiation of Alfvén waves from small disk antennas. Generally, we find the radiated field behaves in the expected fashion. We first briefly present observations of Alfvén waves radiated from a single disk exciter [Gekelman et al , 1997], verifying the spreading of magnetic energy across field lines . Typically, the Alfvén wave radiation spreads slowly across the magnetic field because $k_A\delta << 1$, but wave currents and their associated magnetic fields do indeed broaden across the ambient magnetic field. This spreading can be significant at large distances from the source of excitation. Next, we present the results of radiation from multiple sources to show the effects of constructive and destructive interference on determining the wave pattern.

a) Radiation from a single-small disk antenna.

The magnetic field pattern of Alfvén wave radiation from a small disk antenna with radius equal to the electron skin depth was measured with electron beta both larger and smaller than the mass ratio. The antenna was placed in the center of the plasma column and the field pattern measured in planes across the magnetic field at several axial locations. A phase locked tone burst consisting of several cycles is applied to the disk and received by a tri-axial magnetic probe. Typically, at each spatial location the received signal from each induction loop is recorded and stored on computer disk for ten to twenty plasma pulses. The probe is then moved to a new location and the process repeated.

The radiation pattern produced from the disk antenna is expected to be azimuthally symmetric with the magnetic field entirely in the azimuthal direction. The axial magnetic field component of the radiated field was indeed observed to be much smaller than the radial component $(\delta B_z)/(\delta B_\theta) \approx .01$) but departures from azimuthal symmetry were observed. A magnetic field profile for the case of the kinetic Alfvén wave ($\beta_e = 3.0 \times 10^{-4}$, $s^2 \approx 0.73$) is shown in figure 2.

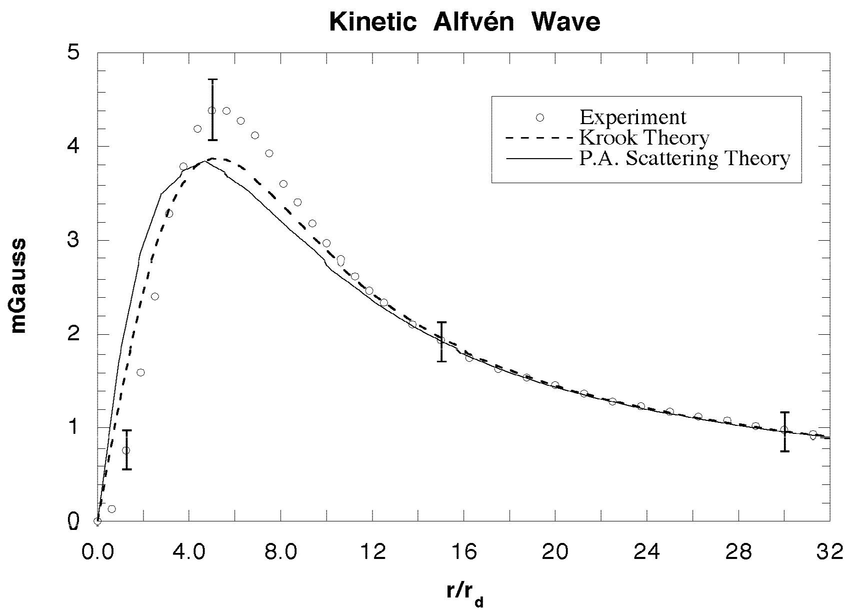

figure 2) Radial profile of $|B_\theta|$ for a low amplitude tone burst in Helium. Kinetic shear wave at $\omega / \omega_{ci} = 0.58$, $n_0 = 2.5 \times 10^{12}$ cm $^{-3}$, $B_0 = 1.1$ kG and $T_e = 3.0$

e.V. The measurements are shown with open circles and two theoretical predictions with a solid and dashed line. The solid curve shows the field profile predicted from assuming electron pitch angle (P.A.) scattering (Koch and Horton, 1975) and uses the measured values of n_0 and T_e. The dashed curve uses the Krook model of collisions and uses an ad-hoc Γ-value that gives the best fit (in this case Γ = 3.25 wher e $\Gamma = \nu_{collisions}/\omega$).

