Updates on Study of Magnetic Fluctuation during Reconnection

Hantao Ji

Center for Magnetic Self-organization in Laboratory and Astrophysical Plasmas
Princeton Plasma Physics Laboratory, Princeton University

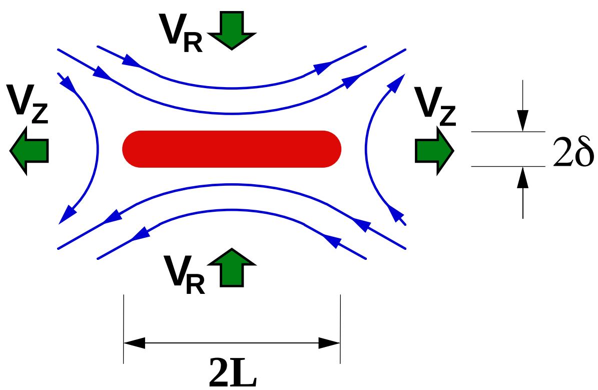
Contributors:
Russell Kulsrud
Masaaki Yamada
Will Fox
Yansong Wang
Brendan McGeehan
Yang Ren

General Meeting of CMSO
San Diego, March 3-4, 2005

Modern Leading Theories for Fast Reconnection:

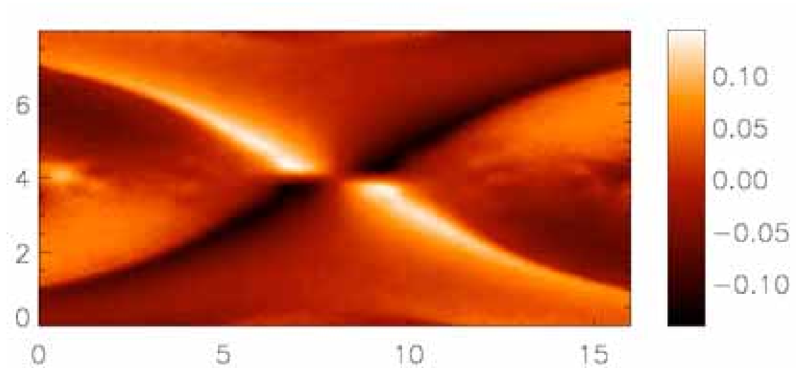
Turbulent vs. Laminar Models

"anomalous" resistivity



(Ugai & Tsuda, '77; Sato & Hayashi, '79; Scholer, '89….)

Facilitated by Hall effects



(e.g. Drake et al.)

- **Enhanced due to (micro) instabilities**
- **Faster Sweet-Parker rates**
- **Re-establish Petschek model by localization**

- **Separation of ion and electron layers**
- **Mostly 2D and laminar**
- **Out-of-plane quadrupole field**

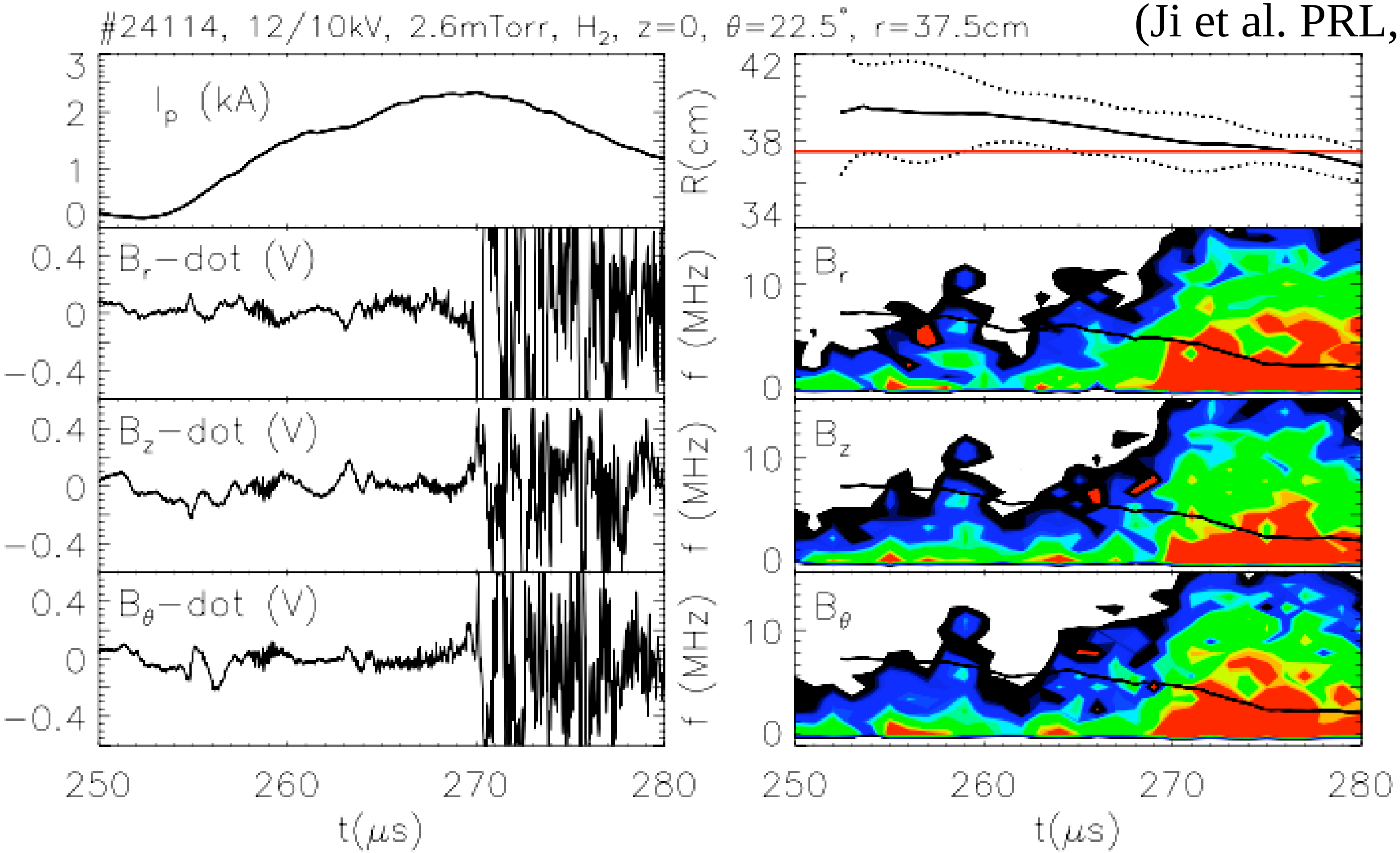
Expect:
high-frequency fluctuations

Expect:
Out-of-plane quadrupole field

We have seen both!

