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Title: Excitation of Magnetosonic Waves in the Terrestrial Magnetosphere: Particle-in-cell Simulations

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Abstract

Two-dimensional electromagnetic particle-in-cell simulations are performed to study the temporal development of an ion Bernstein instability driven by a proton velocity distribution with $\partial f(v_\perp)/\partial v_\perp > 0$. The simulation results demonstrate that the instability grows at propagation angles nearly perpendicular to B_0, and at frequencies close to the harmonics of Ω_p. The simulation results also show that the presence of the cold background protons and the increase of the shell velocity shift the excited waves close to the low-beta plasma dispersion relation for magnetosonic waves ($\omega = kv_A$). The general features of the simulated field fluctuations resemble observations of fast magnetosonic waves, near the geomagnetic equator in the magnetosphere. A test particle computation of energetic electrons interacting with the simulated electromagnetic fluctuations suggests that this growing mode may play an important role in the acceleration of radiation-belt relativistic electrons.

Excitation of Magnetosonic Waves in the Terrestrial Magnetosphere: Particle-in-cell Simulations

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Introduction: Magnetosonic Waves

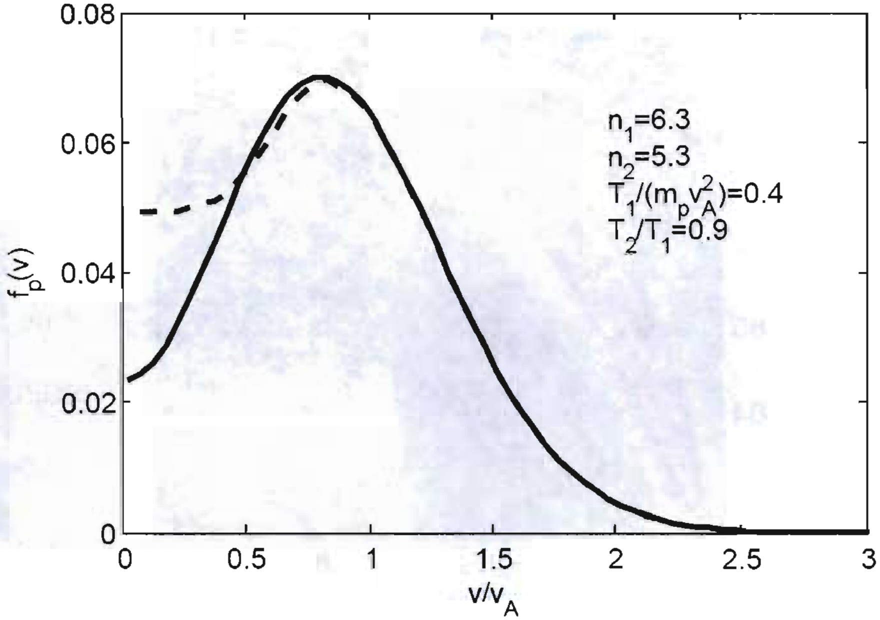
- “Equatorial Noise”, “Magnetosonic waves” or “Bernstein waves”
- Often structured spectrum at multiple ion cyclotron harmonics between Ω_p and ω_{LH}
- Near perpendicular propagation, primarily confined within 2 ~ 3^o of the geomagnetic equator
- Driven by proton distributions with $\partial f(v_\perp)/\partial v_\perp > 0$
- Typical amplitude 0.03 ~ 0.2 nT ($\delta B/B_0$ ~1e-4)
- At radial distance between 2 ~ 8 R_E, primarily in the afternoon and premidnight sectors
- Important role in the transverse heating of thermal protons and the acceleration of radiation-belt electrons