The probe is located 1.57 m ($\approx 0.75\ \lambda_{||}$) away from the exciter along the magnetic field. The kinetic wave pattern has a 1/r dependence at large r. Also from Fig. 2 we see the signal is close to zero at r = 0. Furthermore the spreading of the wave magnetic field across field lines is evident in both the location of the beginning of the 1/r portion ($r/r_d \cong 8$) of the pattern and the peak amplitude of the magnetic field.

b) Superposition of Alfvén wave Pulses

Propagation of Alfvén waves across the magnetic field makes nonlocal interactions between waves radiated from different sources possible as illustrated schematically in Figure 3.

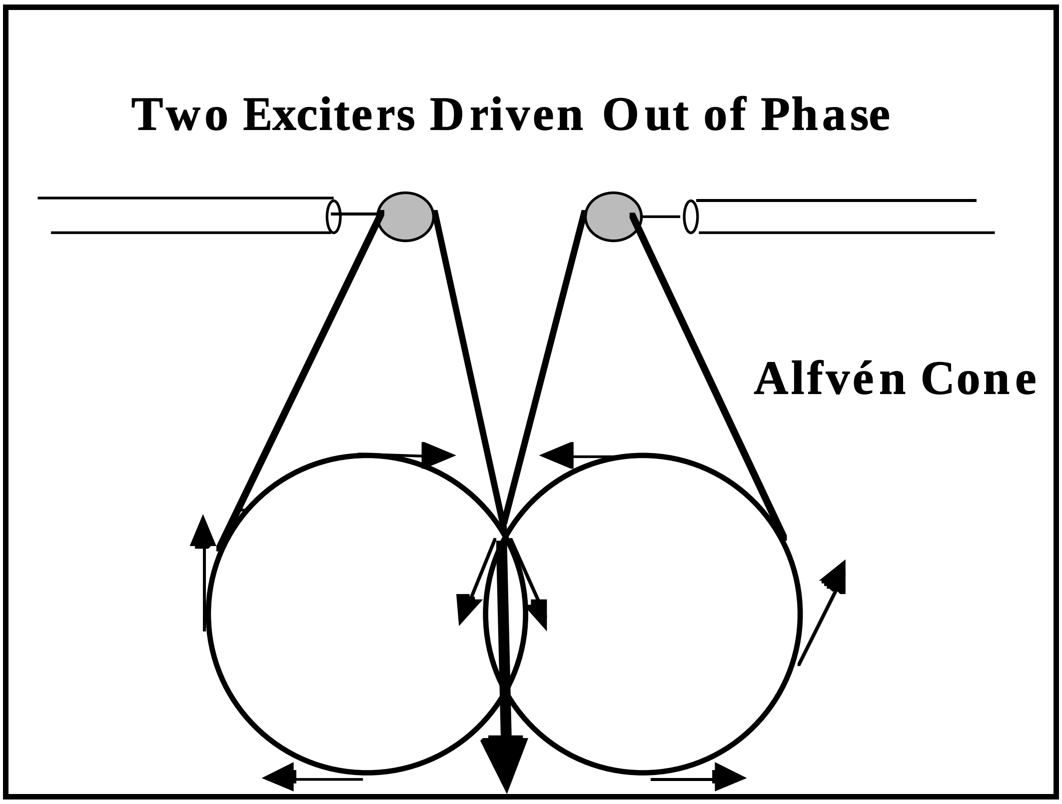

figure 3) Schematic illustrating two intersecting Alfvén cones. The interference pattern on axis produces an oscillating vertical field

To investigate the interaction between Alfvén waves, two identical disk antennas are situated in a uniform, magnetized plasma at the same axial location but on separate field lines. Each disk is excited by an RF signal coupled to the plasma through an isolation transformer to separate power amplifiers. The amplitude and phase of the signals are controlled by an arbitrary waveform generator. The signal ground is referenced to an electrically floating Cu plate terminating the plasma column. The interaction of the waves was investigated at low and high wave currents. As discussed above small wave currents are obtained with the disks at floating potential because ion current is collected on half the RF cycle. Large wave currents are produced by biasing the disks positive and modulating the subsequent electron saturation current. Antenna currents of several Amperes are easily attained using this technique.