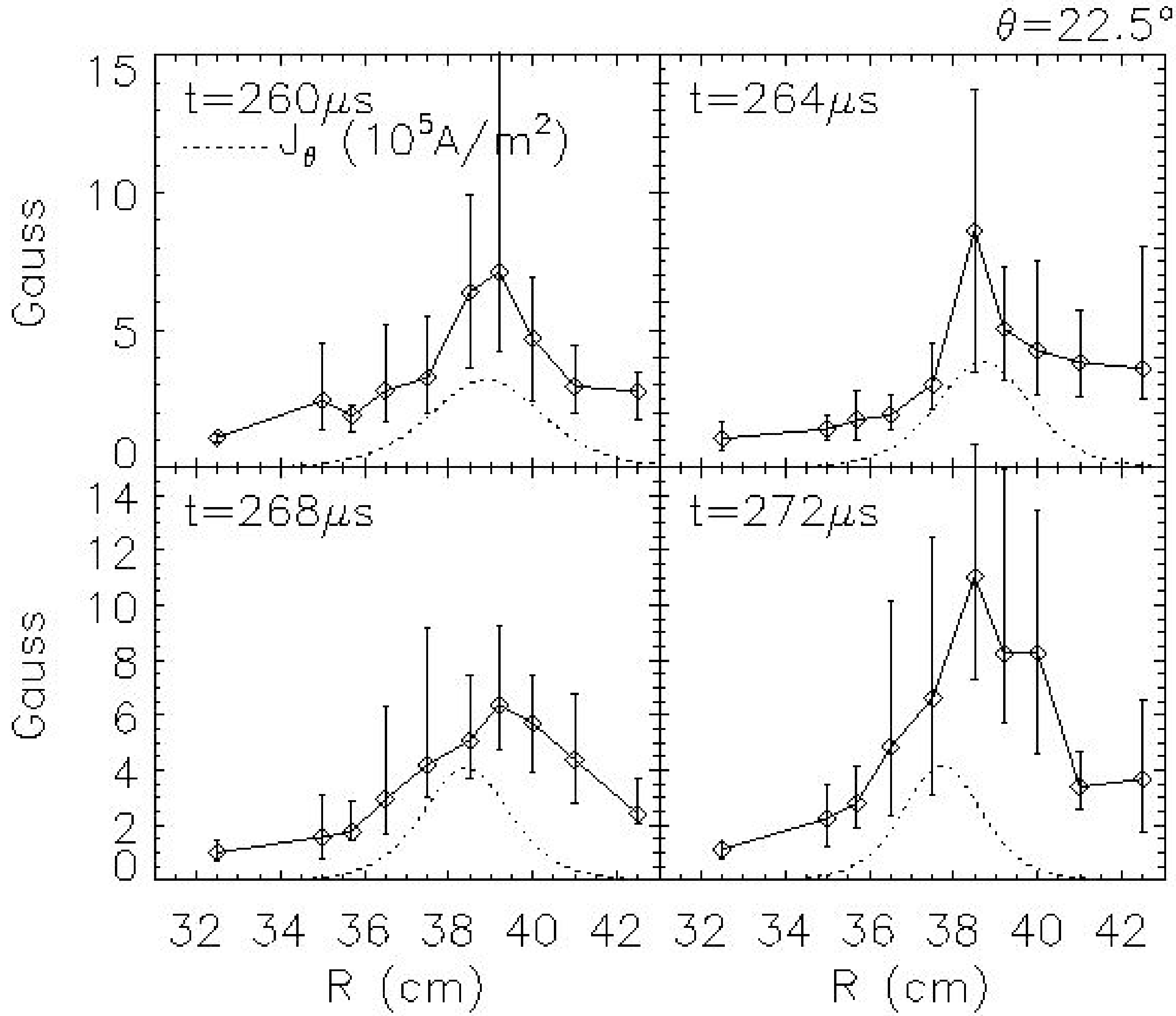
Magnetic Fluctuations Measured in Current Sheet Region

(Ji et al. PRL, '04)



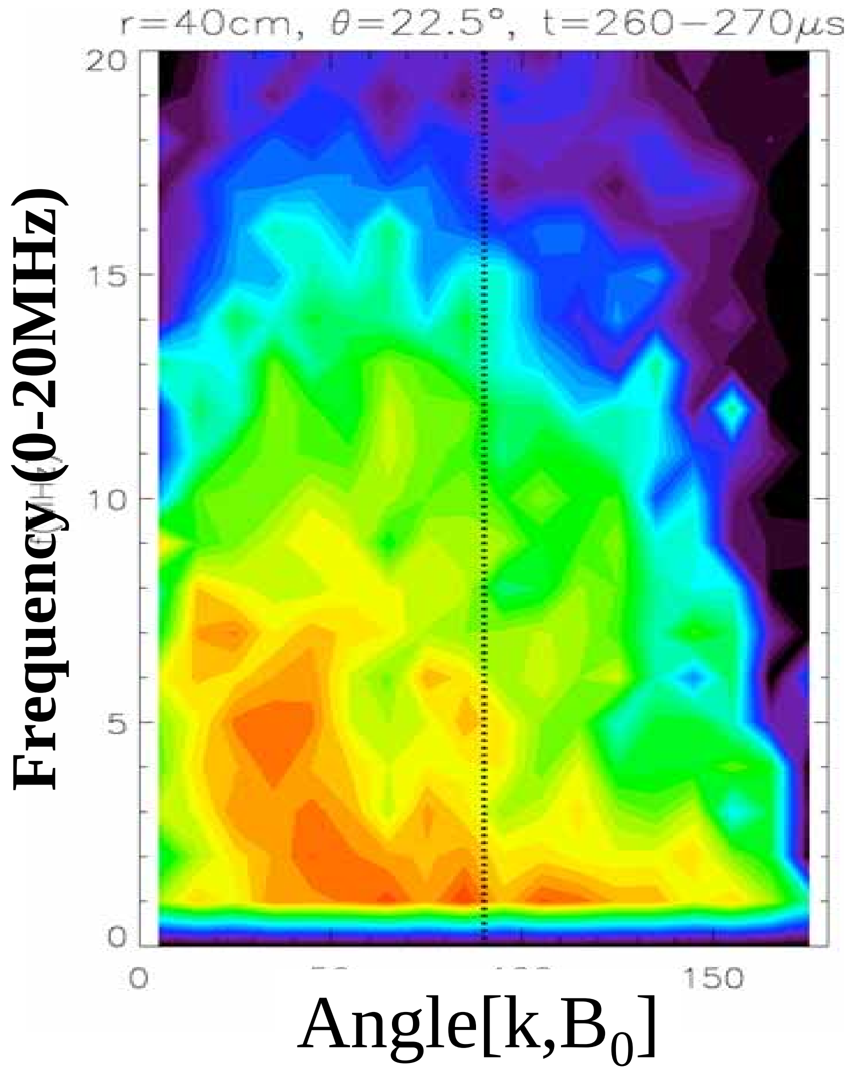
- **Comparable amplitudes in all components**
- **Often multiple peaks in the LH frequency range**