Subtracted Maxwellian Distribution of Protons

$$f_p(v) = f_1(v) - f_2(v)$$

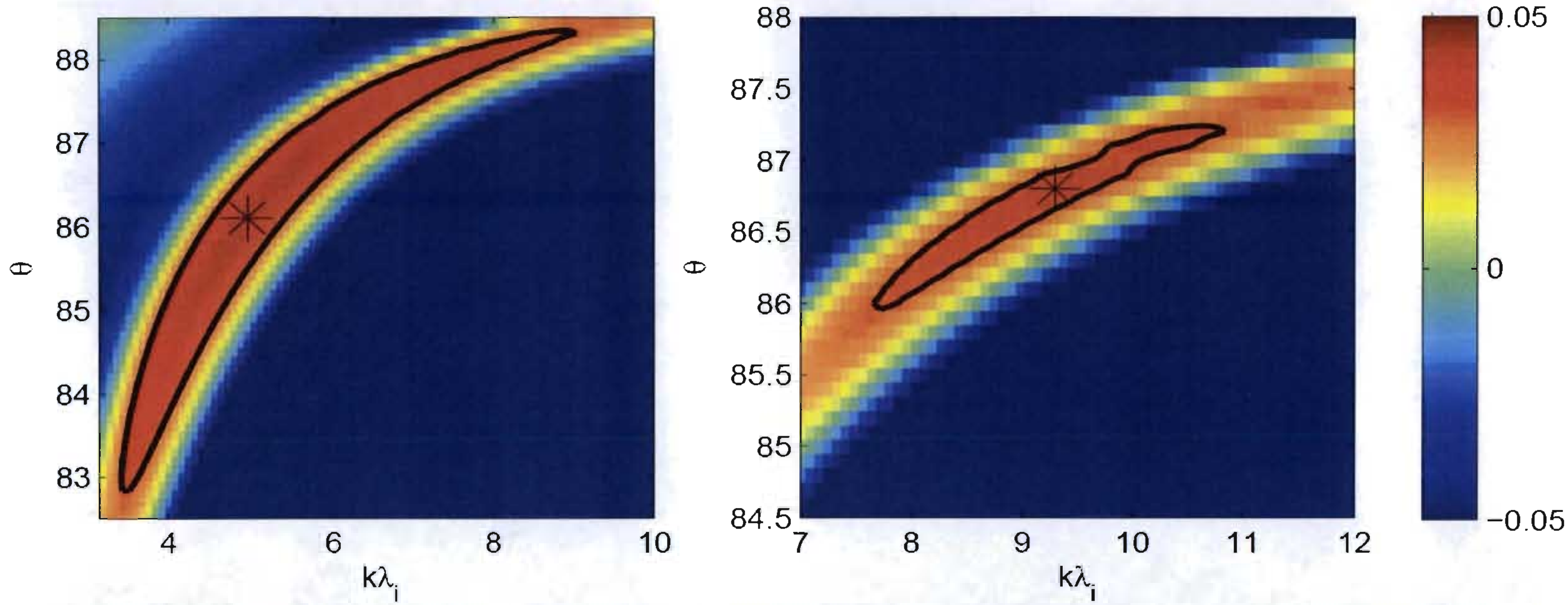
$$f_j(v) = \frac{n_j}{(\pi v_j^2)^{3/2}} \exp(-v^2/v_j^2)$$

$$v_j = \sqrt{2T_j/m_p}$$



- Subtracted Maxwellian distribution of protons (solid line) used in linear analysis and the PIC simulation of Case I
- Isotropic distribution is used to exclude possible Alfvén cyclotron instability
- The dash-dotted line displays $f_p(v_\perp)$ for protons of $|v_{||}|/v_A \leq 0.01$ at the end of the simulation (Case I)

Linear Kinetic Dispersion Theory



- Linear dispersion theory results show the Bernstein instability at the first (left) and the second (right) ion cyclotron harmonics, and at nearly perpendicular propagation angles
- Instability found up to the fifth cyclotron harmonic for the given ion distribution. The first cyclotron harmonic grows fastest
- Only first two harmonics are unstable for the reduced parameters used in the PIC simulation (m_p/m_e=100, ω_p/Ω_p=15), but the essential physics is the same
- Solid black contour lines mark γ/Ω_p=0.03. Asterisks represent γ_{max}

