Laboratory Investigation of Nonlinear Whistler Wave Processes*

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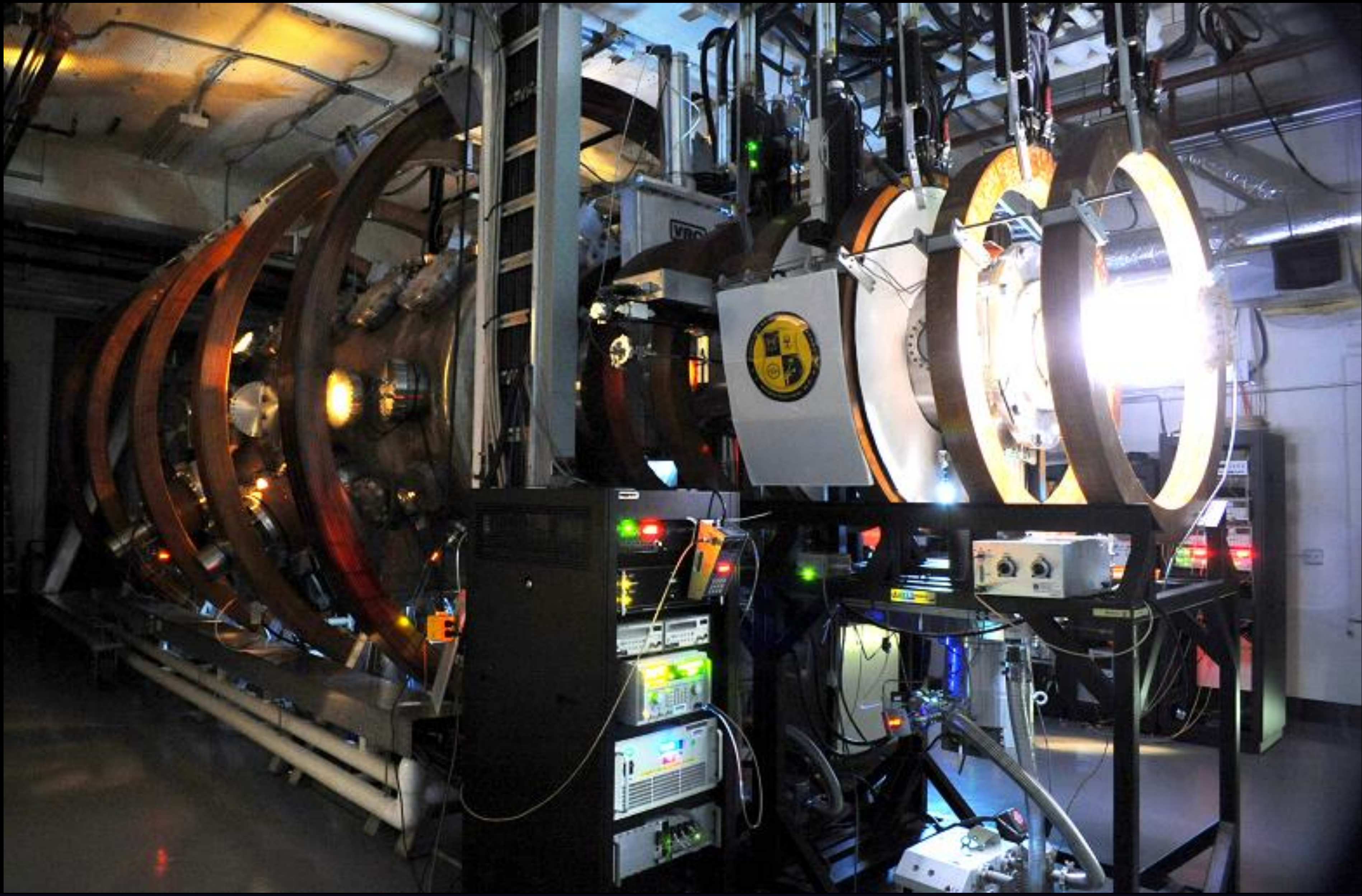
NRL Space Physics Simulation Chamber