Magnetic Fluctuations Peak Near the Current Sheet Center



f ≥ 250KHz

Waves Propagate in the Electron Drift Direction with a Large Angle to Local B

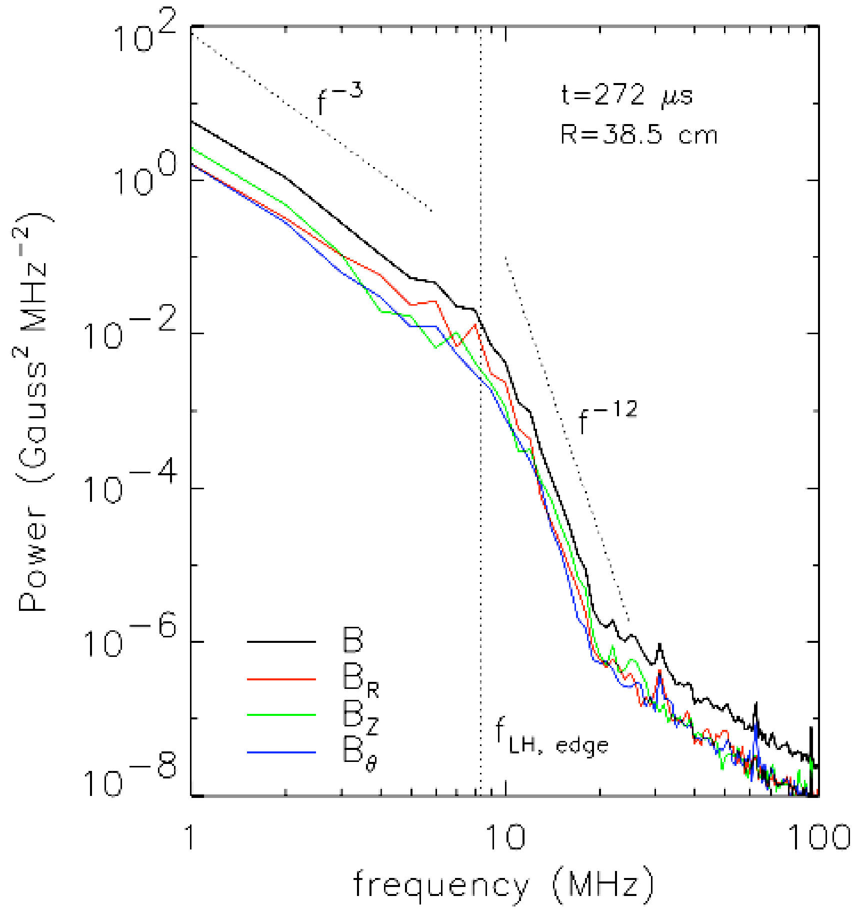


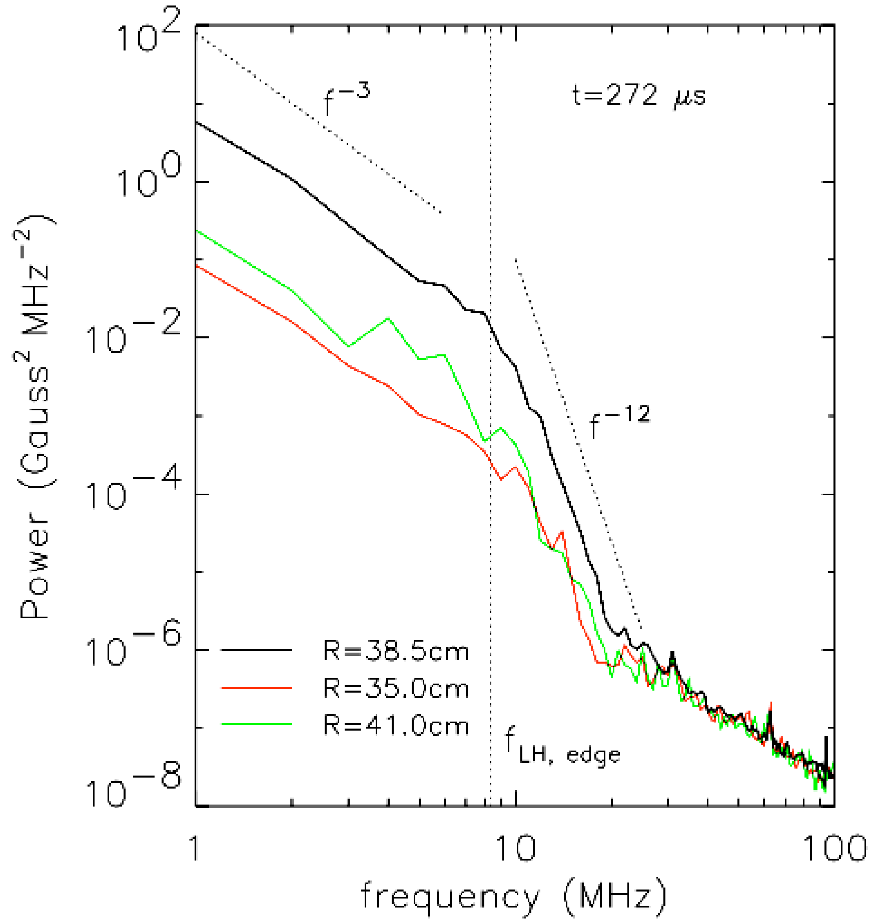
Local to certain angle

R-wave

$\mathbf{V_{ph} \sim V_{drift}}$

Frequency Spectra of Magnetic Turbulence





Slope changes at f_{LH} (based on edge B) from f^{-3} to f^{-12}

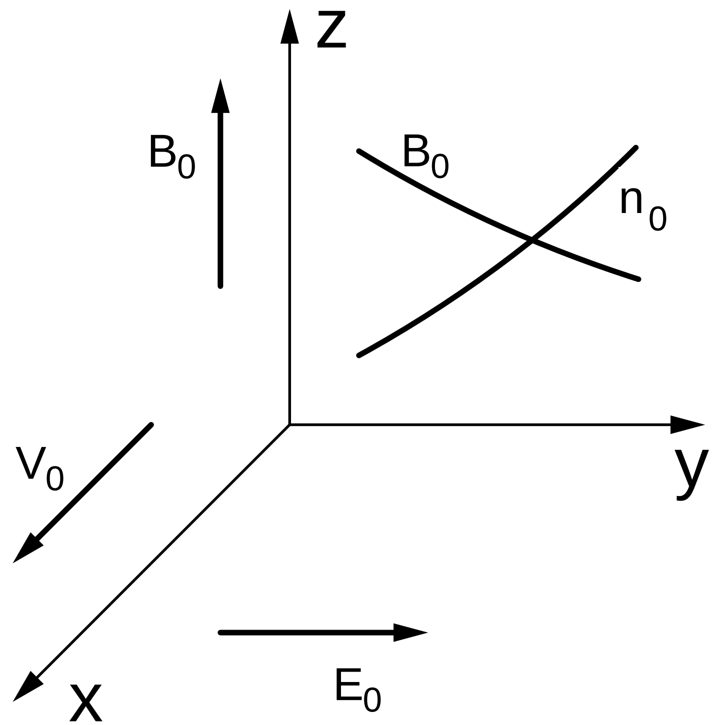
A Local 2-Fluid Theory

- **Regime:** $\omega_{ci} << \omega << \omega_{ce}$ (Ji et al. submitted to JGR, '04)
- **Assumptions**
  - **Massless, isotropic, magnetized electrons**
  - **Unmagnetized ions**