PIC Simulation: Case I-Subtracted Maxwellian

- Simulation parameters

  $\mathbf{B}_0 = B_0\hat{y}$

  $L_x = 9.6\lambda_i,\ N_x = 128$

  $L_y = 64\lambda_i,\ N_x = 64$

  $m_p/m_e = 100,\ \omega_p/\Omega_p = 15$

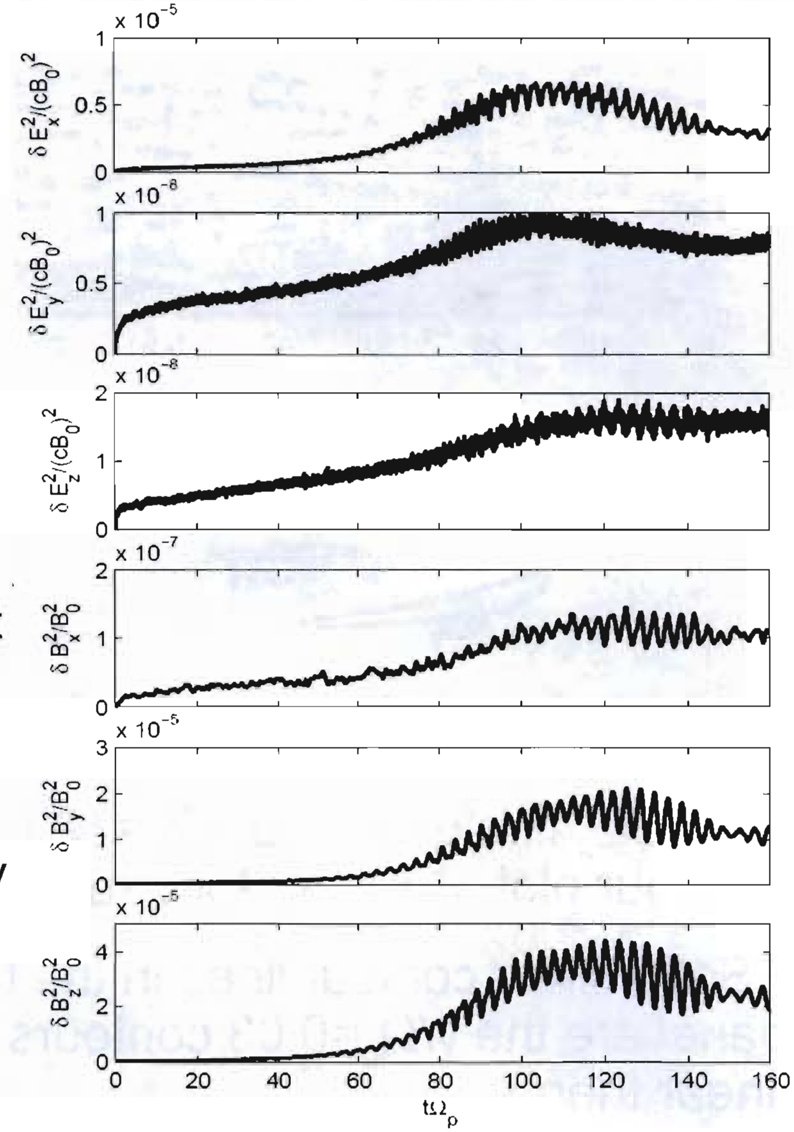
  $\Delta T\Omega_p = 0.001$, 48000 particles/cell