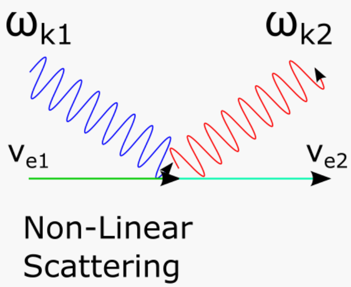


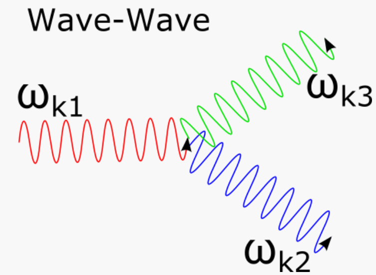
Collaborators

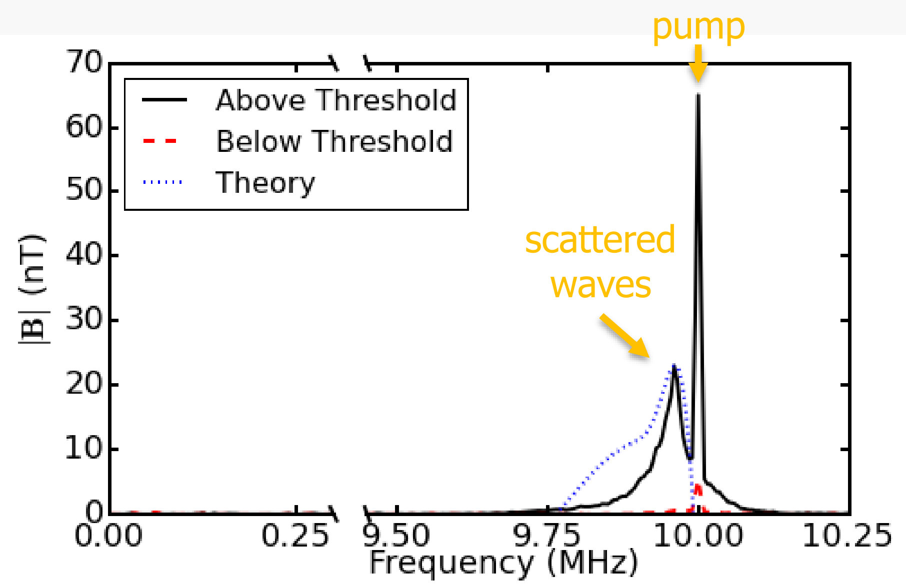
- Laboratory Experiments
  - Lon Enloe (NRL)
  - Bill Amatucci (NRL)
- Theory
  - Chris Crabtree (NRL)
  - Guru Ganguli (NRL)
- Space Observations
  - David Malaspina (UC Boulder)
- Simulations
  - Dong Lin (VA Tech)
  - Wayne Scales (VA Tech)

Studying the Building Blocks of Weak Turbulence

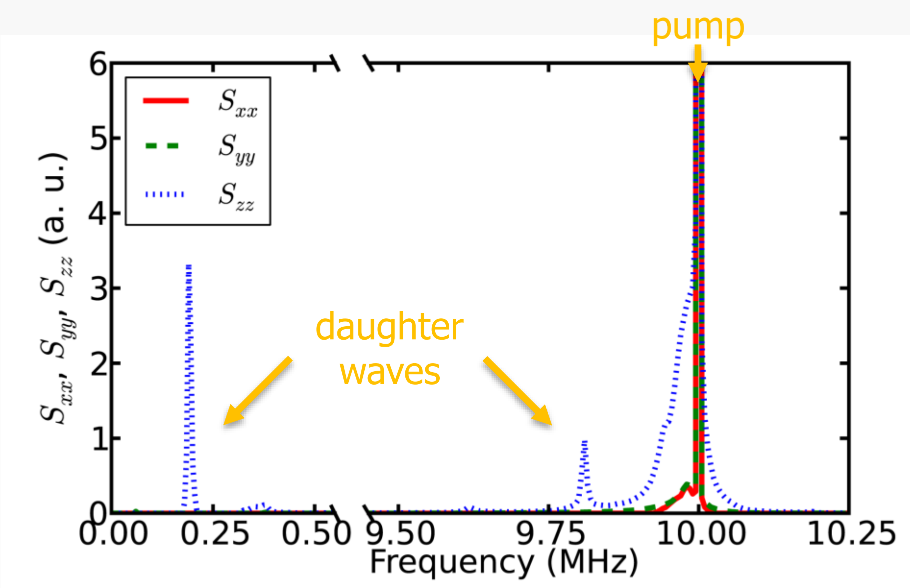
NRL PPD







Nonlinear Scattering



Parametric Decay

Tejero *et al.*, *Phys. Plasmas*, **22**, 091503 (2015)

Verification of Nonlinear Conversion of ES to EM

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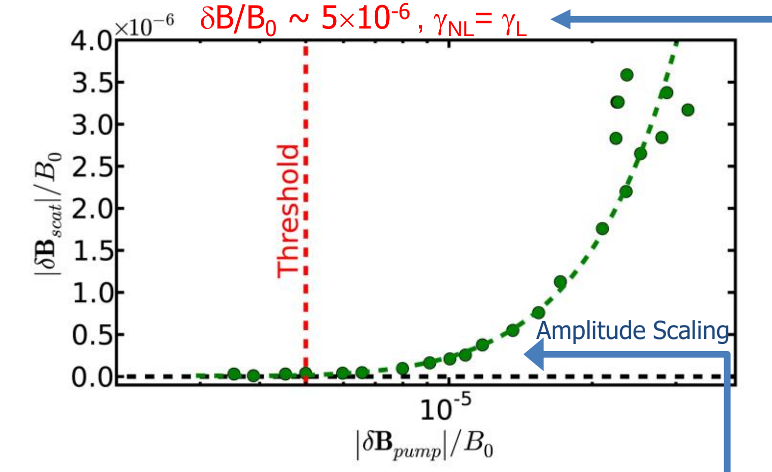
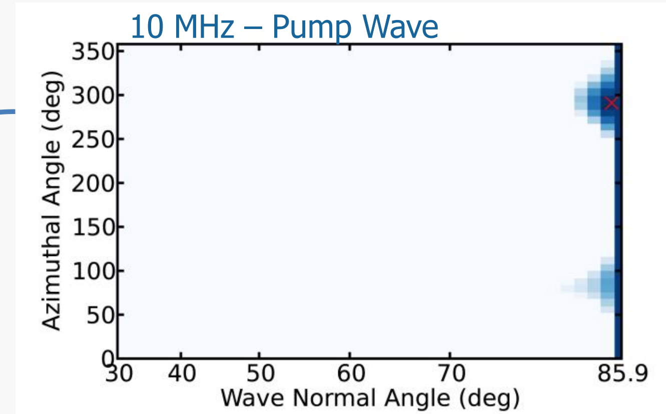
$\delta B/B_0 \sim 5\times10^{-6}$, $\gamma_{NL} = \gamma_L$