Wave currents were obtained by applying a bias pulse of 32 Volts to both exciters 40 μsec before transmitting a 250 kHz, (ϖ = 0.50), five cycle tone burst. The antenna current was measured to be 6.0 Amps peak to peak. The two launch antennas were separated by 2 cm across the magnetic field and driven 180^{o} out of phase. The background magnetic field was 1.32 kG, the plasma density 2.6 x 10^{12} cm^{-3}, and the plasma electron beta 6.0x10^{-4}. Data was acquired on 9 x-y planes and **B** was measured at 472 spatial positions at each plane and 3000 time steps, 40 ns/step. The data was taken on a nearly rectangular grid 19 cm on a side at a 1 cm spacing but additional data was acquired with a spacing of 0.5 cm in the center section (3cm X 6 cm). The data was subsequently interpolated to a 0.5 cm spacing. Data on the interpolated plane were corrected to reflect the actual trajectory of the probe as it moved in the planes. The data planes along z were separated by approximately 30 cm. This is justified since the parallel wavelength of the shear wave under these conditions is 4.0 meters, while structural differences in $B_\perp$ varied over centimeters.

The magnetic field in a plane is contrasted in the case of a single exciter and that of two exciters driven out of phase in figure 4.

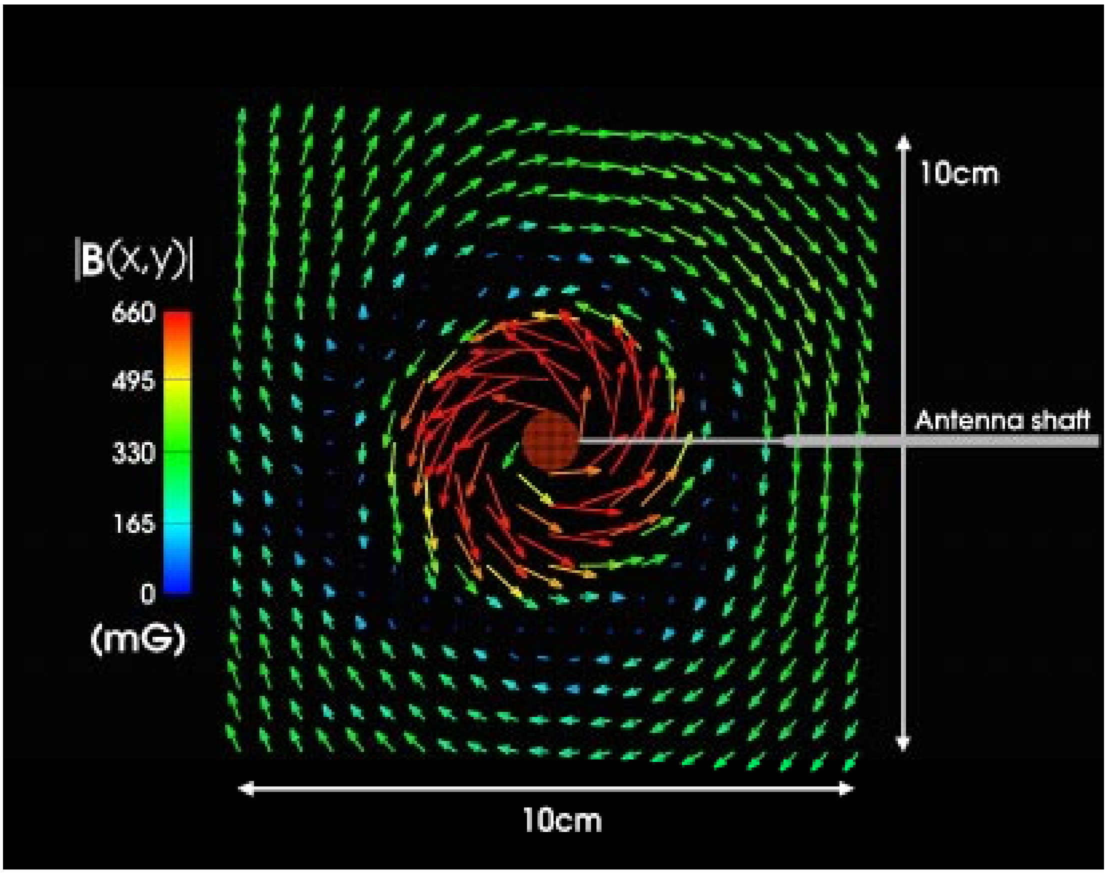

figure 4a) Measured magnetic field $B_\perp$ (x,y) for a wave with ϖ = 0.77, in a plane 1.54 meters (approximately one parallel wavelength) from the disk exciter. A scale model of the exciter is superposed on the data. The vectors are color coded in accord with their magnitude.