  - **No e-i collisions**
  - **Charge neutrality**
  - **Constant ion and electron temperature**
- **Equilibrium**
  - **Background magnetic field in z direction**
  - **Density gradient in y direction**
  - **Ions are at rest**

$$en_0 E_0 = T_i \frac{\partial n_0}{\partial y}$$

  - **Electrons drift across B in x direction**

$$-en_0\left(E_0 - V_0 B_0\right) = T_e \frac{\partial n_0}{\partial y}$$



Dispersion Relation

- **Normalizations:**

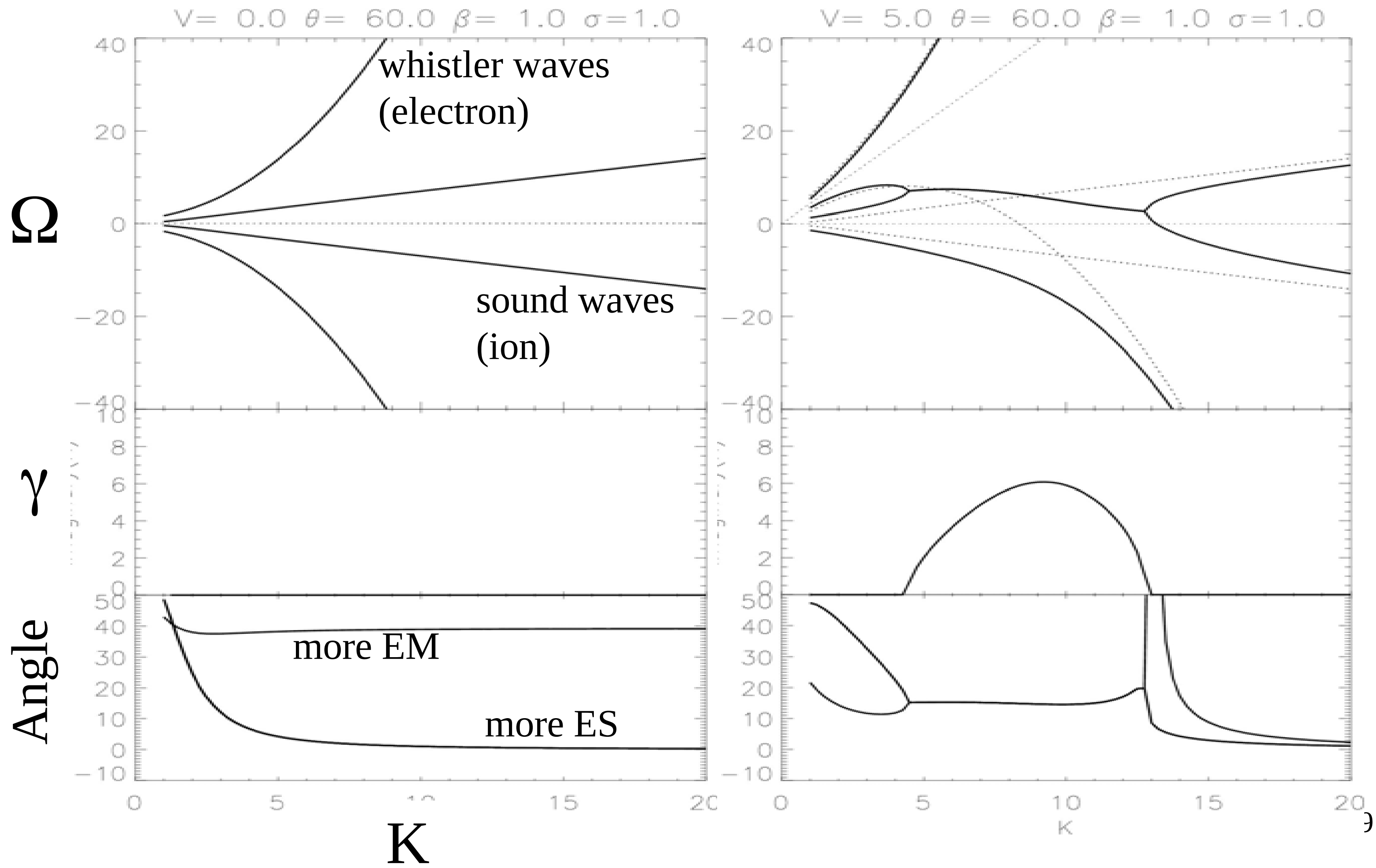
$$\Omega = \frac{\omega}{\omega_{ci}}, K = k\frac{c}{\omega_{pi}}, V = \frac{V_0}{V_A}, \beta_e = \frac{n_0 T_e}{B_0^2/2\mu_0}, \sin\theta = \frac{k_x}{k}, \sigma = \frac{T_i}{T_e}$$

