Nonlinear processes associated with Alfvén waves in a laboratory plasma

Troy Carter
Dept. Physics and Astronomy and
Center for Multiscale Plasma Dynamics, UCLA

acknowledgements:
Brian Brugman, David Auerbach, Jean Perez,
Stanislas Boldyrev, Steve Cowley, Pat Pribyl
Summary

• Experimental study of large amplitude Alfvén waves and wave-wave interactions

• Strong nonlinear beat-wave interaction between co-propagating shear kinetic Alfvén waves observed [T.A. Carter, B. Brugman, et al., PRL 96, 155001 (2006)]

• Strongly driven beat response, sideband generation

• Initial counter-propagating interaction experiments show some evidence for nonlinear cascade

• Weak broadening perpendicularly; stronger parallel cascade?

• Strong electron heating by large amplitude Alfvén waves

• Waves are strongly damped, leads to structuring of background plasma, secondary instabilities
The Large Plasma Device at UCLA

- Barium Oxide cathode source (50V, 10kA)
- $0.5 < B < 2 \text{ kG}$, $n_e \sim 10^{12} \text{ cm}^{-3}$, $T_e \sim 5 \text{ eV}$, $T_i \sim 1\text{eV}$
- 1m diameter, 20m long chamber
- He, Ne, Ar, H plasmas
- 1Hz rep rate, 10ms pulse length
- International user facility (http://plasma.physics.ucla.edu/bapsf)
Alfvén waves and interactions in LAPD

Experiment: generate large amplitude Alfvén waves in LAPD and study wave-wave interactions

- Incompressible MHD theory of interactions (e.g. Goldreich-Sridhar): Only counter-propagating waves interact
Alfvén waves and interactions in LAPD

Experiment: generate large amplitude Alfvén waves in LAPD and study wave-wave interactions

- Incompressible MHD theory of interactions (e.g. Goldreich-Sridhar): Only counter-propagating waves interact
- In LAPD experiments, waves have $k_{\perp} \rho_s \sim 1$, $\omega/\Omega_i \sim 1$
  - dispersive kinetic or inertial Alfvén waves
  - Co-propagating interaction allowed (waves can pass through one another)
  - Collisional (Coulomb) and Landau damping (finite $E_{||}$)
Kinetic and inertial Alfvén waves in low $\beta$ plasmas

$$\frac{k_{\perp}^2 c^2}{\omega_{pe}^2} - \left[ \frac{v_A^2}{v_{th,e}^2} \frac{(1 - \omega^2/\Omega_{c,i}^2) \mu}{1 - e^{-\mu} I_o(\mu)} - \zeta^2 \right] Z'(\zeta) = 0$$

Cold ion, low $\beta$ ($v_A \gg v_{th,i}$)

KAW $v_A \ll v_{th,e}$

$$\omega^2 = k_{\parallel}^2 v_A^2 \left( 1 + k_{\perp}^2 \rho_s^2 - \frac{\omega^2}{\Omega_{c,i}^2} \right)$$

IAW $v_A \gg v_{th,e}$

$$\omega^2 = k_{\parallel}^2 v_A^2 \frac{1 - \omega^2/\Omega_{c,i}^2}{1 + k_{\perp}^2 c^2/\omega_{pe}^2}$$

- In LAPD, $\beta \approx m_e/M$, $v_A \approx v_{th,e}$

- KAW, IAW have parallel E-fields, can damp on electrons through Landau damping or collisional (Coulomb) damping
3.3 Ordering of Physical Parameters

A perturbative expansion of Braginskii’s equations is complicated by the need to generate an ordering scheme which assigns relative values to quantities of interest. Many of these terms may vary over a wide range of values, as they represent physically distinct processes. Consequently any ordering is not universally valid. However, dividing parameter space into regions which have similar orderings yields a great deal of insight to the physics at work and so is a worthwhile enterprise. Here the niche of parameter space explored is that relevant to recent Alfvén waves experiments on LAPDU.

The parameter which will be used to estimate the relative size of quantities is the ratio of parallel to perpendicular Alfvén wave number:

$$\epsilon \equiv \frac{k_\parallel}{k_\perp}.$$  

For typical LAPDU Alfvén waves, $\lambda_\parallel \sim 3.5\, m$ and $\lambda_\perp \sim 10\, cm$ leading to $\epsilon \sim 0.035$. Terms which are not related to $\epsilon$ in some fundamental way will be related based on this numerical value. It will become clear as the expansion proceeds that the small term upon which the expansion should be based is $\epsilon^{1/2} \sim 1/5$.

