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Nonlinear Alfvén Wave Dynamics: Steepening and Particle Acceleration

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Outline

Alfven waves in space/astrophysical plasmas

Simulation Approaches

Dynamical Evolution of Nonlinear Alfven Waves
- perpendicular and oblique propagation

Particle Acceleration in Nonlinear Wave Fields

Possible Connection to Orion Facility

Alfven Waves in Space/Astrophysical Plasmas

- Alfven waves are a fundamental normal mode of plasma observed in laboratory and space plasmas
- Nonlinear Alfvenic structures populate various regions of the solar wind and magnetosphere – good satellite observations (Freja and FAST satellites)
- Connection to particle acceleration has been made – considered serious candidate as an auroral region accelerator ($\sim 1\text{eV} \rightarrow \sim 10\text{keV}$)

- Interesting questions

- What are the limits of Alfvén-wave based accelerators?
- What are the properties of Alfvén waves in ‘extreme’ astrophysical plasma conditions?
- Can tests of these ideas be implemented in the lab and are the results scalable?

Simulation Approaches

- Fully nonlinear relativistic EM PIC
 - good for high frequency, short-time scales
 - used in shock studies (Aarons, Langdon, Lembege, Dawson, Ohsawa, Buneman , et al.)
- Hybrid approach
 - massless electrons, particle ions (Winske, Quest, et al.)
 - fluid ions, particle electrons
- 2-species low frequency relativistic EM PIC
 - implicit and semi-implicit time stepping (Langdon, Lapenta, Brackbill, Tanaka, et al.)
 - most suitable for Alfvén wave dynamics

Simulation Model for Nonlinear Magnetosonic Wave Propagation

- Relativistic electromagnetic particle-in-cell (PIC)
- Full electron and ion dynamics since emphasis on detailed electron motion
- 1D spatial, 3D velocities
- External B-field in (x,z) plane
- Wave propagation in x-direction



(Ref. Ohsawa, et al., '99)

Dynamical Evolution : Finite Amplitude Pulse

- Consider finite amplitude disturbance, wavenumber k
- Simplified magnetosonic wave linear dispersion relation ($\omega \sim k V_A (1 - c^2 k^2 / 2 \omega_{pe}^2)$)
- Since propagation velocity depends on intensity of wave, nonlinear evolution becomes a balance of:
Steeping \leftrightarrow dispersion \leftrightarrow dissipation (eg. wave-particle trap)
- Issue of stationary versus non-stationary structure important

- Propagation characteristics (Barnes, '76)

$$B_T = B_w + B_o$$

- Steepening time

$$T_s = (2/3\omega) (B_w / B_o)$$

- Wave-particle trapping time (dissipation)

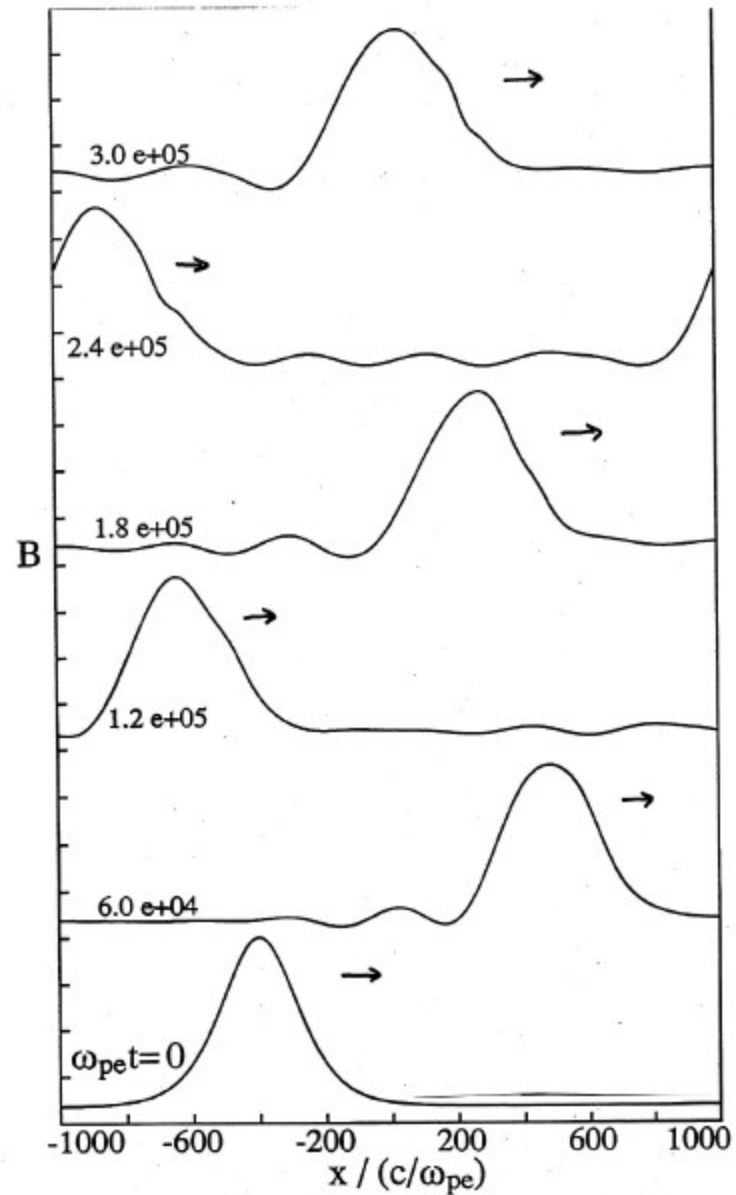
$$T_{tr} \sim (\omega / k_{||} V_{perp}) [\sin\theta (B_w/B_o)]^{-1/2}$$

