3D Observations of Electromagnetic Ion Cyclotron Wave Propagation in a Laboratory Plasma Column

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Abstract

The propagation of Electromagnetic Ion Cyclotron Waves (EMICW's) as launched by an antenna of small transverse scale has been studied in a laboratory plasma. Effects of the finite perpendicular size of the plasma column on the wave magnetic field pattern are observed, and their analysis is aided by visualizing the wave fields in three dimensions.

These experiments are carried out in the LArge Plasma Device (LAPD) [1] at the University of California, Los Angeles. The LAPD is a large, cylindrical steel chamber one meter in diameter, 10 meters long, surrounded by 68 pancake electromagnets. The helium plasma column is typically 40 cm in diameter (300 ion gyroradii), and 9.4 m in length ($\approx 10^6$ Debye lengths). The plasma is produced via a direct current discharge from an oxide-coated cathode. The device is operated in a pulsed mode with a one-Hertz repetition rate which extends the life of the cathode and allows for efficient digitization and storage of large data sets.

Electromagnetic Ion Cyclotron Waves (EMICW's) are shear Alfvén waves whose frequency, ω, is comparable to the ion-cyclotron frequency, ω_{ci}. In this experiment, $\omega = 0.9\omega_{ci}$. EMICW's are found in the Earth's auroral ionosphere and may play a role in the transport of energy from the photosphere of the sun to the corona.

In the laboratory, these waves are launched [2] by modulating a DC electron current drawn to a small, circular copper mesh within the plasma. The resulting wave patterns are mapped with a triaxial magnetic induction probe which is used to acquire an ensemble average of time series at a single spatial location. After averaging, the probe is moved to a new location and the process is repeated until a desired volume has been sampled. The reproducibility of the plasma discharge allows data acquired over many days to be merged into a single, volumetric data set.

When sampling a volume, the probe is moved in a series of planes, either xz or xy. One of the many methods to visualize the data thus acquired is to create (for each digitized timestep) a computer-generated two-dimensional grid corresponding to each of the physical data planes. Each grid point in these planes is assigned a color which represents field magnitude or field strength (both magnitude and sign.) This collection of points is then made into a geometry suitable for rendering by connecting the grid points with Gouraud-shaded polygons.

Fig. 1 is a composition of several of the measured instantaneous magnetic field amplitude data planes. Fig. 2 is a more detailed view of the z=189cm xy-plane from Fig. 1 and shows the azimuthally symmetric pattern of the radiated EMICW field magnitude. The geometry used to create this image comprises 2000 triangles and was produced using the commercial software package, AVS, from Advanced Visual Systems Incorporated.

When the plane in Fig. 2 is viewed as a function of time, the wave maximum near the center of the pattern (marked with a short, vertical line) propagates radially outward until it is met at the point ‘X’ by an inward-propagating phase front. With only this view of the data, one might conjecture that two modes have been excited: a central, radially outward-propagating ion-cyclotron wave launched by the antenna and an inward-propagating surface wave (perhaps a compressional Alfvén wave) possibly excited by the radial current feed to the antenna. This quandary is resolved by examining an xz cross-section of the wave.

Fig. 3(a) shows an image of wave magnetic field strength composited from three experimental xz-planes. The planes of data were acquired over a three-day period using three different axial access ports on the LAPD. With this perspective, the “two separate” phase fronts as seen in the xy-view are now seen to form a continuous phase surface. They are the same wave.