- Evolution of the energies in different E and B components

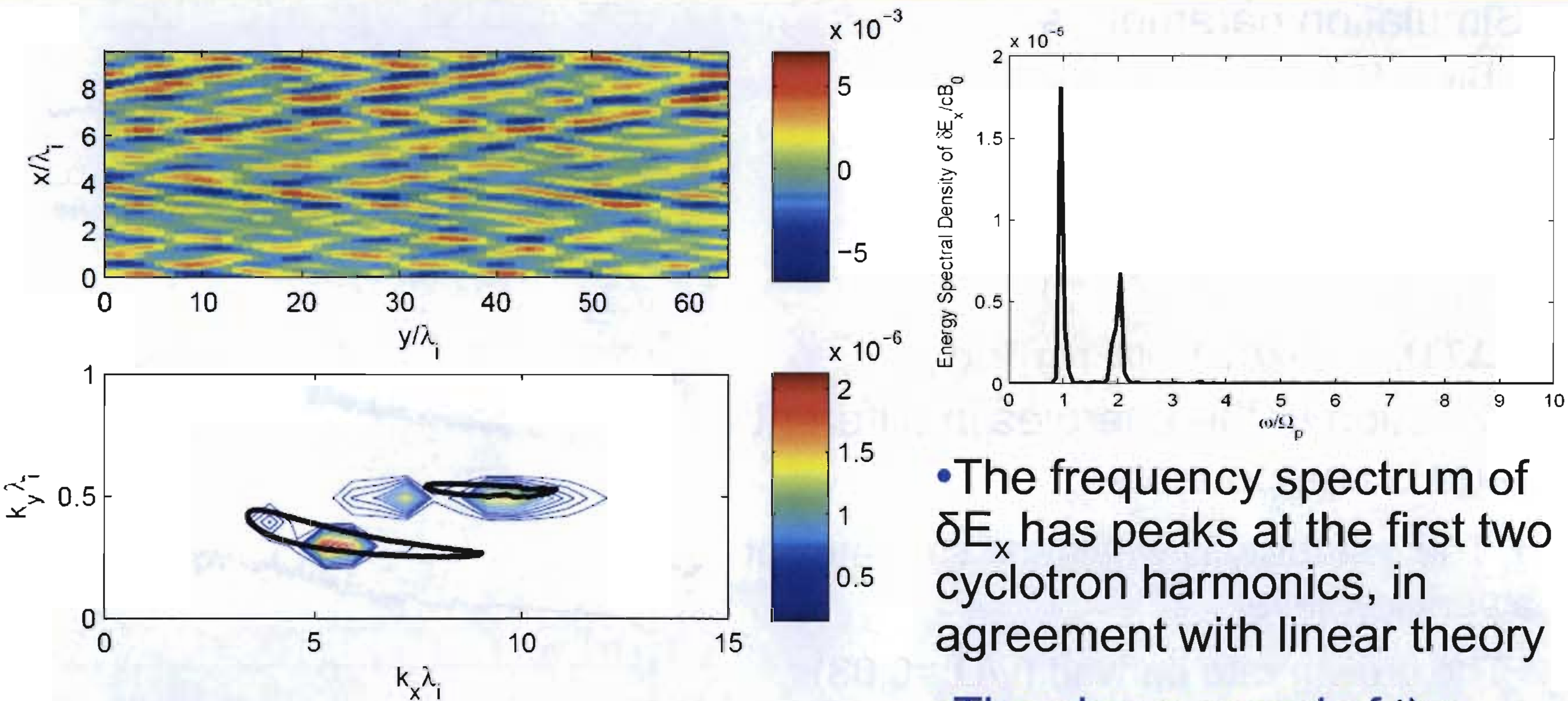
  + The instability is weak and saturates at a very low level

  + The growth rate derived (γ/Ω_p=0.03) and the relative component amplitudes agree with the predictions of linear theory

  + E_x dominates among E components and is mainly electrostatic contribution, but most of the wave energy is still in B



PIC Simulation: Case I-Subtracted Maxwellian



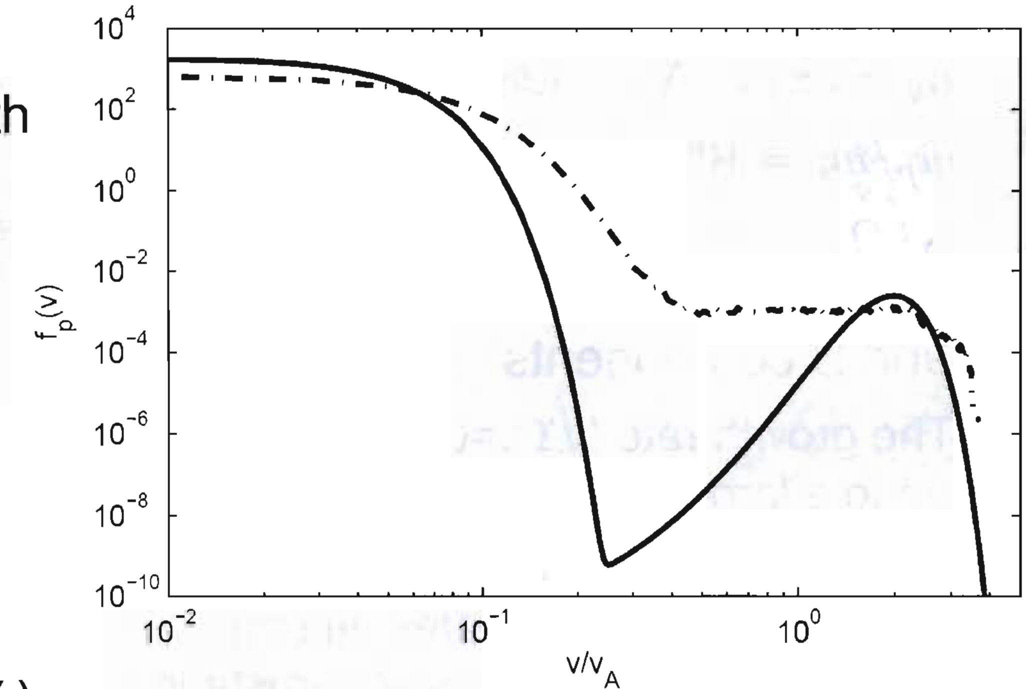
- The δE_x fluctuations at $t\Omega_p$=120 (Top: Contour plot, Bottom: Spectrum)
- Solid black contour lines in the bottom panel are the γ/Ω_p=0.03 contours from linear theory