Magnetosonic Solitary Wave Pulse

Perturbation theory result (weak amplitude limit)
-2-fluid non-relativistic theory

$$\begin{aligned}n_1 &= n_0 \frac{B_1}{B_0} \\V_{x1} &= V_A B_1 / B_0 \\E_{y1} &= (V_A / c) B_1 \\E_{x1} &= -\frac{V_A^4}{c^3} \left(\frac{\omega_{pe}^2}{\Omega_e^2} + \frac{\omega_{pi}^2}{\Omega_i^2} \right) \frac{\partial B_1}{\partial x} \\V_{y1} &= \frac{V_A^2}{B_0 n_0 m_i} \left(\frac{1}{\Omega_e} - \frac{1}{\Omega_i} \right) n_0 m_e \frac{\partial B_1}{\partial x} \\V_{ey1} &= \frac{V_A^2}{B_0 n_0 m_i} \left(\frac{1}{\Omega_i} - \frac{1}{\Omega_e} \right) n_0 m_i \frac{\partial B_1}{\partial x}\end{aligned}$$

Magnetosonic Solitary Pulse Propagation

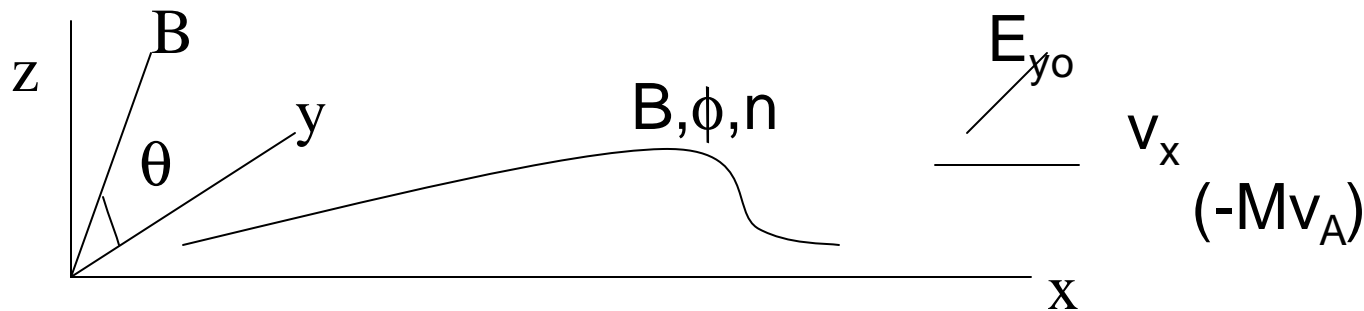


Quasi-perpendicular Magnetosonic Shock

- Wave frame ($d/dt = 0$)