A theoretical investigation of the radiation pattern produced by the type of antenna used in this experiment has been performed by Morales and Maggs [3] wherein they derive an integral expression for the azimuthal wave magnetic field. Their formulation is used here to create the theoretical patterns in Figs. 3(b) and 3(c). Figure 3(b) shows a wave pattern calculated by numerical integration using experimentally measured parameters. Figure 3(c) shows the results of the same integrations but any density-dependent quantities such as the Alfvén velocity are allowed to vary as functions of r in accord with a smooth-fit density profile to Langmuir probe data (the full-width at half-max of the density profile is labeled as the ‘plasma radius’ in Fig. 1.) While it is true that the theory assumes an infinite, homogeneous plasma, there is still good general agreement between the wave morphology in the visualized experimental plane and in the plane produced with this non-uniform model. The explanation may even appear to be intuitively obvious when seen in this *xz*-slice--at large *r* the plasma density, *n*, drops rapidly, and since the wave phase velocity is approximately equal to the Alfvén speed, it increases as $1/\sqrt{n}$; the result is an increasing displacement of the phase fronts in the *z*-direction as a function of *r* compared with the uniform case. It must be stressed that the ease of understanding follows from observing the appropriate cross-section. The *xy*-view is useful for establishing the azimuthal symmetry of this wave, but without the remainder of the volume data, it leaves unanswered questions regarding the production of "secondary modes."

In conclusion, an appreciation of the subtleties of wave propagation in non-uniform plasmas has been gained by visualizing cross-sections of a three-dimensional data set.