Typical physical parameters on LAPDU are listed in Table 5.5. The resulting ordering of dimensionless parameters relevant to these Alfvén waves is given in Table 5.5. The interaction of several Alfvén waves will be shown to result in forced oscillations and waves whose dynamics may differ from those of Alfvén waves significantly. In order to retain the correct physics for each class of perturbation the total perturbation of quantity $\phi_3$ which may possess a static component will be $(\ldots)$.

Typical Alfvén wave parameters ($f \sim 200kHz$):

$$\lambda_\parallel \sim 2\, m \quad k_\parallel \lambda_{mfp} \sim 0.5$$

$$\lambda_\perp \sim 10\, cm \quad k_\perp \rho_s \sim k_\perp \delta_e \sim 0.3$$

$$\frac{\omega}{\Omega_{ci}} \sim 0.5 \quad \frac{\delta B}{B} \sim 0.01$$
Linear properties of IAW and KAW in LAPD


- See also Gekelman, Vincena, Leneman, etc...
Large amplitude wave source: the Alfvén wave maser

- Emission from resonant cavity driven by inverse Landau damping [Maggs, Morales PRL 03]
- Amplitude controllable by discharge current and $B$, up to $\delta B/B \sim \text{few\%}$
- Big enough to be nonlinearly relevant: $\delta B/B \sim k_\parallel/k_\perp$
- Frequency: $f/f_{ci} \sim 0.6$
- Mode hopping observed during current ramp up
Second technique: Alfvén wave loop antennas

- Broadband excitation of large amplitude waves (up to 10G) using novel drivers (up to 1kA @ 1kV pulsed)
- More flexible than maser, easy counter-propagating arrangement
Structure of maser emission: $m=0$ and $m=1$
shear Alfvén eigenmodes
Nonlinear interaction observed during simultaneous emission of two waves (co-propagating)

- Simultaneous emission of large amplitude $m=0$ and $m=1$ cavity modes

Nonlinear interaction observed during simultaneous emission of two waves (co-propagating)

- Simultaneous emission of large amplitude $m=0$ and $m=1$ cavity modes
- Copropagating waves beat together, generate strong nonlinear quasimode at beat frequency ($\delta n/n \sim 10\%$)
- Pump Alfvén waves scatter off of low-frequency quasimode, generating a series of sidebands
- Consistent with nonlinear Braginskii two-fluid theory (drive is nonlinear ion polarization drift)

Phase velocity measurements: Low frequency mode is non-resonant quasimode, consistent with three-wave matching

- Measured phase velocity of density perturbation: $294 \pm 35$ km/s
- Sound (slow wave) speed: $\sim 10$ km/s, Alfvén speed: $\sim 550$ km/s
- Computed phase velocity from three-wave matching: $\sim 290$ km/s

\[ \omega^2 = k^2 v_A^2 (1 + k^2 \rho_s^2 - \omega^2 / \Omega_i^2) \]

\[ \omega_1 + \omega_2 = \omega_3 \]

\[ \vec{k}_1 + \vec{k}_2 = \vec{k}_3 \]
Amplitude and frequency scaling: interaction is strong and shows resonant behavior

- Bilinear scaling, as expected, but magnitude of $\delta n/n \geq \delta B/B$
- Resonant-like behavior of interaction with beat frequency (with significant harmonics)
Beat driven wave is off-resonance Alfvén wave; theory consistent with observed amplitude, resonant behavior

- Nonlinear Braginskii fluid theory, $k_{\perp} \gg k_{||}$, $\omega/\Omega_{ci} \sim 1$

$$
\frac{\delta n}{n_o} = \frac{\delta k_{\perp} v_A}{\Omega_{ci}} \frac{k_{||,1} v_A}{\Omega_{ci}} \frac{k_{||,2} v_A}{\Omega_{ci}} \left( \frac{(\delta k_{\perp} + 2k_{\perp,1}) v_A}{\Omega_{ci}} \left( 1 + 2\frac{\Omega_{ci}}{\delta \omega} \right) - \frac{\delta k_{\perp} v_A}{\Omega_{ci}} \right) \left[ \frac{B_1^* B_2}{B_o^2} \right] \\
\left( 1 - \left( \frac{\delta \omega}{\delta k_{||} v_A} \right)^2 \right)
$$