In 4a the instantaneous values of the perpendicular component of the wave magnetic field at 441 spatial locations in a plane perpendicular to the background magnetic field is shown for a wave with frequency, f = 320 kHz, (ϖ = 0.77, β_e = 2.3X10^{-4}.). The wave burst was 28 cycles long and the data shown was collected during the burst. Vectors are color-coded to aid the eye, with red denoting the largest values and blue the smallest. The largest vector in the diagram has length of 660 mG. ($B_{0z}/B_{\perp max}$ = 6.0X10^{-4}). Shown superimposed on the vector pattern , and to scale, the disk antenna. The axial location of the data plane is 1.02 parallel wavelengths ($\lambda_{||}$ =1.54 m) from the antenna. The planar data illustrates that the wave magnetic field exhibits a high degree of azimuthal symmetry but some departure from symmetry is evident. Wave propagation across the magnetic field is also evident from the reversal of the field direction moving radially outward from the antenna.

The magnetic field pattern for two sources is shown in figure 4b.

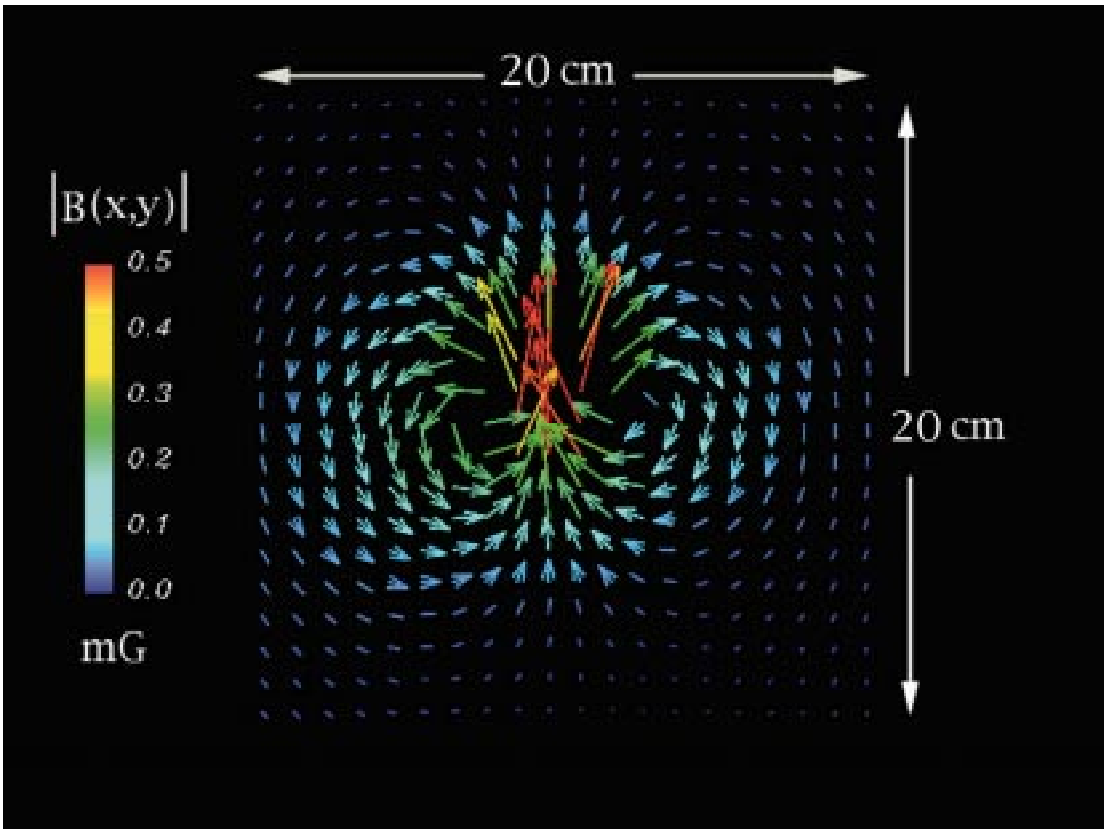

figure 4b) Measured magnetic field $B_\perp$ (x,y) for a wave produced by two radiating current channels (ϖ = 0.50), in a plane 1.26 meters from the disk exciter. Note the plane for this measurement is twice the size as that in 4a