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References

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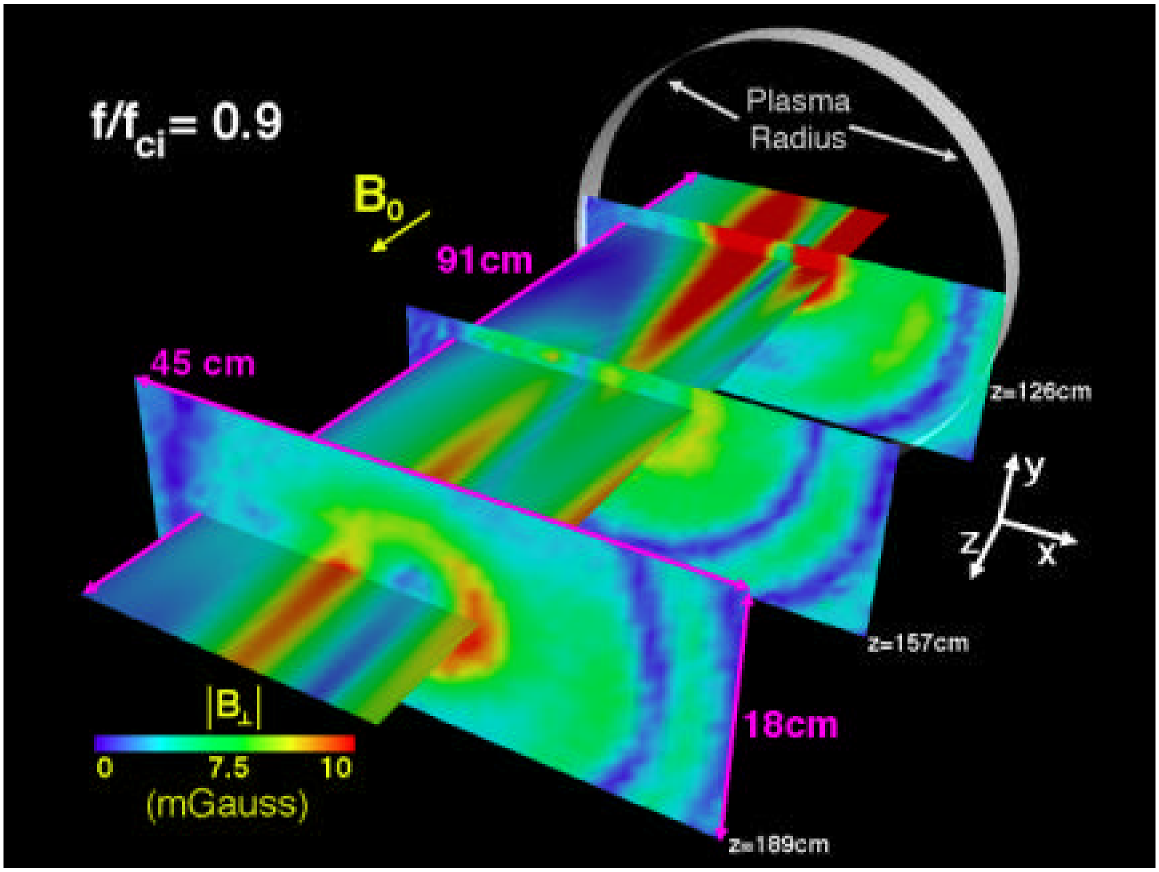
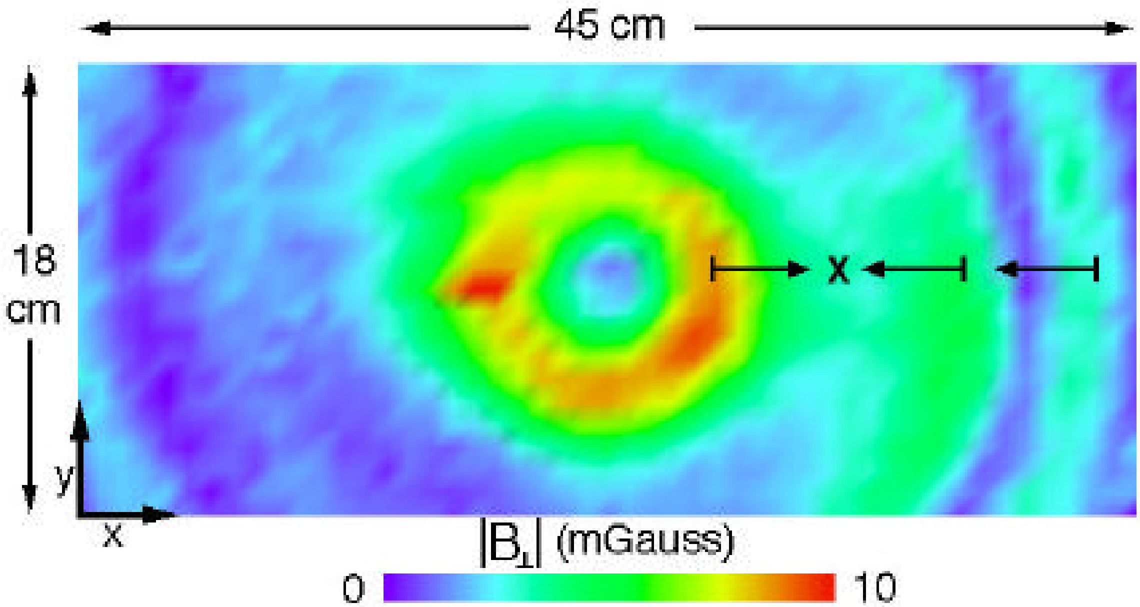
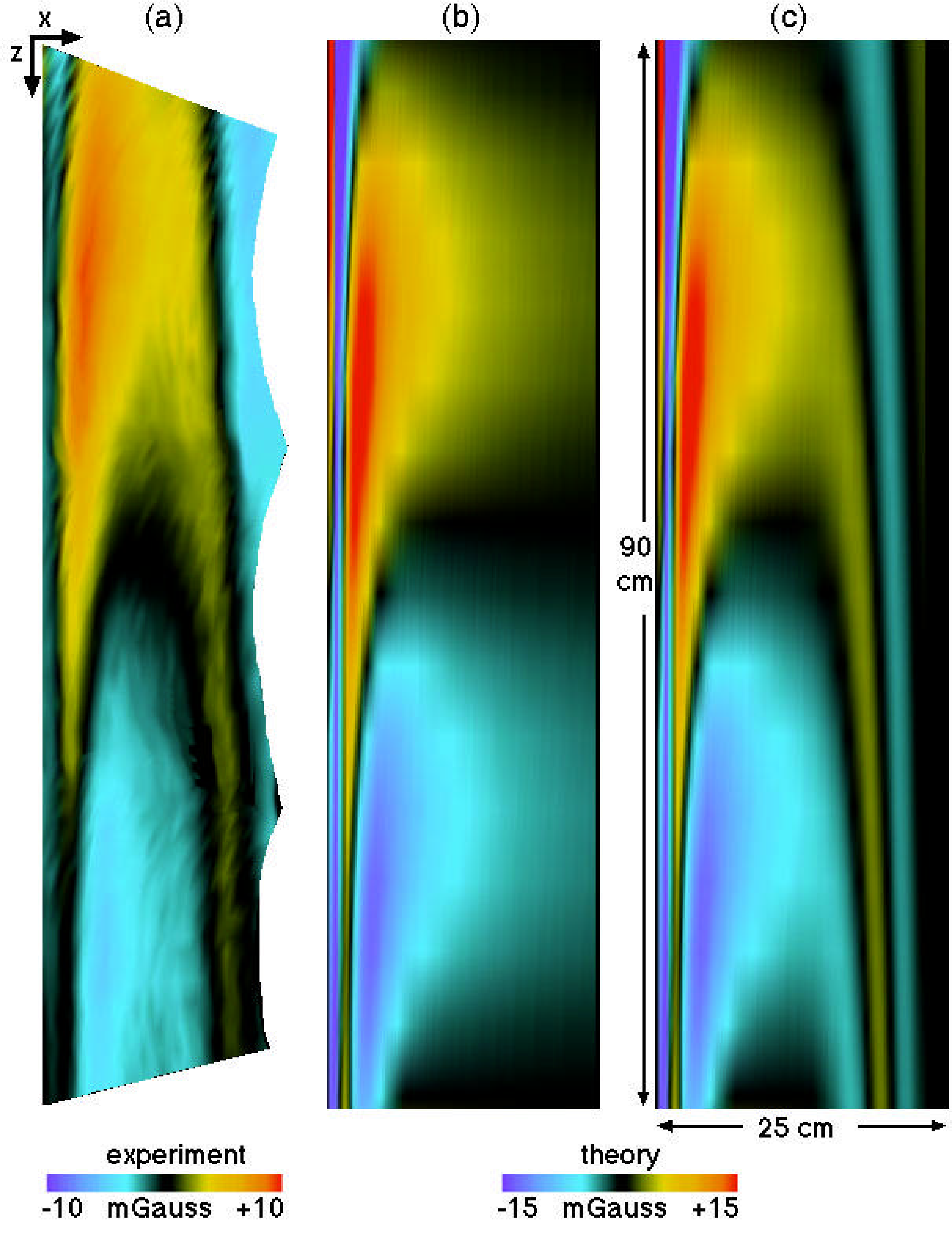


1. Perspective visualization of the measured instantaneous EMICW magnetic field magnitude in three *xy* cross-sections and one *xz* cross-section of the sampled volume. The component of the wave field perpendicular to the background field is shown. The wave is launched by modulating a DC electron current drawn to a one-centimeter diameter copper mesh disk located at *z*=0. The radial extent of the plasma column is indicated by a short, semi-transparent cylinder embedded within the data plane at *z*=126cm.



2. Measurements in a plane perpendicular to the background magnetic field of the perpendicular wave field amplitude at one instant in time. As time advances, the wave crest near the center of the pattern propagates radially outward and is met at the point labeled ‘X’ by inward-propagating wave fronts from the edge of the plasma. With this view of the data one may be led (incorrectly) to believe that two modes have been excited: a central, radially outward propagating ion-cyclotron wave launched by the antenna and a surface (perhaps compressional Alfvén) wave possibly excited by the radial current feed to the antenna.



3. Perpendicular wave magnetic field patterns (showing magnitude and sign) in an *xz* cross-section at an arbitrary instant in time. Shown are (a) a composite of three experimental data planes, (b) a numerical calculation (see text) with a constant density profile, and (c) the same calculation but using a smooth fit to the measured radial (*x*) density profile.