- Exhibits resonant behavior (for Alfvénic beat wave) - reasonable agreement with experiments (except “harmonics”)

- Ignoring resonant denominator, $\delta n/n \sim 1\text{-}2\%$ for LAPD parameters

- Dominant nonlinear forcing is perpendicular (NL polarization drift): easier to move ions across the field to generate density response due to $k_{\perp} \gg k_{||}$
Counter-propagating interactions

- Use two cross-polarized AW antennas to launch counter-propagating waves
- Single wave collision, absorbing boundary conditions (magnetic beach)
- $k_\parallel/k_\perp \sim 2.5\%$, strong interaction might be expected for $\delta B/B \sim \text{few}\%$
- Measure magnetic field perturbations in between antennas
Broadening of perp. spectrum observed, but weak

- FFT of measured spatial correlation
- Broadening scales with increased wave amplitude, but is many orders of magnitude below pump amplitude
- Not yet in strong interaction regime (single collision not enough?)? Nonlinear transfer overwhelmed by damping?
Evidence for parallel cascade?

- Harmonics enhanced during interaction, parallel cascade?
Strong electron heating by antenna-launched Alfvén waves

- Localized heating observed, on wave current channel
- Collisional or Landau damping? Near field heating?
Scaling of heating with frequency: consistent with Alfvén wave heating

- Increasing heating efficiency with frequency, roll-off at cyclotron frequency consistent with collisional/Landau damping of Alfvén waves
- Maximum Poynting flux of ~200kW/m², comparable to plasma source power density (50V, 3kA): wave damping can explain heating
Measured wave decay consistent with collisional damping

- Damping length measured ~5m, consistent with expected damping length due to electron-ion collisions
- Sufficient wave energy damped to explain large fraction (if not all?) of heating
- Wave structure significantly modified (rotated, distorted)
Braginskii calculated shear wave damping consistent with measurements.

- Damping due to Coulomb collisions, yields $\lambda_d \sim 2\lambda_{alfven}$

- Role of Landau damping, nonlinear modifications to wave damping?
Temperature, density and potential modification in afterglow plasmas

- Strong heating on wave current channels
- Density depletion on current channel (density enhancement surrounding)
- Current channels tilt at high amplitude (due to potential, ExB flow? Consistent direction)
- Effect of structuring on wave propagation?
Movie of heating during afterglow: dynamics of wave current channels and heated region

- Low frequency fluctuations observed, current channel wanders
- Drift-Alfvén waves driven by temperature gradients?
Movie of heating during afterglow: dynamics of wave current channels and heated region

- Low frequency fluctuations observed, current channel wanders
- Drift-Alfvén waves driven by temperature gradients?
Low frequency fluctuations observed on heating-produced temperature gradients

- Contours: amplitude of fluctuations with $1 < f < 100$ kHz
Mode structure of low frequency fluctuations: drift-Alfvén waves

- m=2 dominant mode observed
- similar to drift-Alfvén waves seen in electron beam heated filaments in LAPD (talk this meeting by G. Morales)
Mode structure of low frequency fluctuations: drift-Alfvén waves

- $m=2$ dominant mode observed
- Similar to drift-Alfvén waves seen in electron beam heated filaments in LAPD (talk this meeting by G. Morales)
Sideband generation and turbulent broadening from interaction with drift-Alfvén fluctuation

- Sidebands separated by dominant drift-Alfvén wave frequency
- Larger drift wave frequency at lower power: smaller heated channel
Summary

• Experimental study of large amplitude Alfvén waves and wave-wave interactions

• Strong nonlinear beat-wave interaction between co-propagating shear kinetic Alfvén waves observed [T.A. Carter, B. Brugman, et al., PRL 96, 155001 (2006)]

• Strongly driven beat response, sideband generation

• Initial counter-propagating interaction experiments show some evidence for nonlinear cascade

• Weak broadening perpendicularly; stronger parallel cascade?

• Strong electron heating by large amplitude Alfvén waves

• Waves are strongly damped, leads to structuring of background plasma, secondary instabilities
Future directions

• Continue counter-propagating studies

• Higher amplitude, use reflecting boundary condition?

• More quantitative studies of perpendicular and parallel cascade

• Can we overcome damping? Heating needed on LAPD or new experiment may be needed at higher temperature, larger size

• Secondary instabilities associated with KAWs, interaction between KAW and drift-Alfvén waves

• Simulation: Braginskii fluid simulations underway (BOUT), plans for gyrokinetic simulation (AstroGK)