In this case the wave magnetic field is vertical midway between the exciters and is of the order of 0.5 Gauss. There was no evidence of nonlinearity in the received signal. There was, however an axial component in the wave magnetic field with $\frac{B_Z}{B_\perp} \approx .06$, The violates one of the assumptions used to derive Eq. 4 although the theoretical pattern obtained for two sources is in good qualitative agreement with measurement [Gekelman et. al., 1997].

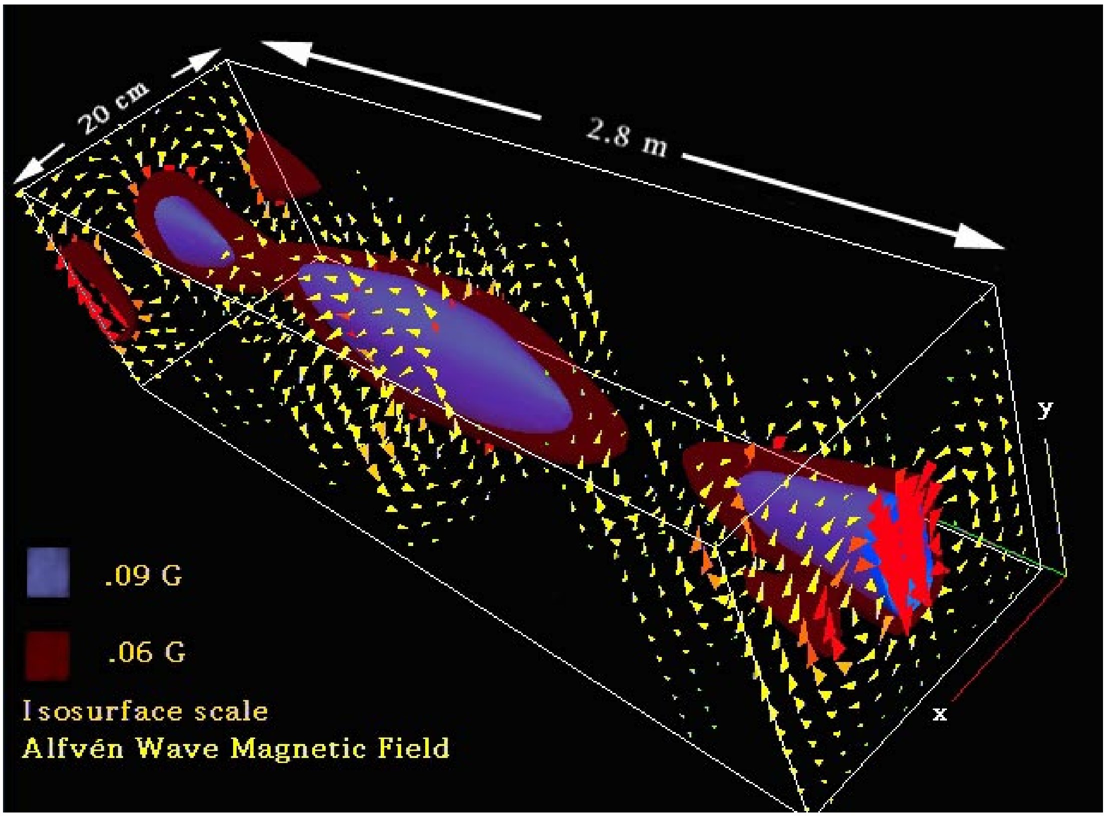

figure 5) Measured magnetic field **B**(x,y,z) of intersecting Alfvén waves with ϖ = 0.50. The volume is a parallepiped δz =2.8 meters long bounded by two planes $\delta x = \delta y$ =20 cm. The magnitude of the field is displayed as two isosurfaces and as vector field on seven data planes. In this case f/fci = 0.5

The volume magnetic field is displayed as isosurfaces and vector fields in figure 5. The magnetic field vectors are displayed on several planes; one can compare data on the rightmost plane with that in figure 4b. Each isosurface is approximately one quarter wavelength in the z direction. The background magnetic field is parallel to z.