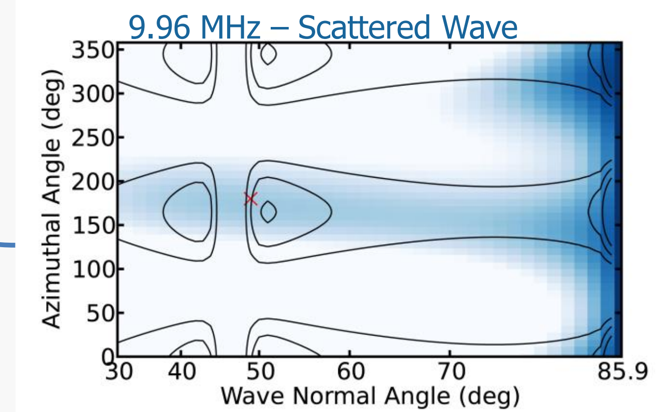


Threshold

$$\gamma_L(k,\omega) = \gamma_{NL}(k,\omega,W)$$

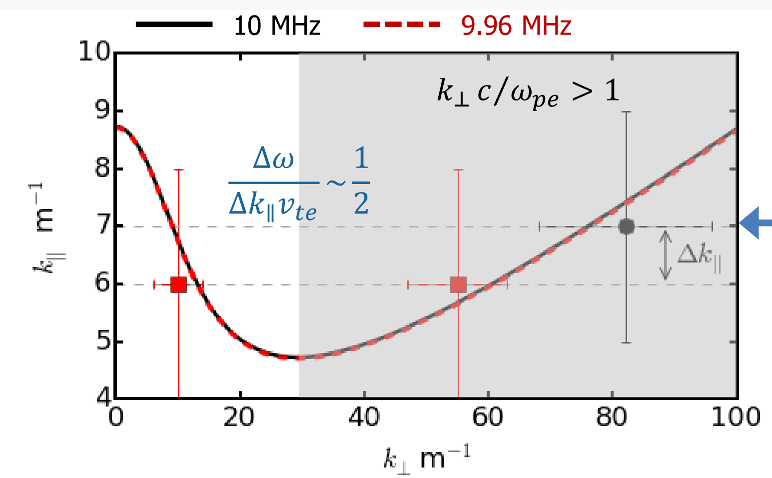
90° turning





$$g_{NL}^{k1\rightarrow k2} \sim \frac{w_{pe}^2}{w_{k2}} \frac{\bar{k}_2^2}{1+\bar{k}_2^2} \sum_{k1} \frac{W_{k1}}{n_0 T} \frac{(\vec{k}_1 \times \vec{k}_2)_{\parallel}^2}{k_{\perp 1}^2 k_{\perp 2}^2} z_e \operatorname{Im} Z\left(\frac{w_{k2} - w_{k1}}{|k_{\parallel 2} - k_{\parallel 1}| \mathrm{v}_{te}} \right)$$

Resonance Condition



Experiment agrees with theory in detail

Tejero *et al.*, *Sci. Rep.*, **5**, 17852 (2015) and Tejero *et al.*, *Phys. Plasmas*, **23**, 055707 (2016)

Wave Distribution Function Technique Validated

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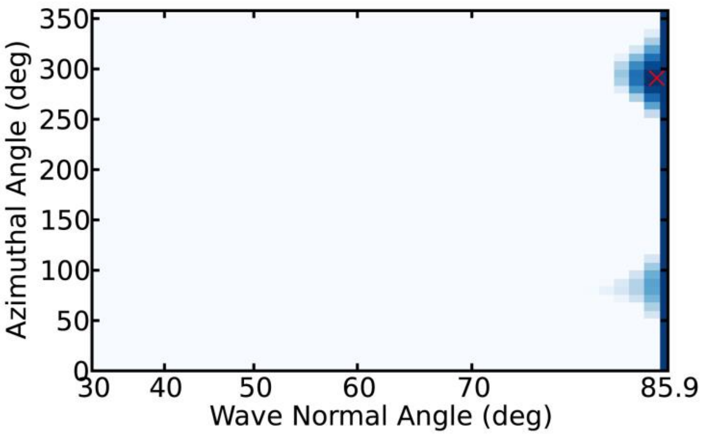
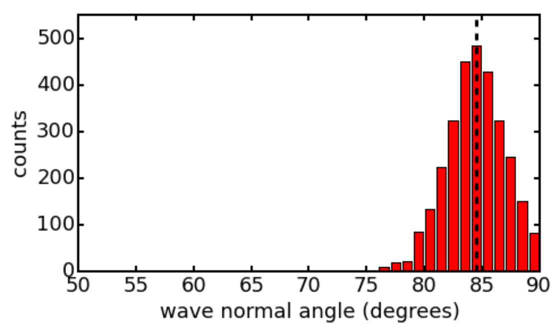
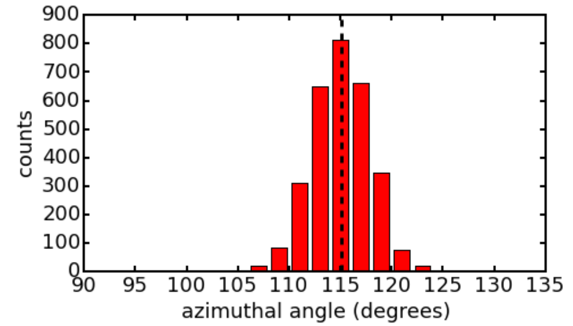
10 MHz – Pump Wave