- The frequency spectrum of δE_x has peaks at the first two cyclotron harmonics, in agreement with linear theory
- The phase speed of the excited waves is ~$0.2v_A$ and does not follow the low-beta plasma dispersion relation for magnetosonic waves ($\omega=kv_A$). They are Bernstein waves!

PIC Simulation: Case II-Generalized Distribution

$$f_p(v) = \frac{n_s}{A}\exp[-(v - v_s)^2/v_{sth}^2] + \frac{n_b}{(\pi v_{bth}^2)^{3/2}}\exp[-(v)^2/v_{bth}^2]$$

- A generalized distribution composed of a proton shell with a finite thermal spread and a relatively cold ion background
- The proton distribution used in Case II (solid line) has 10% shell protons at $v_s/v_A=2$, $v_{sth}/v_A=0.45$, and $v_{bth}/v_A=0.045$
- The major changes in Case II are the significant presence of the cold background ions (90%) and the increase of the shell velocity v_s



- The dash-dotted line displays $f_p(v_\perp)$ for protons of $|v_{||}|/v_A \leq 0.02$ at $t\Omega_p=100$ from the simulation

PIC Simulation: Case II-Generalized Distribution

- Simulation parameters

  $\mathbf{B}_0 = B_0\hat{y}$

  $L_x = 12.8\lambda_i,\ N_x = 128$

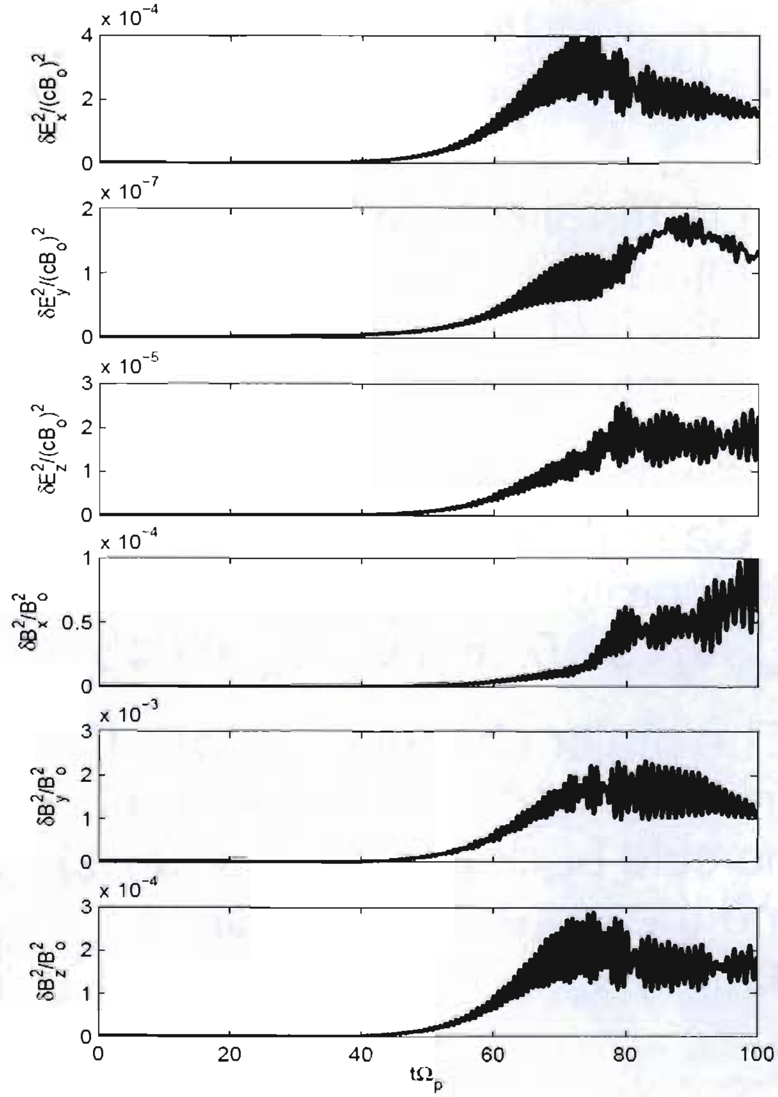
  $L_y = 384\lambda_i,\ N_x = 128$

  $m_p/m_e = 100,\ \omega_p/\Omega_p = 15$

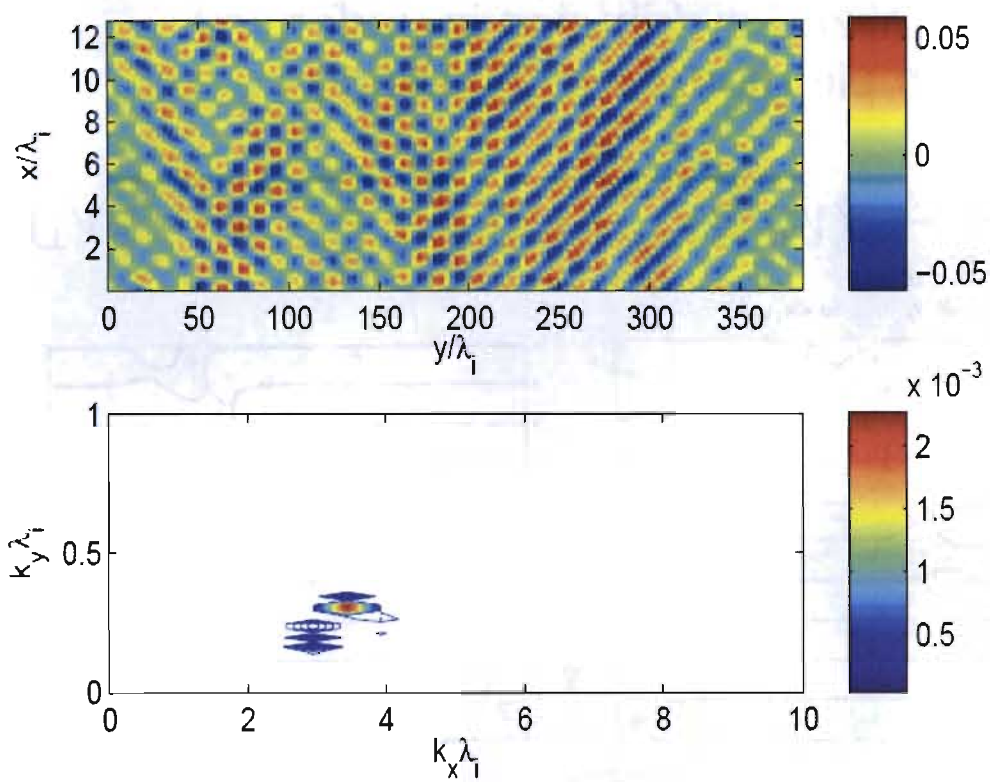
  $\Delta T\Omega_p = 0.001,\ 5000\ \text{particles/cell}$

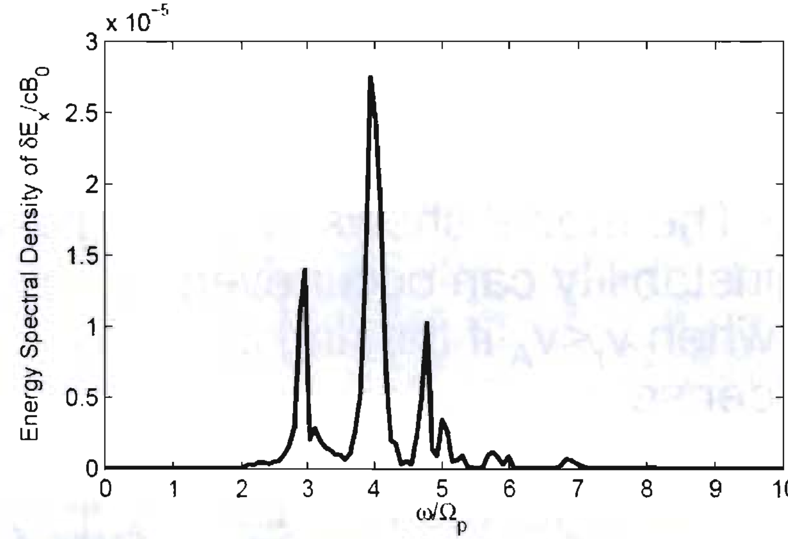
- Evolution of the energies in different E and B components