Three dimensional current was calculated from the magnetic field data using $\nabla \times \mathbf{B} = \frac{4\pi}{c}\mathbf{j}$. The results of this are displayed in figure 6.

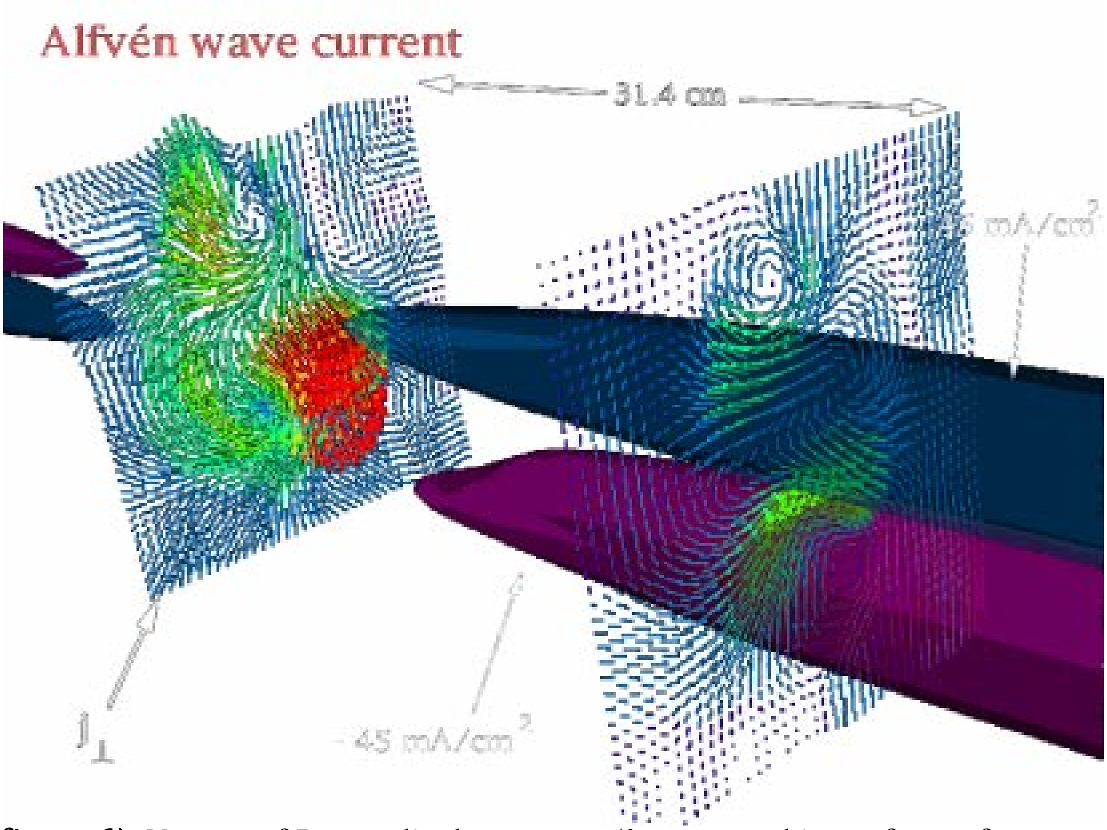

figure 6) Vectors of Perpendicular current (**j** $_\perp$) and isosurfaces of parallel current density ($\mathbf{j}_{||}$). The data is shown for a segment of the volume to focus on the structure of the cross field currents. The isosurfaces are shown close to a quarter wave location where the parallel currents go to zero.. Cross field currents clearly link them to maintain ∇• **j** = 0 for the wave.

Data is shown as a representative isosurface of j_Z, and vector fields of $\mathbf{j}_\perp$. The two isosurfaces illustrate axial currents of opposite polarity which originate at the exciters. The central pair of these are approximately 1/4 wavelength long and move along $\mathbf{B}_0$ at the Alfvén speed ($V_A = 8.8X10^7$ cm/s). The closure of the currents is evident in the perpendicular current which links the two isosurfaces.

