

# Visualizing Shear Alfvén Wave Currents Near the Ion-Cyclotron Frequency

Stephen Vincena and Walter Gekelman

**Abstract**—We present measurements of the three-dimensional structure of shear Alfvén wave currents near the ion-cyclotron frequency. The waves are launched by modulating an electron current filament with transverse size on the order of the electron collisionless skin depth. The component of the current parallel to the background magnetic field is carried by the electrons, while the cross-field current comprises both the ion-polarization and  $E \times B$  currents.

**Index Terms**—Electromagnetic propagation in plasma media, plasma waves, scientific visualization.

## I. INTRODUCTION

WITHIN magnetized plasmas, both in space and in the laboratory, filamentary field-aligned currents are common. When such currents have a transverse scale on the order of the electron collisionless skin depth  $\delta = c/\omega_{pe}$  and vary in time at frequencies below the ion-cyclotron frequency, they radiate shear Alfvén waves [1]–[3]. The current along the background magnetic field is carried by the electrons, while the currents close across the field via the ion-polarization current. Additionally, near the ion-cyclotron frequency, the  $E \times B$  drifts of the ions and electrons no longer cancel which leads to a net current in the azimuthal direction. This current circulates around the central current filament and gives rise to an axial component of the wave magnetic field. Observations of shear Alfvén waves with an axial component and associated with skin-depth-scale tubular current structures have been made in space [4] and in the laboratory [5].

These experiments are performed in the Large Plasma Device (LaPD) at the University of California, Los Angeles [6]. The device is 10 m in length and 1 m in diameter. The helium plasma is created using a pulsed discharge between a heated, oxide-coated nickel cathode at one end of the device and a circular copper mesh anode a distance 94 cm away. A 25-cm radius, fully ionized plasma with no net current and a density of  $2 \times 10^{12}/\text{cm}^3$  extends from the anode to an electrically floating copper plate at the end of the device. The electron temperature is 6 eV and the confining magnetic field is 1.0 kG. The duration of the plasma is approximately 10 ms; this highly reproducible

discharge is repeated once per second which allows for the collection of ensemble datasets.

The antenna used to launch the waves is a 1 cm diameter, circular copper mesh of 50% optical transparency. An electron current is drawn to the antenna using a 20-V bias pulse (relative to the endplate). The waves are launched by modulating this current through an isolation transformer with a 20-cycle, phase-locked tone burst from a radio frequency (RF) amplifier at a frequency of  $\omega/\omega_{ci} = 0.8$ . This method generates shear Alfvén waves with a high degree of azimuthal symmetry [7]. The wave magnetic fields are detected with a three-axis, differentially wound induction coil probe, and the data are averaged over 20 plasma discharges. Using a series of vacuum interlocks and a computerized probe drive and data acquisition system, the probe samples over 4000 spatial locations.

Fig. 1 is a representation of the plasma currents at one instant in time of a shear Alfvén wave. The currents are visualized as streamlines initialized at the points tagged with yellow spheres and followed using a Runge–Kutta scheme. Here, the streamlines trace out one half of one parallel wavelength (along  $z$ .) The currents were calculated using Ampere’s law from measurements of the azimuthally symmetric wave vector magnetic field in a two dimensional plane. The displacement current is negligible for these low-frequency waves. The resulting geometric object was rendered atop a semireflective plane; the plane serves as visual cue for the viewer to grasp the perspective of the scene, and the reflection is a reminder that the second half wavelength is essentially a mirror image of the first. The center “stalk” of concentrated streamlines shows the location of the highly field-aligned electron current. At the top and bottom of the object, the current flows in the radial direction and is due to the ion-polarization current. The azimuthal current is most easily seen in the twisted field lines at the outer radius where the current system closes back on itself along the plasma boundary.

## II. CONCLUSION

In summary, shear Alfvén waves have been launched by modulating an electron current filament with transverse scale on the order of the electron skin depth. Measurements of the wave magnetic field were used to calculate the wave currents which were then visualized using the streamline technique. Creating a well controlled Alfvén wave experiment in the laboratory can aid space scientists by giving them a model for what to expect when a satellite or rocket transits such a structure. However, one is not always guaranteed to encounter such a current structure in isolation; with interacting current systems, the task of interpreting the data becomes more difficult, as pointed out in a companion paper [8].

Manuscript received July 2, 2004; revised December 15, 2004. This work was supported in part by the Office of Naval Research under Grant N00014-97-1-0167, in part by the National Science Foundation under Grant ATM-970-3831, and in part by the Department of Energy under Grant DE-FG03-00ER54598.

S. Vincena is with the Large Plasma Device (LaPD) Plasma Laboratory, University of California, Los Angeles, CA 90095-1696 USA, and also with the Department of Physics and Astronomy, University of California, Los Angeles, CA 90095-1696 USA (e-mail: vincena@physics.ucla.edu).

W. Gekelman is with the Large Plasma Device (LaPD) Plasma Laboratory, University of California, Los Angeles, CA 90095-1696 USA.