+ The growth rate (γ/Ω_p=0.07) is larger due to a larger v_s
+ Most of the wave energy is in B, although δE_x still dominates among E components and is mainly electrostatic
+ Unlike Case I, $\delta B_{||}$ (δB_y) dominates among B components, in agreement with observations of magnetosonic waves



PIC Simulation: Case II-Generalized Distribution





- The frequency spectrum of δE_x has peaks at $\omega \approx 3\Omega_p$, $4\Omega_p$, and $5\Omega_p$
- The phase speed of the excited waves is $\sim 1 v_A$ and approximately follows the low-beta plasma dispersion relation for magnetosonic waves ($\omega = k v_A$)

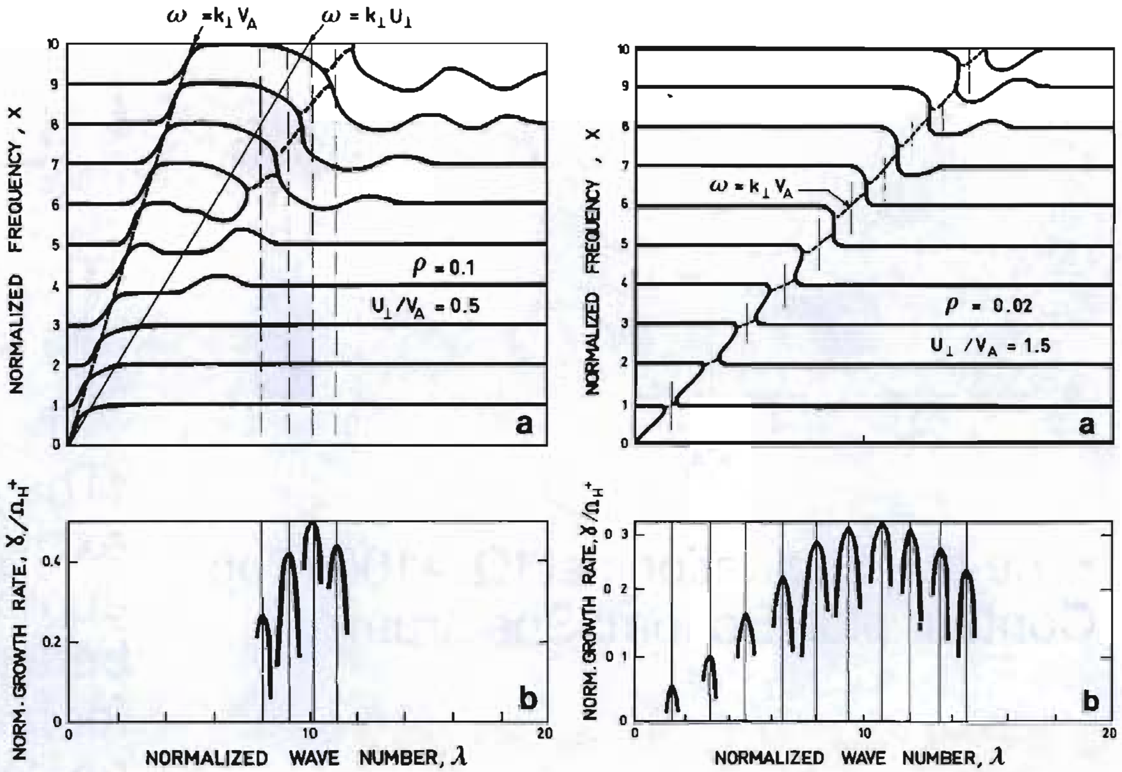
- The δE_x fluctuations at $t\Omega_p = 100$ (Top: Contour plot, Bottom: Spectrum)

Linear analysis for the Generalized Distribution

- Linear kinetic analysis for the generalized distribution is underway
- *Perraut et al.* [1982] developed a simple model which includes a cold background and a cold proton ring

$$f = \frac{n_r}{2\pi v_\perp} \delta(V_\parallel)\, \delta(V_\perp - U_\perp) + \frac{N_c}{2\pi V_\perp} \delta(V_\parallel)\, \delta(V_\perp)$$