3. Conclusions:

A series of laboratory experiments has been performed on the propagation of shear Alfvén waves which originate from sources with physical size across the magnetic field on the order of the electron skin depth. These small sources produce Alfvén wave patterns which contrast with the picture of standard MHD. This difference occurs as a result of corrections in the wave dispersion arising from non-zero perpendicular wave numbers ($k_\perp \delta \approx 1$). The inclusion of corrections arising from finite $k_\perp$ has two important consequences. Alfvén wave energy spreads across the magnetic field and the wave has a non-zero parallel electric field component. Spreading of magnetic energy implies that magnetic fluctuations associated with the shear Alfvén wave can be detected on field lines that do not directly connect with the source. On the other hand, the parallel electric field component gives rise to the possibility that Alfvén waves can interact with particles leading to either wave growth or dissipation.

The properties of Alfvén waves studied in the experiments reported here have several interesting consequences for the investigation of Alfvén waves in space plasmas. Sources with fluctuating field aligned currents with scale sizes across the magnetic field on the order of the electron skin depth certainly exist in and around the magnetosphere. For example, the electron skin depth in the auroral ionosphere varies from several tens of meters at low altitudes to over a kilometer at altitude above 1 R_E. Features in the electron precipitation associated with auroras are commonly observed (Borovsky, 1993) with cross field scale sizes in this range. If these currents have low frequency fluctuations they will radiate Alfvén waves that spread across field lines and have parallel electric field components.

The spreading of magnetic energy across field lines means that multiple current channels can interact giving fluctuations in the field not directly associated with a single source. For example, under the right conditions, constructive interference could produce regions of large, nonlocal, wave fields on field lines not directly connected to a current source. There is, therefore, a possible problem in interpreting the source of magnetic fluctuations detected by spacecraft if the source is a long distance away along the magnetic field.

These laboratory findings bear directly upon those space plasma processes which involve field-aligned currents, fluctuating at frequencies below the ion cyclotron frequency, with cross-field scale lengths on the order of the electron skin depth. These types of situations can be expected to be found in boundary regions or regions where the plasma density or magnetic field configuration is changing rapidly in space. Examples of such regions are the magnetopause, the plasma sheet boundary layer, and the auroral current regions. Recently the Freja satellite (Lundin et. al., 1994a) has observed what its team calls Solitary Kinetic Alfvén Wave Structures (SKAWS). These intense electromagnetic bursts with $(\frac{\Delta E}{\Delta B})c \approx V_A$ were observed with electromagnetic energy comparable to the background particle energy. The waves observed by Freja are structured at the electron inertial length and could be directly related to the results reported here. Indeed low frequency fluctuations in the magnetic field that have been interpreted as Alfvén waves have been observed by a sounding rocket [Boehm, et al., 1990] and satellites [Chmyrev, et al., 1988; Lundin, et al.,1994b]. These observations have been associated with short scale length, cross-field density gradients and electron precipitation.

Finally the three dimensional wave current has been derived from the data. In the case of a plane wave and a single exciter the current closes at infinity. It is observed that the current in this experiments closes across the field on distances comparable to the width of the channels of current which propagate along z (j_Z). The cross field current is presumed to be carried by the ions and is observed to be significantly smaller than the the parallel current but is spread over a greater volume than j_z.

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References

Alfvén, H., *Existence of Electromagnetic-Hydromagnetic Waves, Nature*, **150**, 405-406 (1942).

Amagishi, Y., J., *Experiments on mode conversion of m=-1 fast wave into a shear Alfvén wave in a cylindrical plasma*, Phys. Soc. of Japan, **59**, 2374 -2381 (1990).

Amagishi Y., Saeki K., Donnelly I.J., *Excitation of MHD surface waves propagating with shear Alfvén waves in an inhomogeneous cylindrical plasma*, Plasma Physics and Controlled Fusion, **31**, 675-691 (1989)

Amagishi, Y., Tanaka, M, *Ion-Neutral Collision Effect on an Alfvén Wave,* Phys. Rev. Letts, **71**, 360-363 (1993)

Amagishi, Y. Nakagawa, H., Tanaka, M., *Propagation velocity of Alfvén Wave Packets in a dissipative plasma*, Phys. Rev. E, **50**, 2217-2221 (1994)

Boehm et al., *High Resolution sounding rocket observations of large-amplitude Alfvén waves*, Jour. Geophys. Res., **95**, 12157 (1990)

Borg, G.G., R.C. Cross, *Guided Propagation of Alfvén waves and ion-ion hybrid waves in a plasma with two ion species*, Plasma Phys. and Controlled Fusion, **29**, 681-691 (1987).