- **Dispersion relation after re-arrangements:**

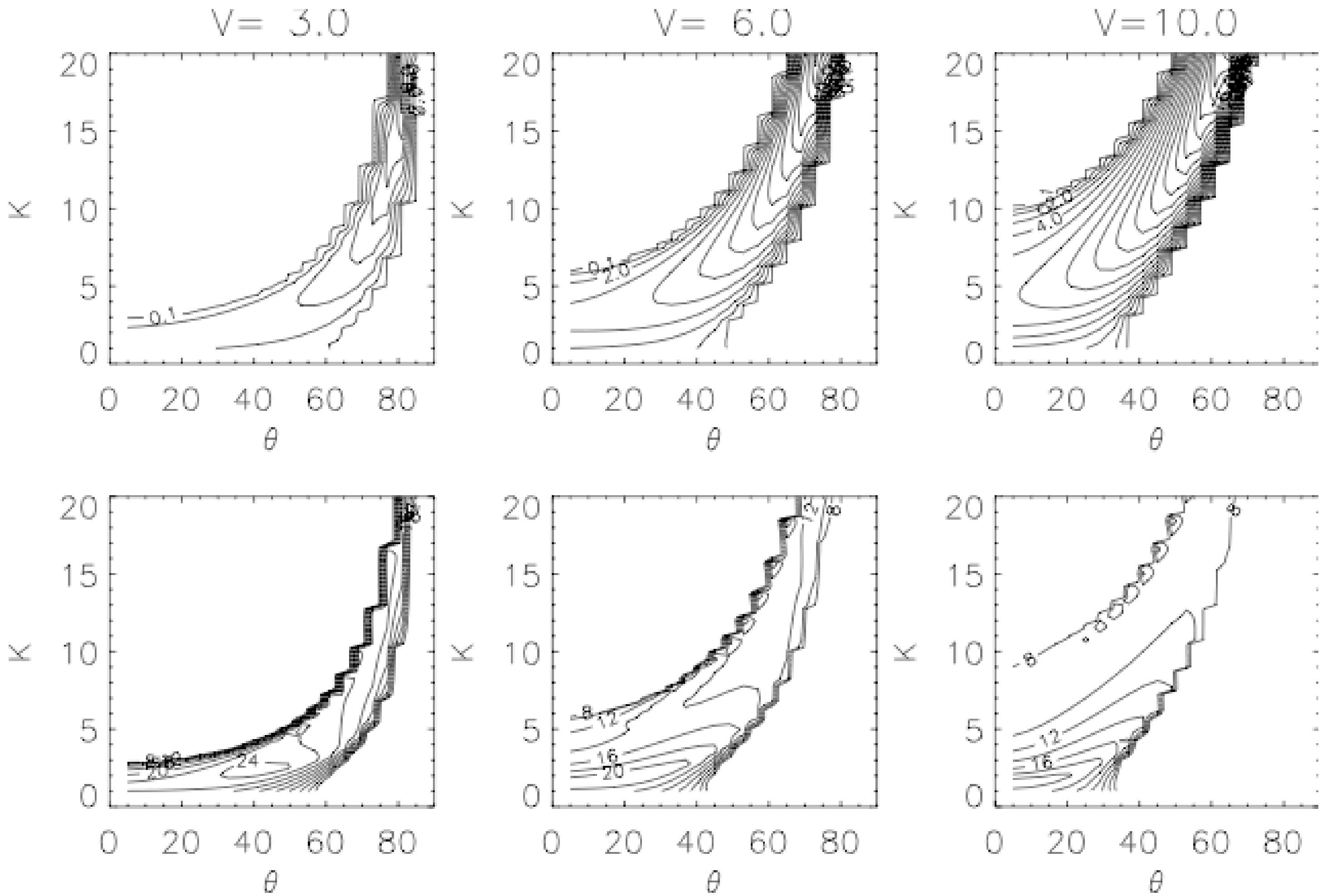
$$\begin{vmatrix} K^2\cos^2\theta + 1 - \frac{\sigma}{1+\sigma}\frac{KV\sin\theta}{\Omega} & i(\Omega - KV\sin\theta) & -K^2\sin\theta\cos\theta - \frac{\sigma}{1+\sigma}\frac{KV\cos\theta}{\Omega} \\ -i\left(\Omega - \frac{\beta_e}{2}\frac{K^2\sin^2\theta}{\Omega}\right) & K^2+1 & i\frac{\beta_e}{2}\frac{K^2\sin\theta\cos\theta}{\Omega} \\ KV\cos\theta - \frac{\beta_e}{2}\frac{K^2\sin\theta\cos\theta}{\Omega} & 0 & \Omega - KV\sin\theta - \frac{\beta_e}{2}\frac{K^2\cos^2\theta}{\Omega} \end{vmatrix} = 0$$

- **Fourth order in Ω(K), with controlling parameters of V, β, θ, σ.**

Instability: Large Drifts Cause Coupling between Whistler and Sound Waves



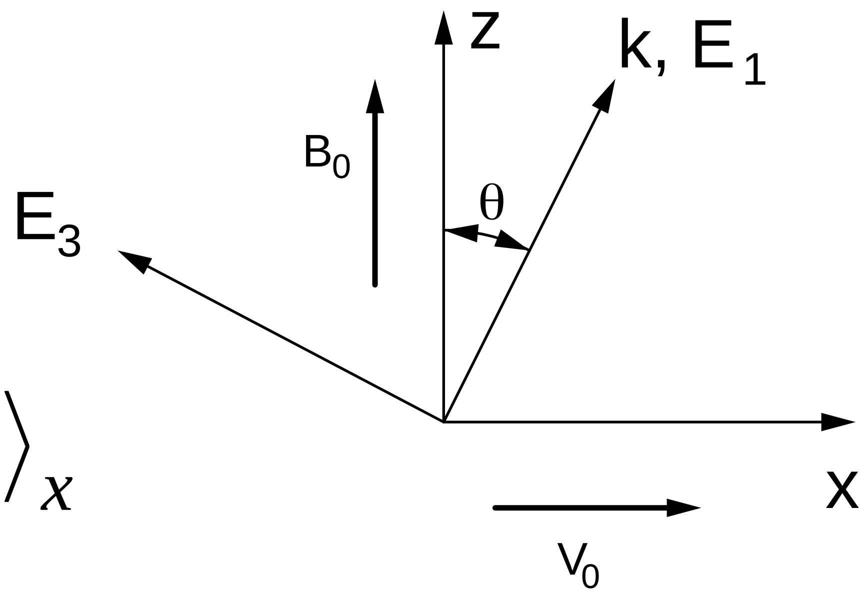
Unstable only at Certain Angles and K, Consistent with Observations



V=1 V=3 V=6

Quasi-linear Calculation of Wave Force on Electrons

(Kulsrud et al. submitted to PoP, '04)



$$F_x = -e\langle nE_x\rangle + \langle \mathbf{j}_e \times \mathbf{B}\rangle_x$$

$$-e\langle nE_x\rangle = -\frac{i}{2K}\left(\frac{|E_1|^2 \sin\theta + (E_3 E_1^* - E_3^* E_1)\cos\theta}{|E_2|^2 + |E_3|^2}\right)\frac{|B|^2}{\delta_i 2\mu_0}$$

$$\langle \mathbf{j}_e \times \mathbf{B}\rangle_x = \frac{i\cos\theta}{K}\frac{E_3 E_1^* - E_3^* E_1}{|E_2|^2 + |E_3|^2}\frac{|B|^2}{\delta_i 2\mu_0}$$