Digital Object Identifier 10.1109/TPS.2005.845288

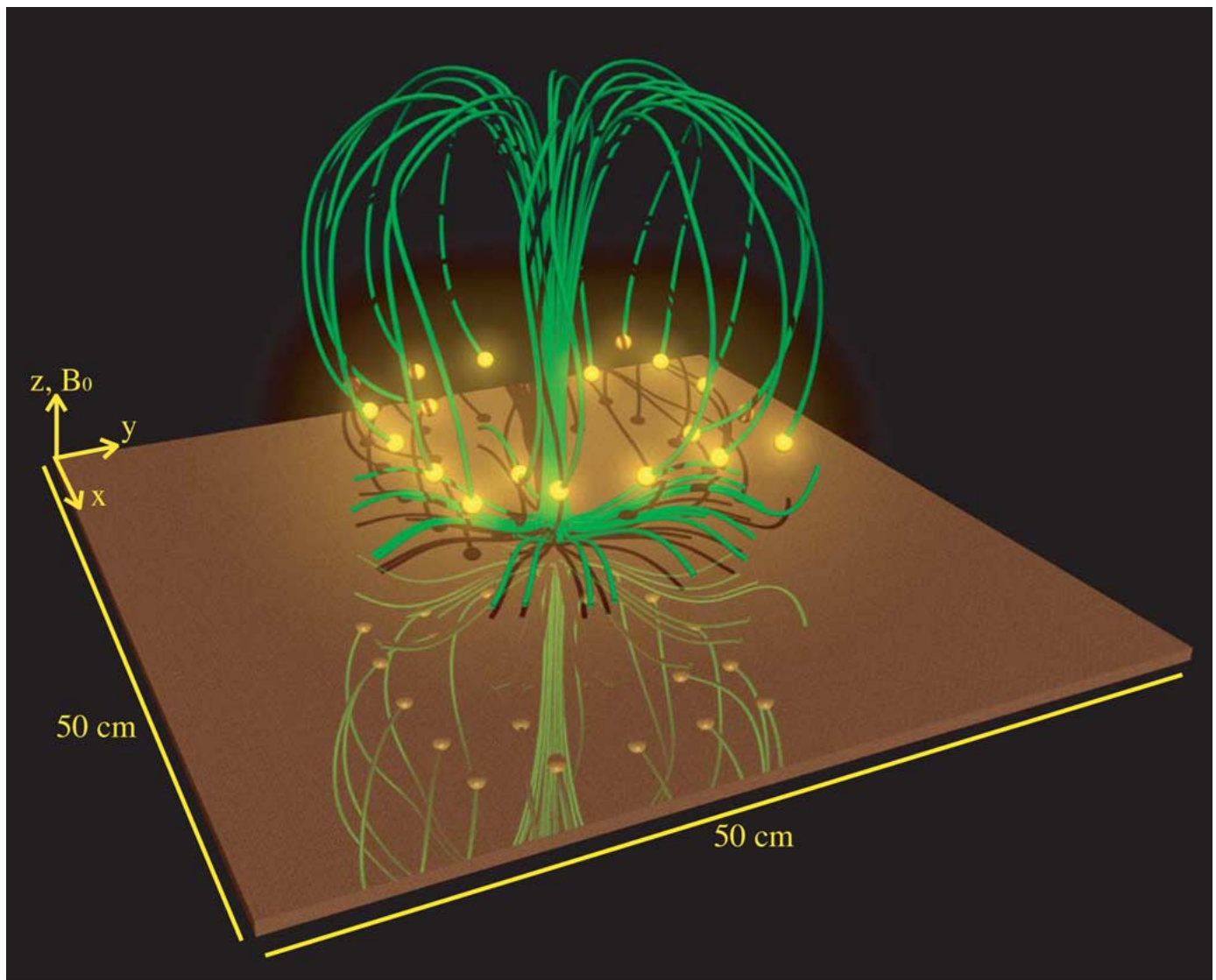


Fig. 1. Perspective view of the instantaneous current streamlines of one half wavelength a shear Alfvén wave. Streamlines are initialized at the points tagged with yellow spheres and followed using a Runge–Kutta scheme. The parallel (along  $B_0$ ) wavelength is 140 cm, and the perpendicular extent of the streamlines is 32 cm. Currents were calculated from measurements of the azimuthally symmetric wave vector magnetic field in the  $xz$  plane. The structure is compressed by a factor of two in the  $z$  direction for more compact viewing.

#### REFERENCES

- [1] G. G. Borg, M. H. Brennan, R. C. Cross, L. Giannone, and I. J. Donnelly, "Guided propagation of Alfvén waves in a toroidal plasma," *Plasma Phys. Control. Fusion*, vol. 27, no. 10, pp. 1125–1149, 1985.
- [2] G. J. Morales, R. S. Loritsch, and J. E. Maggs, "Structure of Alfvén waves at the skin-depth scale," *Phys. Plasmas*, vol. 1, no. 12, pp. 3765–3774, 1994.
- [3] W. Gekelman, D. Leneman, J. Maggs, and S. Vincena, "Experimental observation of Alfvén wave cones," *Phys. Plasmas*, vol. 1, no. 12, pp. 3775–3783, 1994.
- [4] M. Volwerk, P. Louarn, T. Chust, A. Roux, H. de Feraudy, and B. Holback, "Solitary kinetic Alfvén waves: A study of the poynting flux," *J. Geophys. Res.*, vol. 101, no. A6, pp. 13 335–13 343, 1996.
- [5] S. Vincena, W. Gekelman, and J. Maggs, "Shear Alfvén waves in a magnetic beach and the roles of ion and electron damping," *Phys. Plasmas*, vol. 8, no. 9, pp. 3884–3896, 2001.
- [6] W. Gekelman, H. Pfister, Z. Lucky, J. Bamber, D. Leneman, and J. Maggs, "Design, construction, and properties of the large plasma research device—the LAPD at UCLA," *Rev. Sci. Instrum.*, vol. 62, no. 12, pp. 2875–2883, 1991.
- [7] W. Gekelman, S. Vincena, D. Leneman, and J. Maggs, "Laboratory experiments on shear Alfvén waves and their relationship to space plasmas," *J. Geophys. Res.*, vol. 102, no. A4, pp. 7225–7236, 1997.
- [8] W. Gekelman and S. Vincena, "Imaging complex three dimensional Alfvén wave currents," *IEEE Trans. Plasma Sci.*, vol. 33, no. 2, pp. 546–547, Apr. 2005.