Borovsky, J.E., *Auroral Arc Thicknesses Predicted by Various Theories*, J. Geophys. Res., **98**, 6101-6138 (1993)

Bostick, W., M. Levine, *Experimental demonstration in the laboratory of the existence of Magneto-Hydrodynamic waves in ionized Helium*, Phys. Rev., **94**, 815 (1952).

Chmyrev, V.M., S.V. Bilichenko, O.A. Pokhotelov, V.A. Marchenko, V.I. Lazarev, A.V. Streltsov, L. Stenflo, *Alfvén Vorticies and related phenomena in the ionosphere and the magnetosphere*, Physica Scripta, **38** , 841-854 (1988).

Cross, R.C., J.A. Lehane, *Compressional Alfvén wave propagation below the ion cyclotron frequency*", Aust. J. Phys., **21**, 129 (1967a).

Cross, R.C., J.A. Lehane, *Propagation of Compressional and Torsional Alfvén waves under identical plasma conditions*, Nuclear Fusion, **7**, 219-222 (1967b).

Cross, R.C., Plasma Physics, *Experimental Observations of localized Alfvén and ion acoustic waves in a plasma*, **25**, 1377-1387 (1983).

Cross, R.C., *An Introduction to Alfvén waves*, Adam Hilger series on Plasma Physics, IOP Publishing, Philadelphia, PA (1988)

Gekelman, W., H. Pfister, Z. Lucky, J. Bamber, D. Leneman, J Maggs, *Design Construction and Properties of the Large Plasma Research*

Device-The LAPD at UCLA, Rev. Sci. Instrum. **62**, 2875-2883 (1991).

Gekelman, W., D. Leneman, J. Maggs, S. Vincena, *Experimental Observation of Alfvén Wave Cones*, Phys. Plasmas, **1**, 3775-3785 (1994).

W. Gekelman, S. Vincena, D. Leneman, J. Maggs, *Laboratory Experiments on Shear Alfvén Waves, and their Relationship to Space Plasmas,* Jour. of Geophys. Research, (1997)

Jephcott, D.F., *Alfvén waves in gas discharge*, Nature, **183**, 1652 (1959).

Jephcott, D.F., P.M. Stocker*, Hydrodynamic waves in a cylindrical plasma: an experiment,* J. Fluid Mech, **13**, 587 (1962).

Koch, R.A., W. Horton Jr., *Effects of electron pitch angle scattering in plasma waves*, Phys. of Fluids, **18**, 861-865 (1975).

Lehane, J.A., F.J. Paoloni, *The propagation of Non-Axisymmetric Alfvén waves in an Argon plasma*, Plasma Physics, **14**, 701-711 (1971).

Lundin, R., G. Haerendel, S. Grahn, *The Freja Project*, Geophys. Research. Letts., **21**, 1823-1826 (1994a).

Lundin, R., L. Eliasson, G. Haerendel, M. Boehm, B. Holback, *Large Scale Auroral plasma density cavities observed by Freja*, Geophys. Research. Letts., **21**, 1903-1096 (1994b).

Maggs J. E., R. J. Taylor and W. Gekelman, *Neutral Burnout in a Ten Meter Liner Device*, Bull. Amer. Phys. Soc., **36**, 2415 (1991).

Morales, G.J., R.S. Loritsch, J.E. Maggs. *Structure of Alfvén Waves at the Skin-Depth Scale*, Phys. Plasmas, **1**, 3765 (1994).

Müller, G., *Experimental Study of torsional Alfvén waves in a cylindrical partially ionized magnetoplasma*, Plasma Physics, **16**, 813 (1973)

Sawyer, G.A., P.L. Scott, T. F. Stratton, *Experimental Demonstration of Hydrodynamic waves in an ionized gas*, Phys. Fluids, **2**,47-51 (1959).

Wilcox, J. M., F. I. Boley, A.W. De Silva, *Experimental Study of Alfvén wave properties*, Phys. Fluids, **3**, 15 (1960).