Resistivity due to Waves

$$F_x \equiv kC\frac{|B|^2}{2\mu_0} \equiv en\eta_w j$$

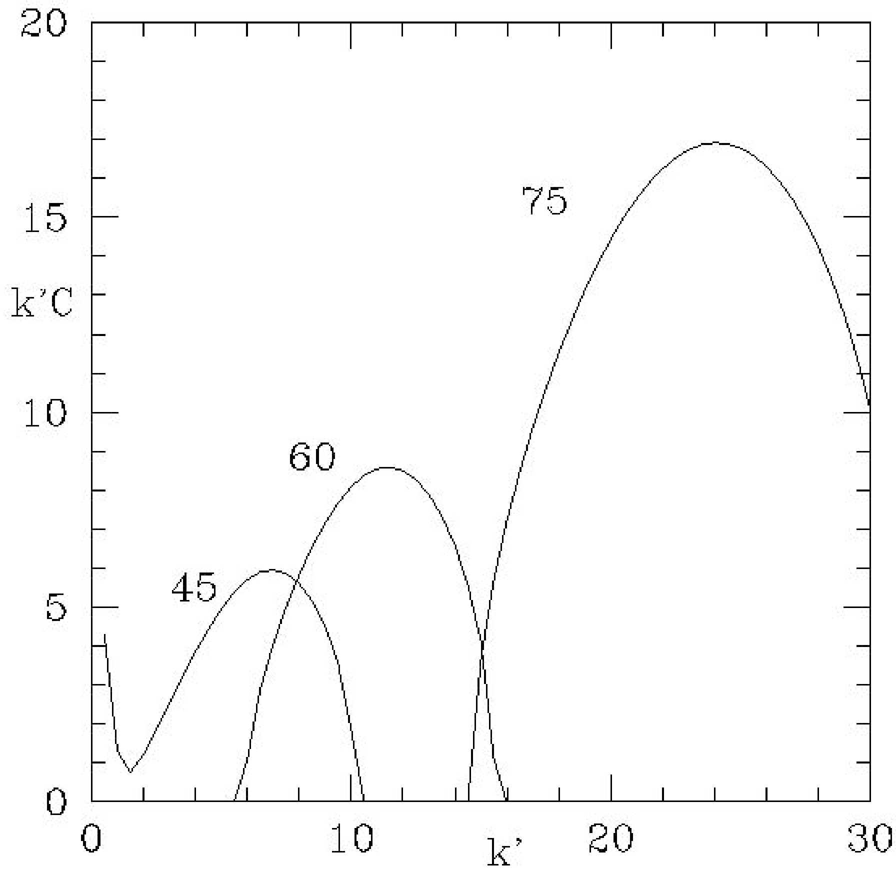
$$\eta_w \approx \frac{KC|B|^2}{6enB_0}$$

$$= 1.3\times10^{-4}(\Omega m)$$

versus

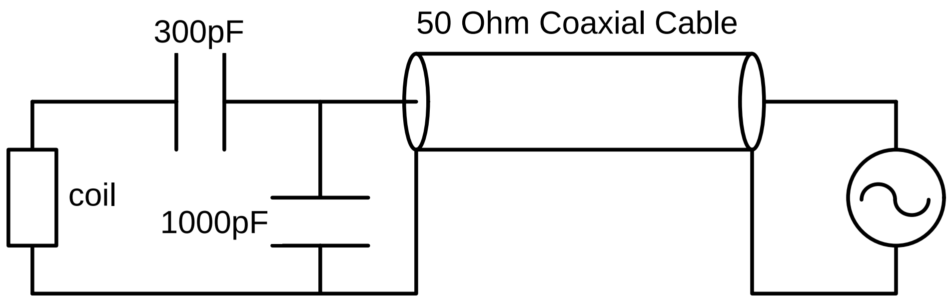
$$\eta_\perp = 0.7\times10^{-4}(\Omega m)$$

at Te=6eV



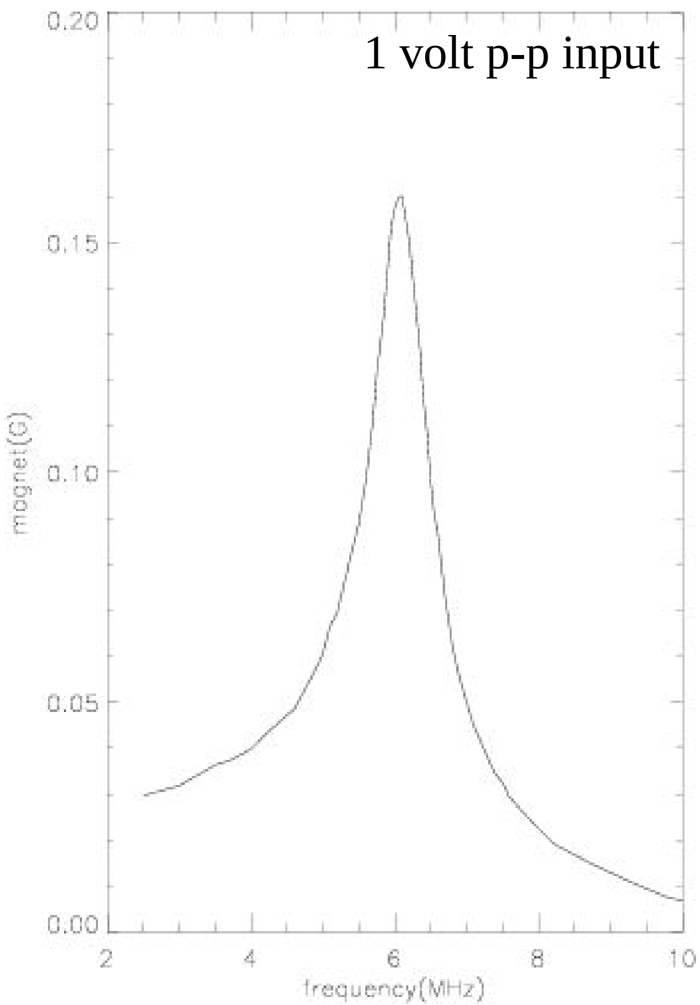
Active Magnetic Perturbations

(Y. Wang, '04)