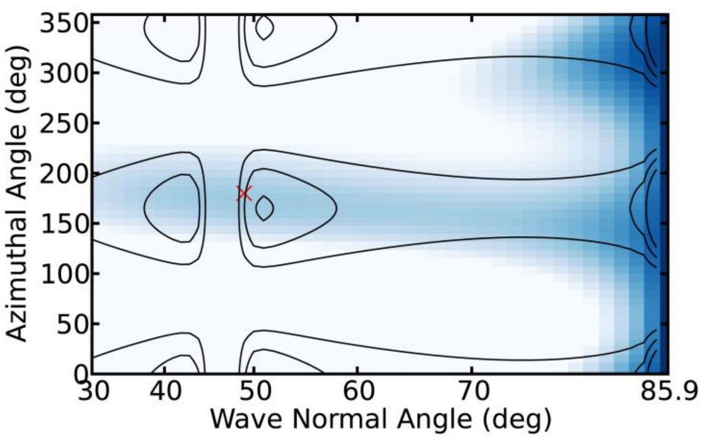


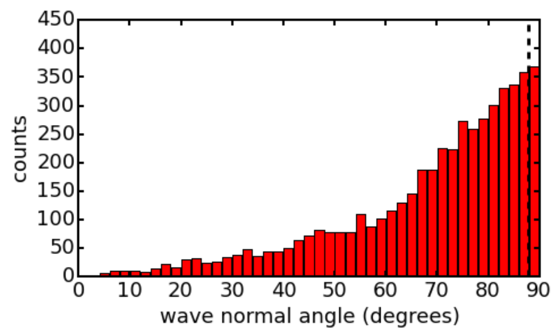


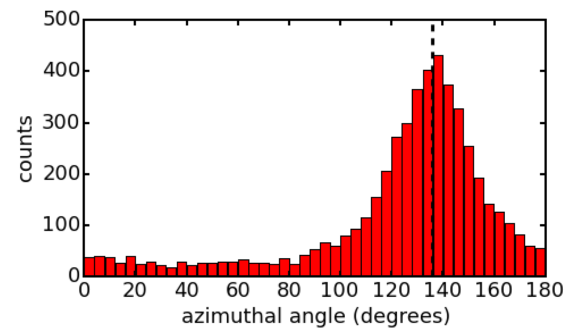


Histogram Results Using Spectral Techniques (SVD)

9.96 MHz – Scattered Wave





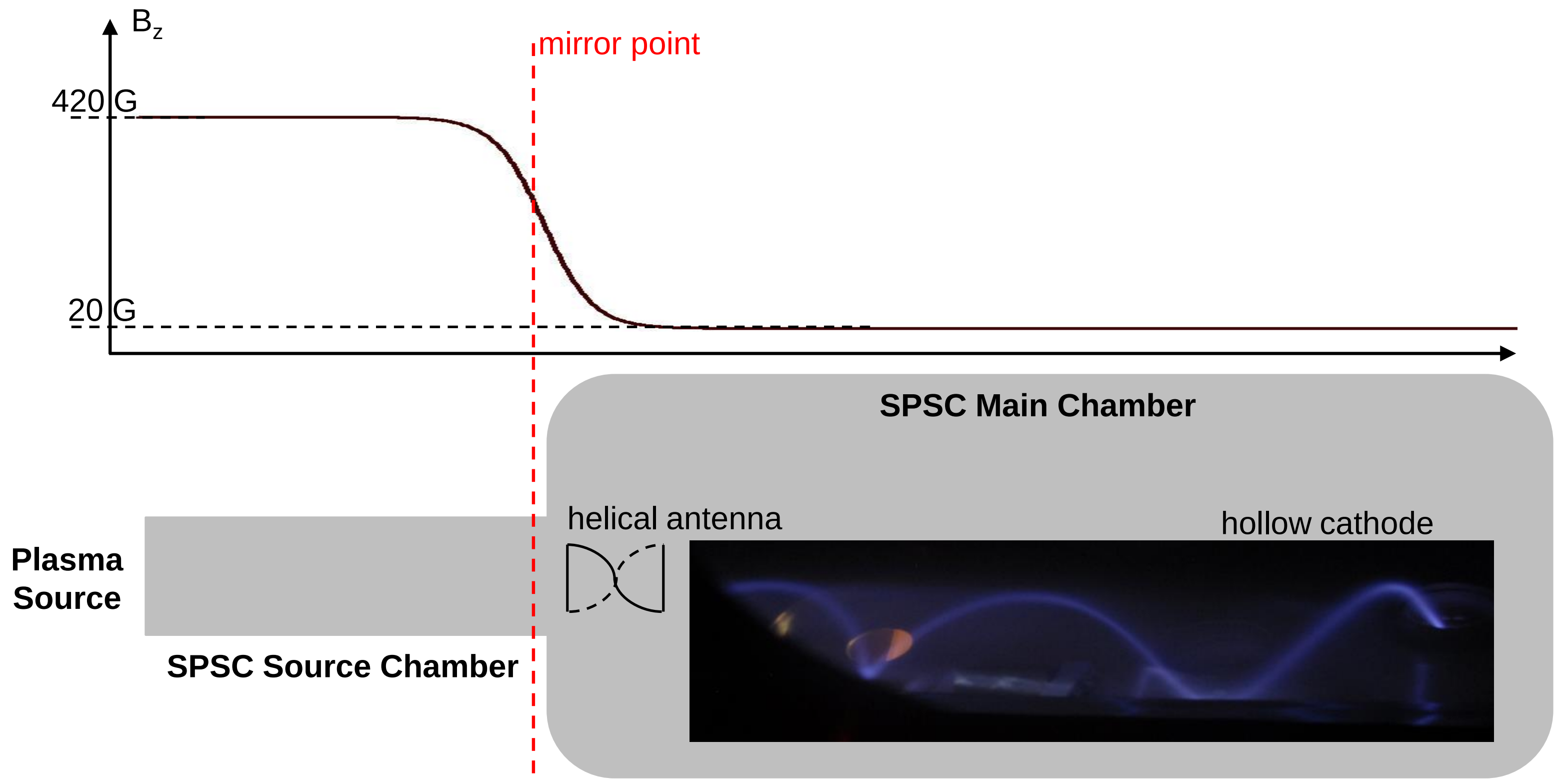


Results from WDF and spectral techniques are consistent with laboratory *k* measurements.