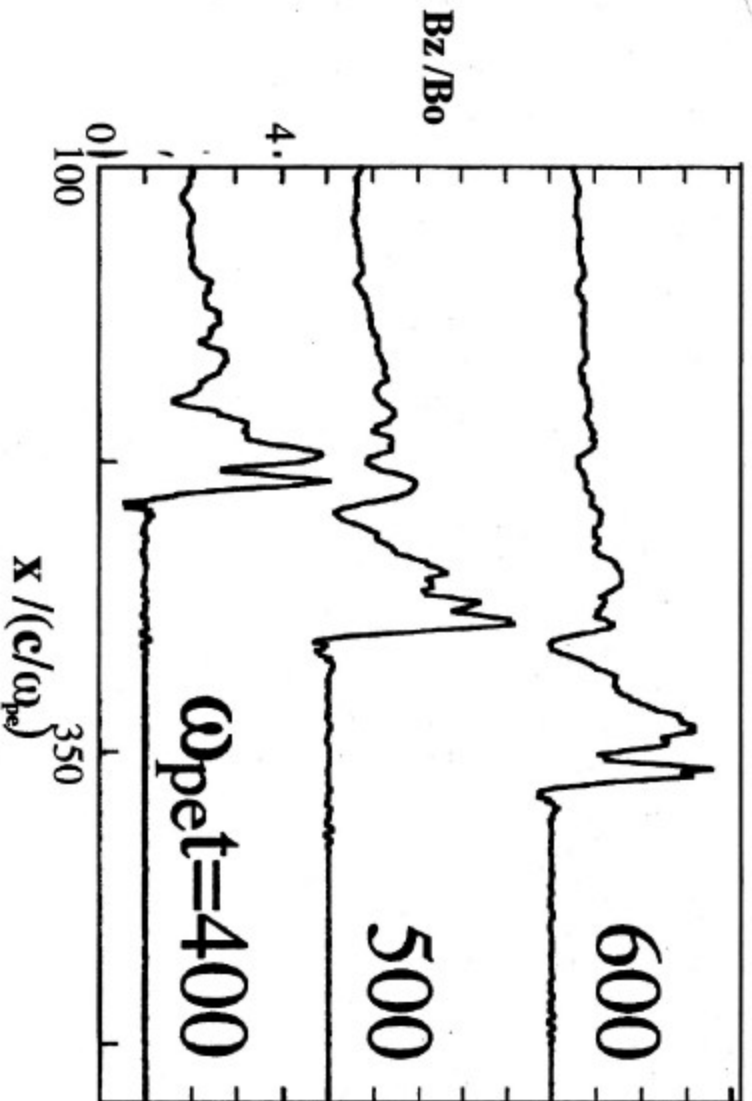
$$v_x = c E_{y0} / B(x)$$

$M > 1$, shock front forms, charge separation generates E_x field

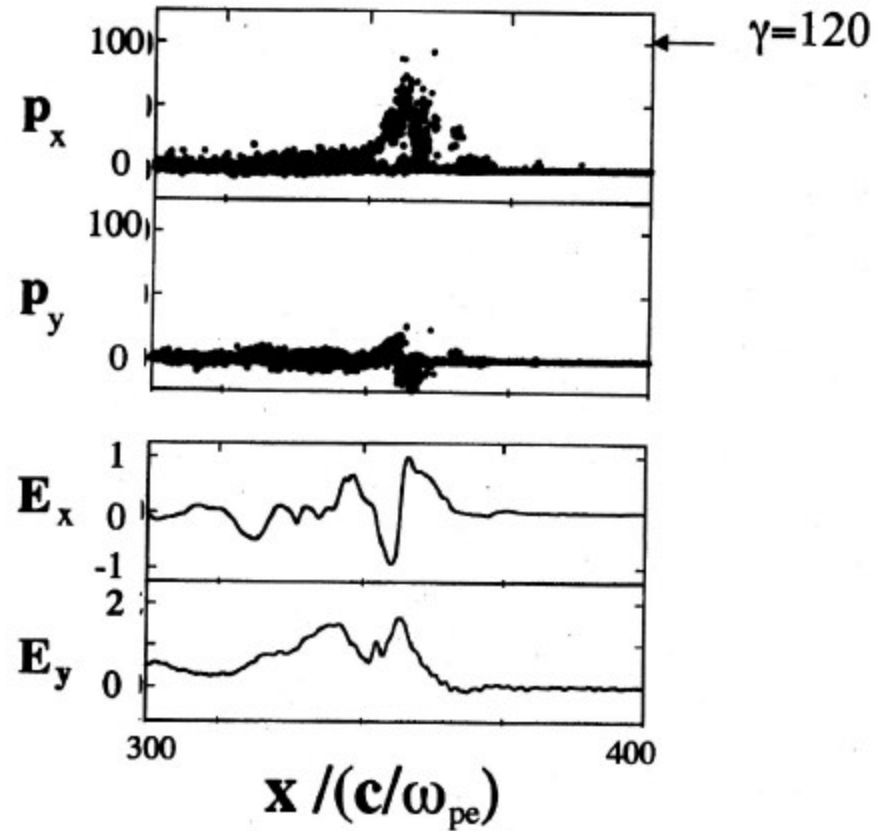


M = 2 (low Mach number)

Magnetic Field Evolution



Electron Phase Space and E_x and E_y Fields



Cross-Field Particle Acceleration

- Nonlinear wave structure mainly determined by the electrons
- Electric potential

$$e\phi \sim K = (m_i / 2) M^2 V_A^2$$

$$\text{with } E_x \sim \phi / \Delta \quad \text{and } \Delta \sim c / \omega_{pe}$$

$$\rightarrow v_{ey} = -cE_x/B$$

- Particle acceleration ($v_{ph} \times B$ mechanism)
 - Ions and electrons trapped in E_x field, normal to the wavefront.
Acceleration up to the $E_x \times B$ drift

$$v_{ph} \sim eE_x/m\omega \quad \text{and } v^{\max} \sim cE_x / B$$

(Katsouleas, Dawson, Lembege, Ohsawa, Sugihara, et al.)

Connection to Orion Facility

- Electron and positron beam convergent into a relativistic plasma
- 1m long column consisting of solenoid and undulator fields. These fields could be designed to emulate the magnetic field shock structure
- $V_{ph} \times B$ cross field particle acceleration mechanism could be used to boost electron and positron energies
- Spectrometer would be used to construct energy spectrum and power law
- 3D PIC simulations could be used to optimize field gradients

Summary

- Solitary magnetosonic and quasi-perpendicular magnetosonic shocks can be used as effective particle accelerators
- Generation of wakefields possibly leads to 'rear acceleration' into the shock front which gets a further energy boost (under investigation)
- Extension of these results to very high Mach number may lead to considerable change of physics as compared with low Mach number case, typically found in the Earth's magnetosphere (solar wind)