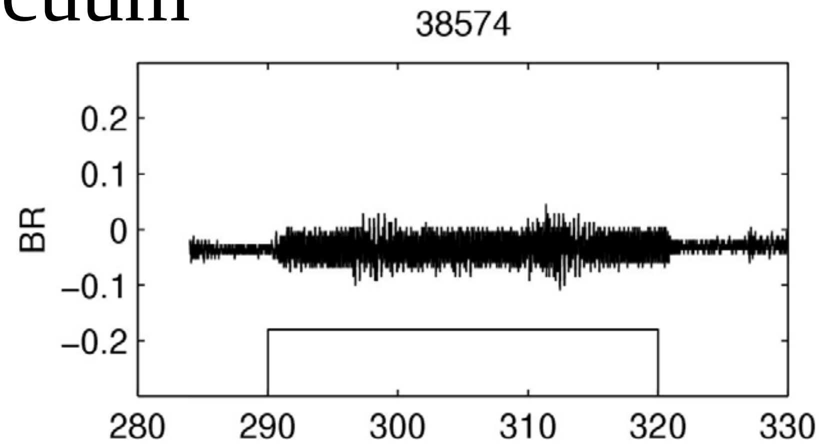
Coil: 2.5mm diameter, 6 mm long
2 layers, and 30 turns/layer
wound with 0.2mm diameter wire

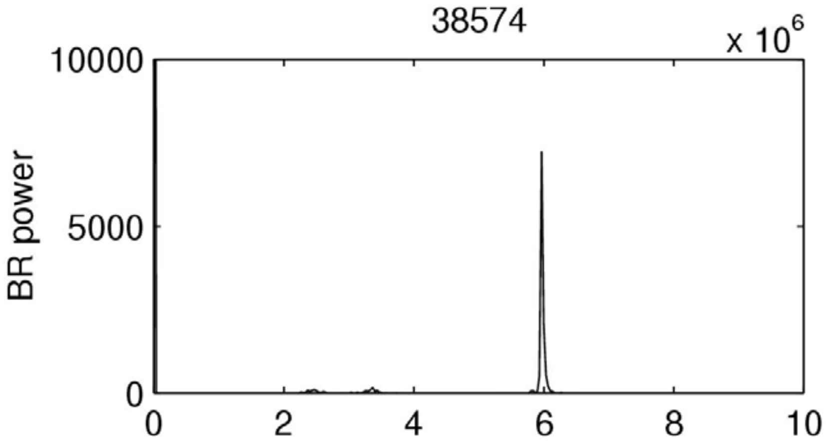
- **LC resonant circuit**
- **Best efficiency at ~6MHz**
- **Inserted to current sheet**
- **Monitored by a magnetic probe ~1cm away in the electron flow direction**