Tejero *et al.*, *Phys. Plasmas*, **22**, 091503 (2015)

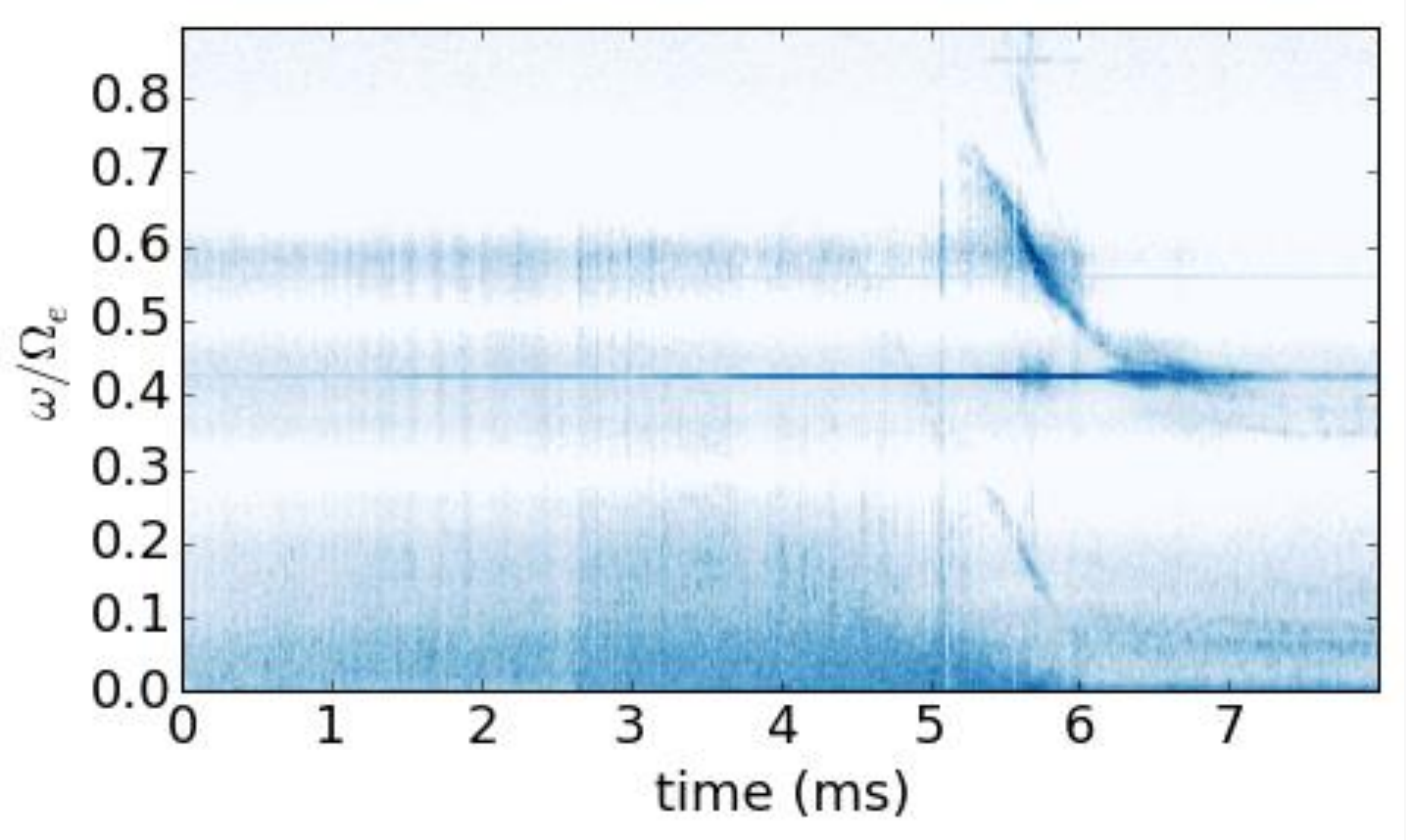
Triggered Emissions Experimental Setup

NRL PPD



Triggered Emission Observed in Laboratory