- The model shows that instability can occur even when $v_r < v_A$ if the ring is dense
- The model also shows that the decrease of the relative ring density and the increase of v_r shift the excited waves toward $\omega = kv_A$, the low-beta plasma dispersion relation for magnetosonic waves
- The trend revealed by Case I and Case II agrees with this model

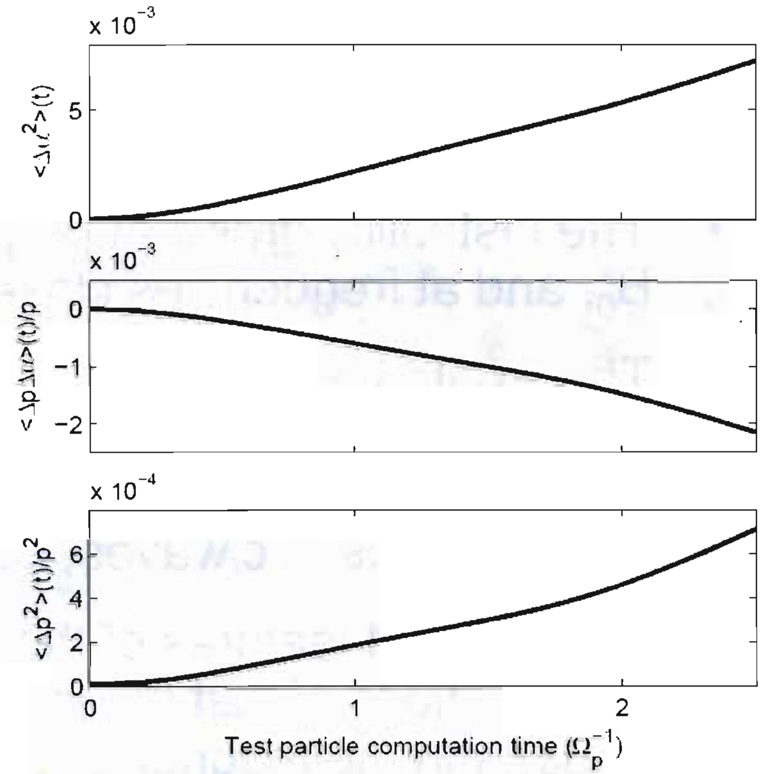


Scattering of Relativistic Electrons: Test Particle Computation

- The diffusion coefficients $D_{\alpha\alpha}$, $D_{\alpha p}=D_{p\alpha}$, and D_{pp} can be determined from the linear growth phase of $<\Delta\alpha^2>$, $<\Delta\alpha\Delta p>$, and $<\Delta p^2>$, respectively, from a test particle computation, e.g.,

$$D_{\alpha\alpha} = \frac{<\Delta\alpha^2>(t_2) - <\Delta\alpha^2>(t_1)}{2\Delta t}$$

- Test particle computation determines $D_{\alpha\alpha}=1.6\times10^{-3}\Omega_p$, $D_{\alpha p}/p=D_{p\alpha}/p=-4.3\times10^{-4}\Omega_p$, and $D_{pp}/p^2=1.2\times10^{-4}\Omega_p$
- The relative amplitude of $D_{\alpha\alpha}$, $D_{\alpha p}=D_{p\alpha}$, and D_{pp} agrees with QL theory
- QL theory estimates $D_{\alpha\alpha}=2\times10^{-3}\Omega_p$.
- Magnetosonic waves both pitch-angle scatter and accelerate relativistic electrons



- The time evolution of $<\Delta\alpha^2>$ (top), $<\Delta\alpha\Delta p>/p$ (middle), and $<\Delta p^2>/p^2$ (bottom) of 8192 test electrons of 500 keV and $\alpha=75^o$ in the test particle computation

Summary

- Proton distributions with $\partial f(v_\perp)/\partial v_\perp > 0$ can drive proton Bernstein instability
- The instability grows at propagation angles nearly perpendicular to B_0, and at frequencies close to the harmonics of Ω_p
- The excited waves are Bernstein waves, but the presence of the cold background protons and the increase of the shell velocity shift the excited waves close to the low-beta plasma dispersion relation for magnetosonic waves, i.e., $\omega = kv_A$
- The general features of the simulated field fluctuations resemble observations of fast magnetosonic waves, near the geomagnetic equator in the magnetosphere
- This growing mode may play an important role in the acceleration of radiation-belt relativistic electrons

❖ A manuscript on this work can be downloaded from *http://public.lanl.gov/pgary/Publications/manuscripts.html*