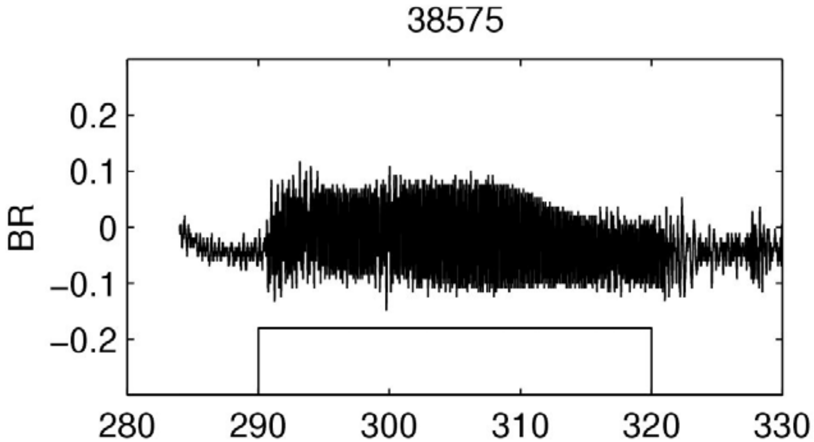
Initial Indication of Wave Growth

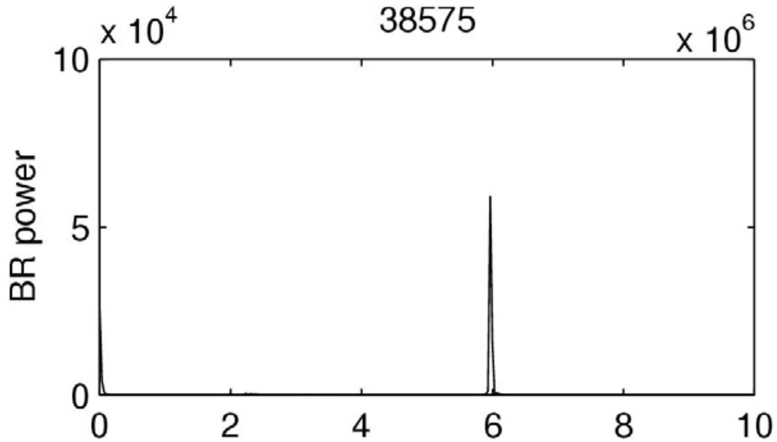
vacuum





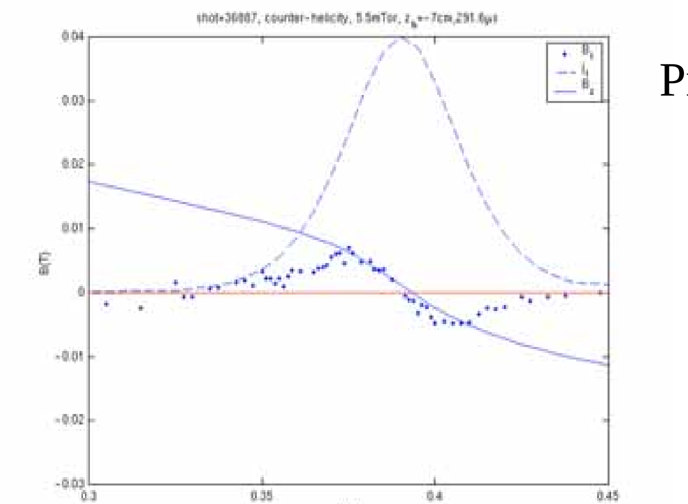
plasma



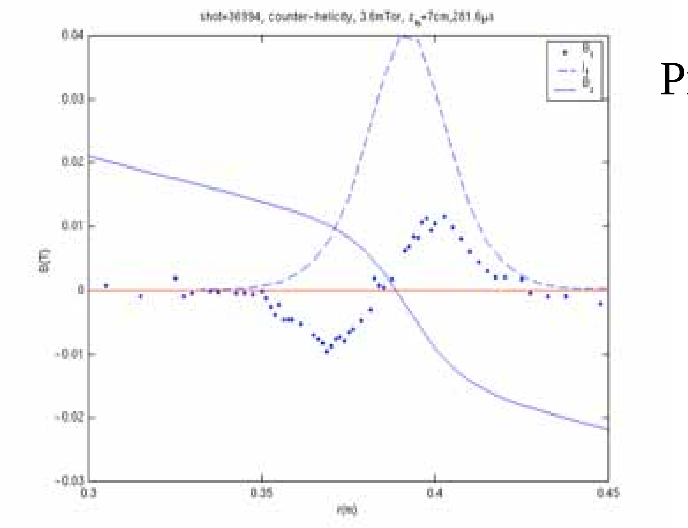


Out-of-plane Quadrupole Field (Hall effects) Observed

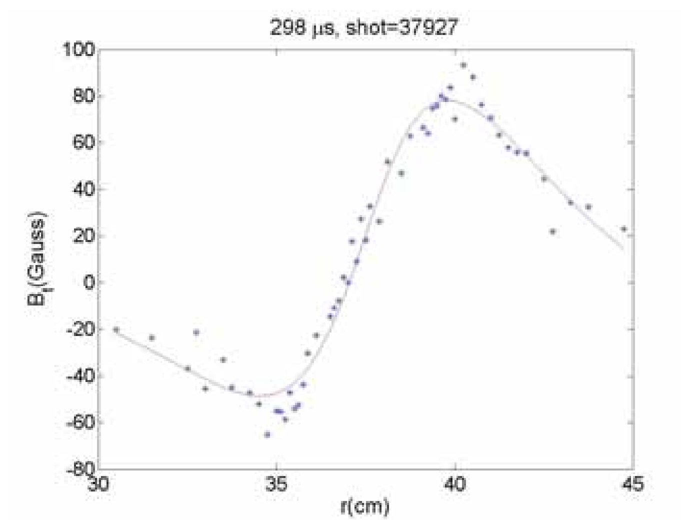
(Y. Ren et al., ‘05)



Probe at z = -7 cm

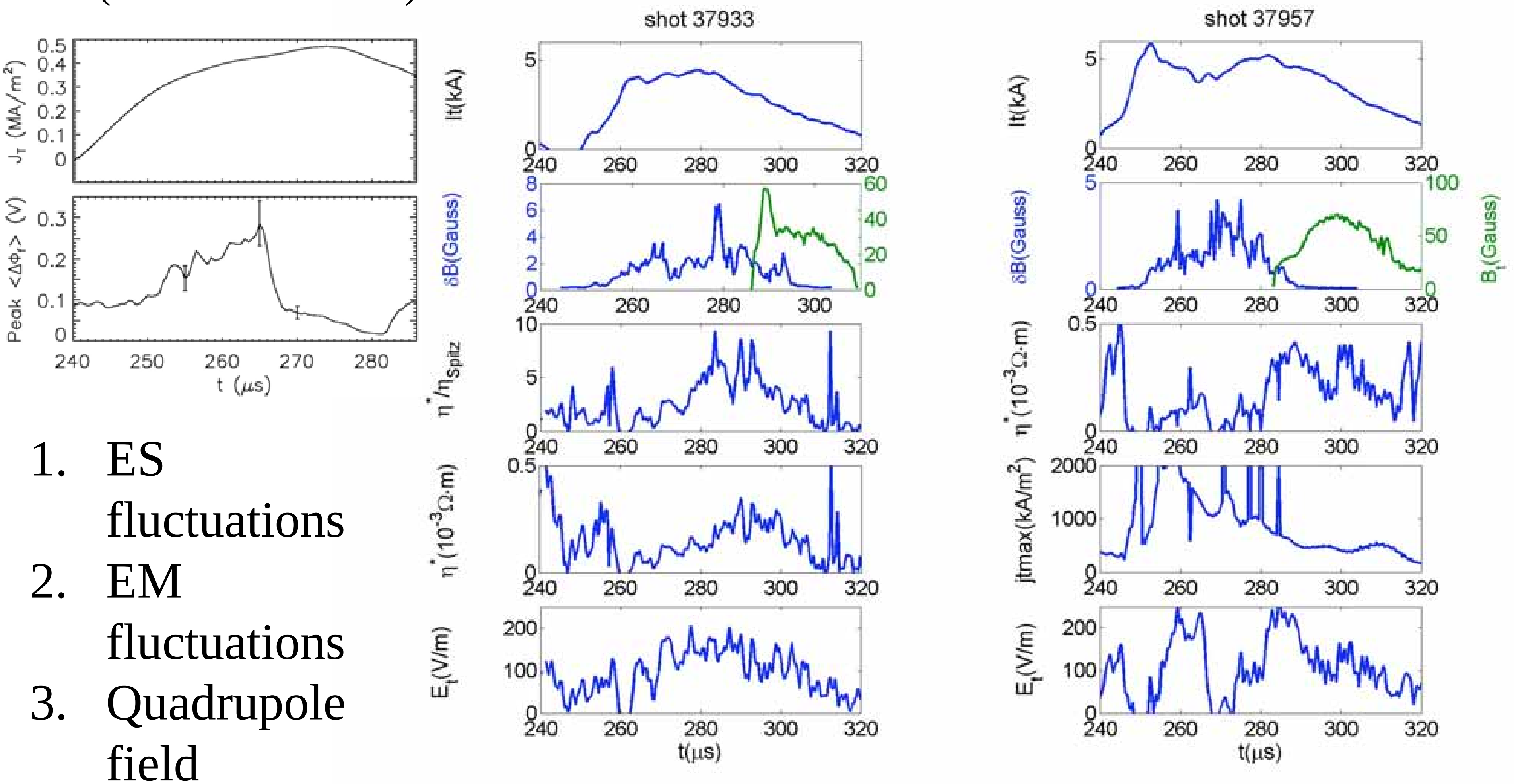


Probe at z = +7 cm



Relation between Turbulence and Hall effects

(Carter et al. 2001)



1. ES fluctuations
2. EM fluctuations
3. Quadrupole field

Summary

- **A local 2-fluid theory developed**
  - **"reactive coupling" leads to unstable oblique Whistler waves**
  - **Sizable resistivity based on quasi-linear estimate**
  - **Compare with simulations**

- **Active wave experiments underway**
  - **Initial indication of wave growth in the downstream of e flow (more detailed exp underway and planned)**

- **Relation between fluctuations and quadrupole field being studied**
  - **Clue for reconnection onset mechanism? (more detailed exp planned)**

- **Spectral index changes at f_{LH}**
  - **Indication of dissipation of waves? (More exp underway with ion heating)**