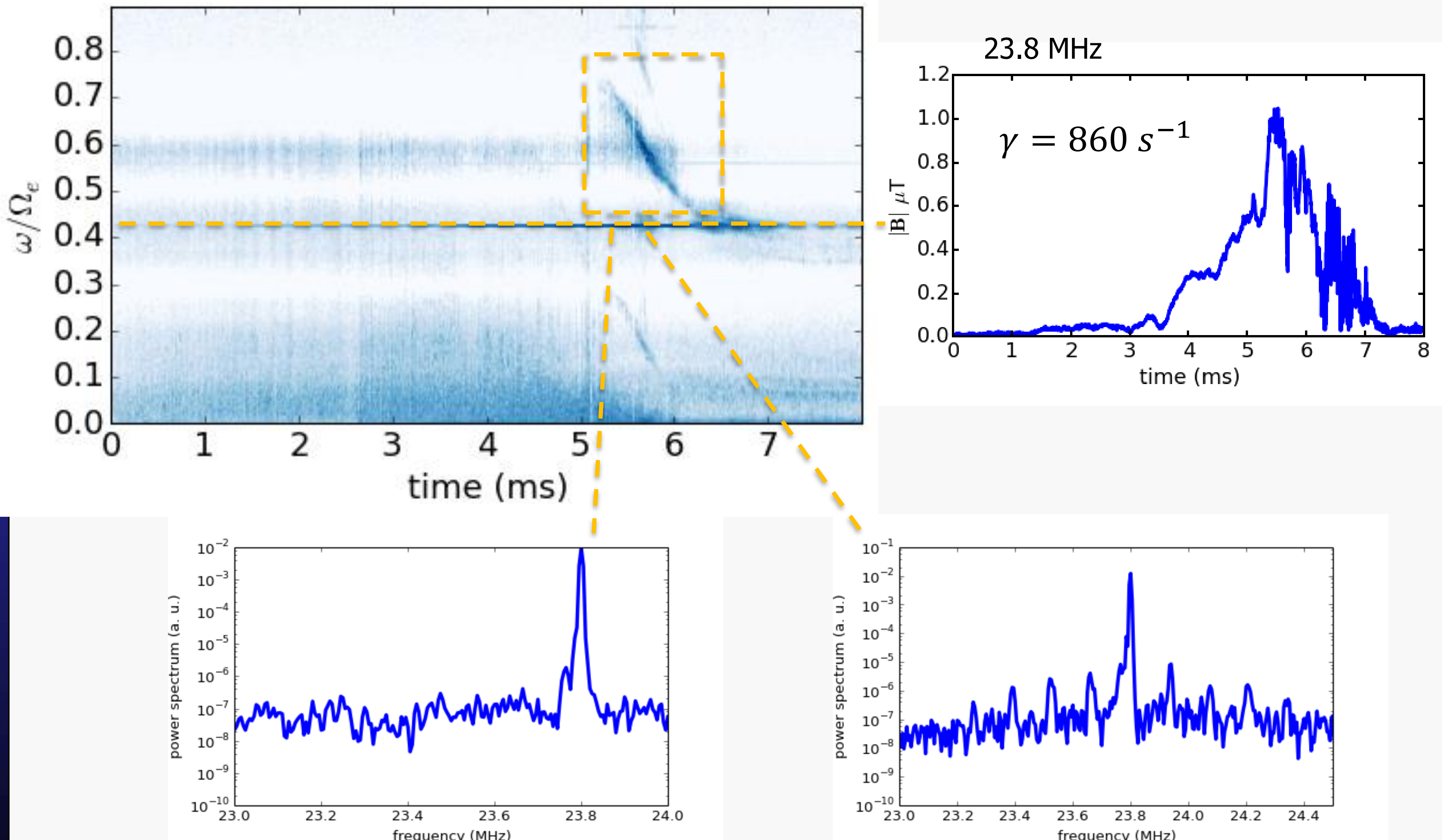
NRL PPD



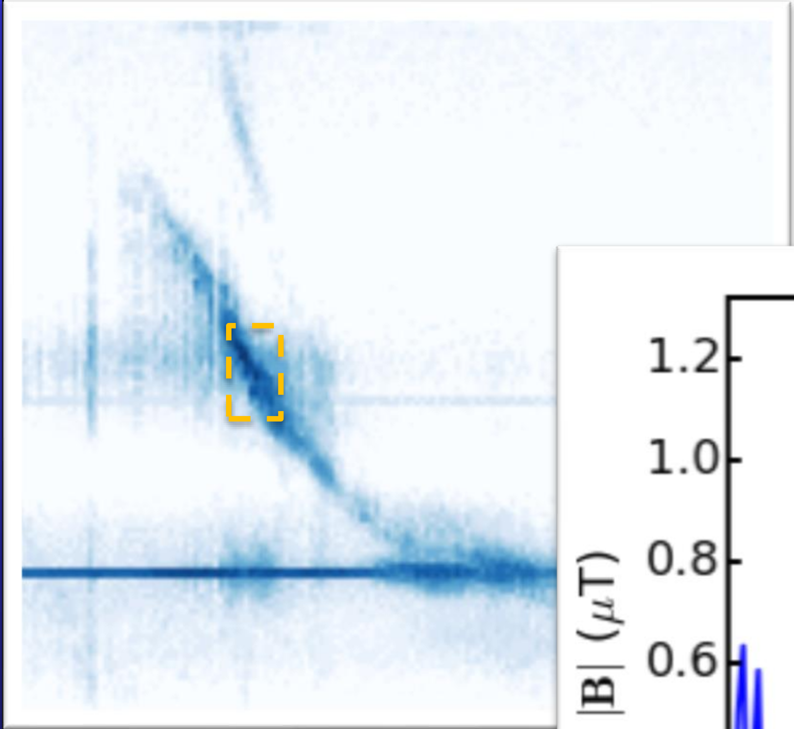
$E_b = 1.8\ keV$ $I_b = 20\ mA \rightarrow\ n_b/n_0 = 0.5 - 13\%$ $\alpha = 40°$

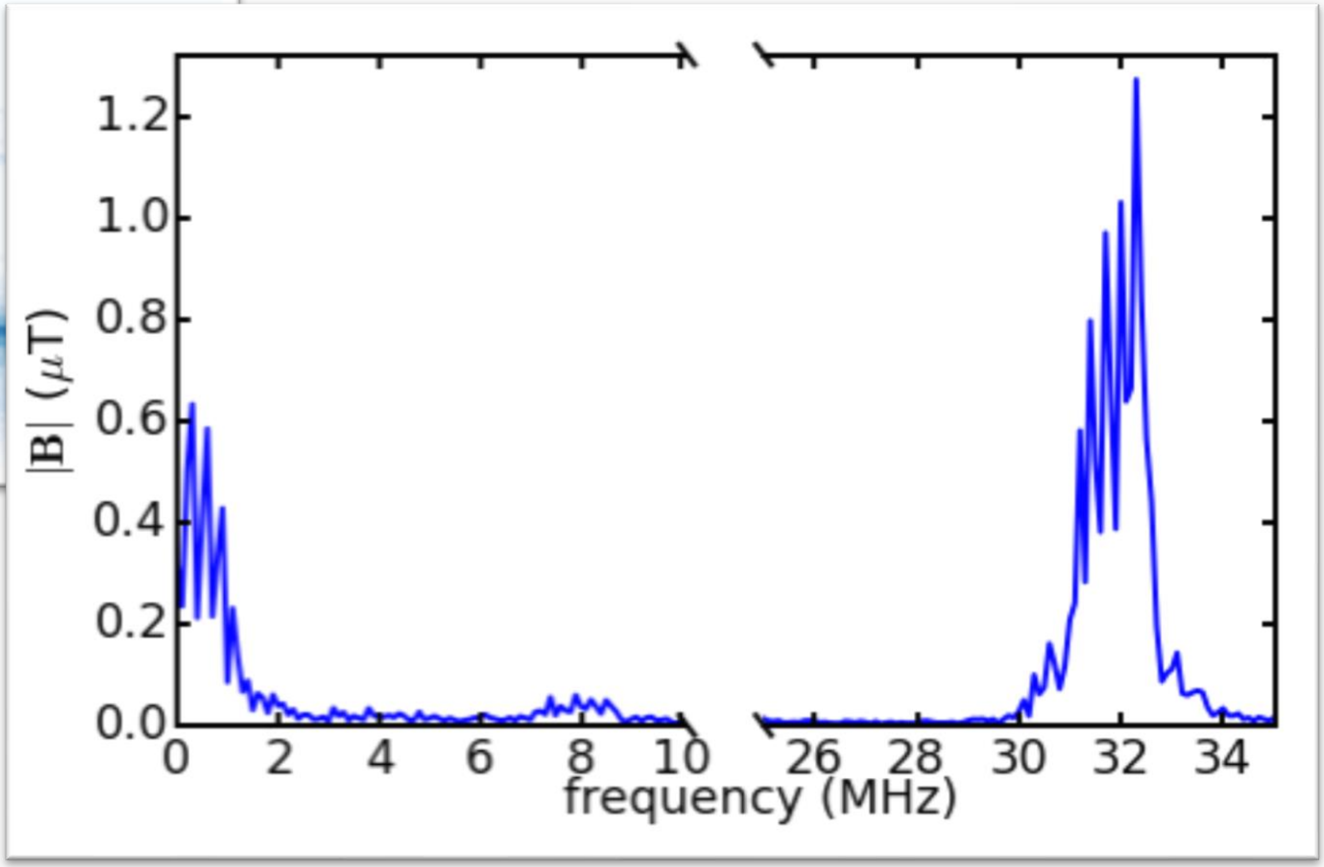
$\omega_{pe}/\Omega_e = 1.75 - 9.2$ $\omega_0/\Omega_e = 0.425$

Nonlinear Scattering in Triggered Emission Data

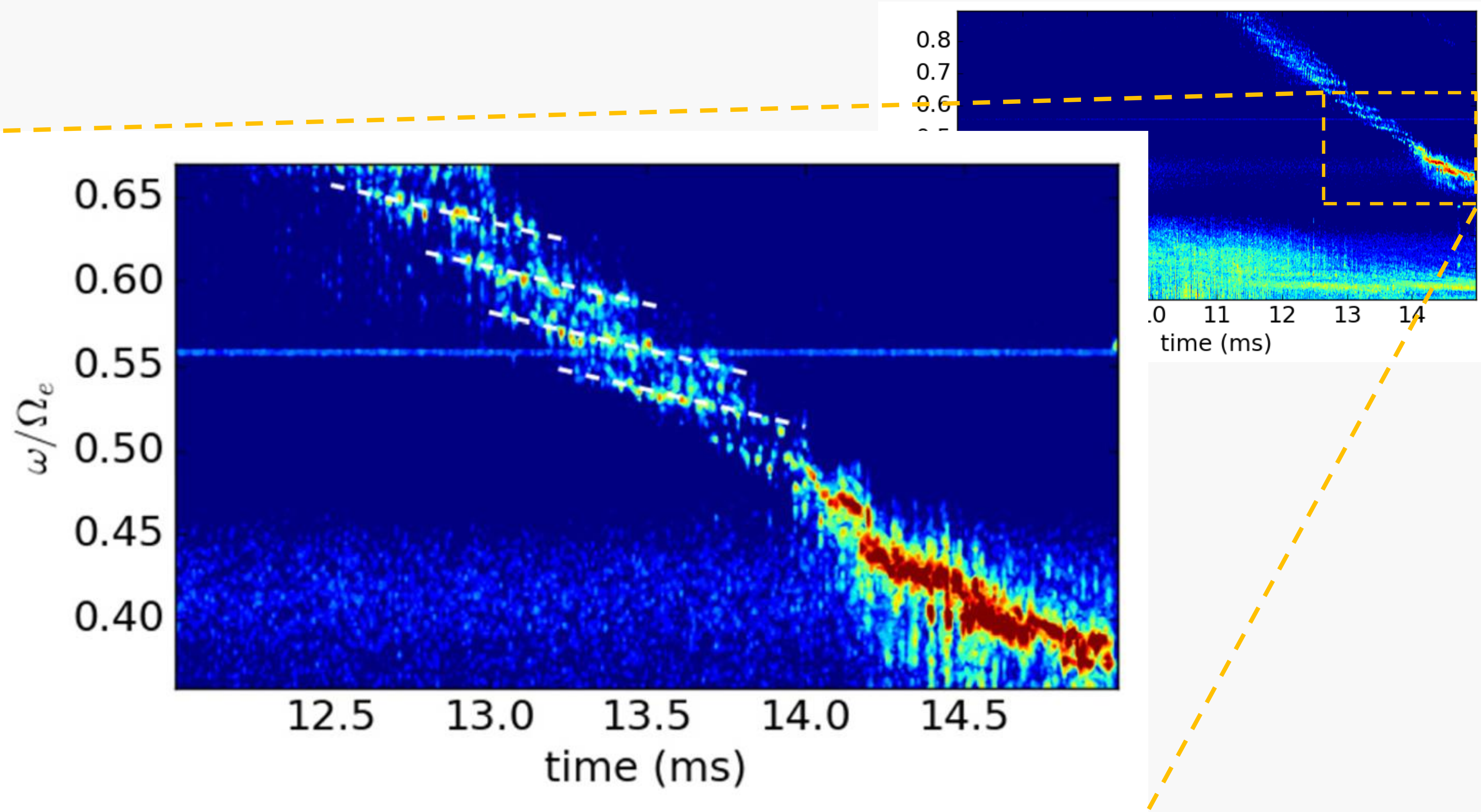


Three Wave Decay in Triggered Emission Data



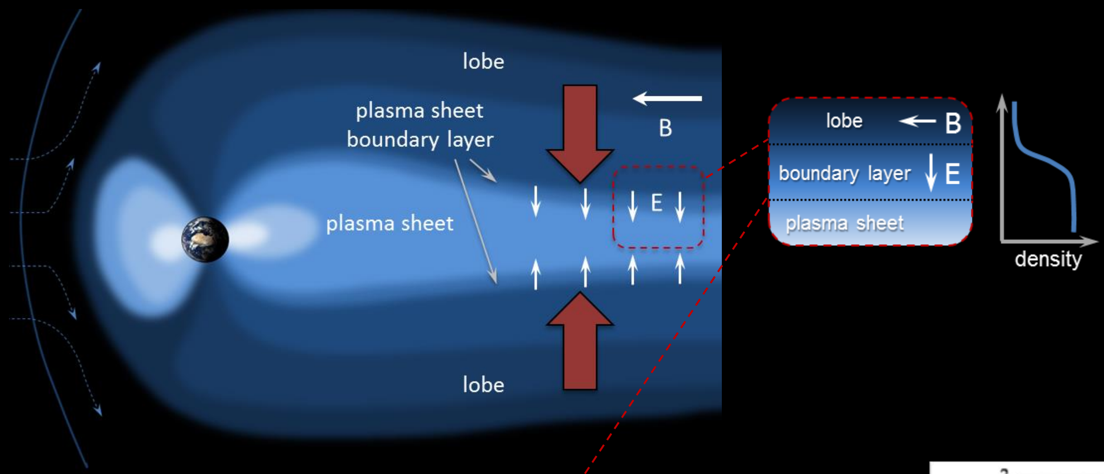


Chorus-like Emissions Exhibit Subpacket Structure

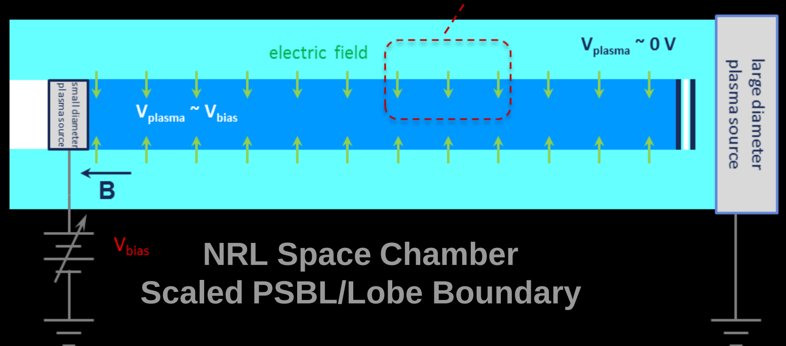


Chorus-like emissions observed in laboratory experiments.

Laboratory Simulation of Broadband Noise in Boundary Layers

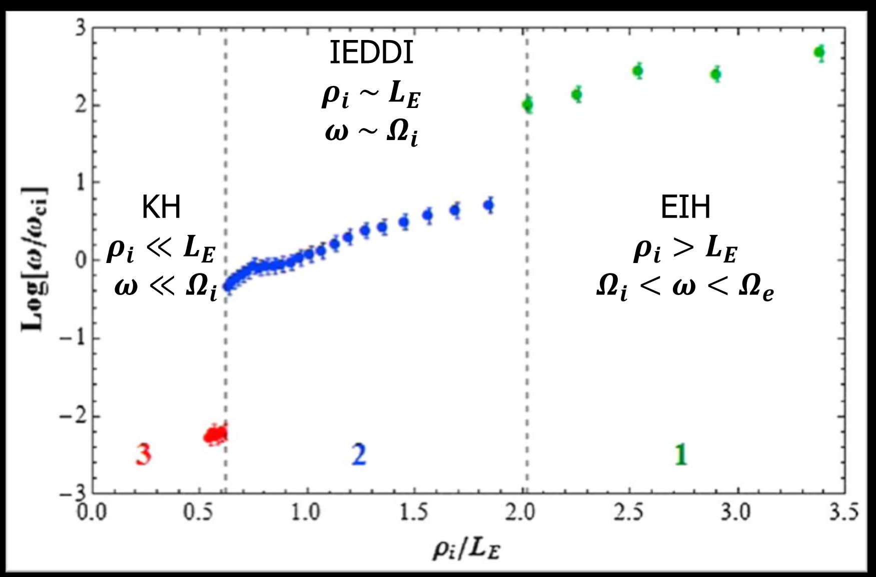


- Plasma Sheet/Lobe Boundary Layer simulated by interpenetrating plasmas
- EIH wave generation around the lower hybrid frequency relaxes boundary layer
- Results in lower frequency shear-driven waves to form broadband electrostatic noise



NRL Space Chamber
Scaled PSBL/Lobe Boundary

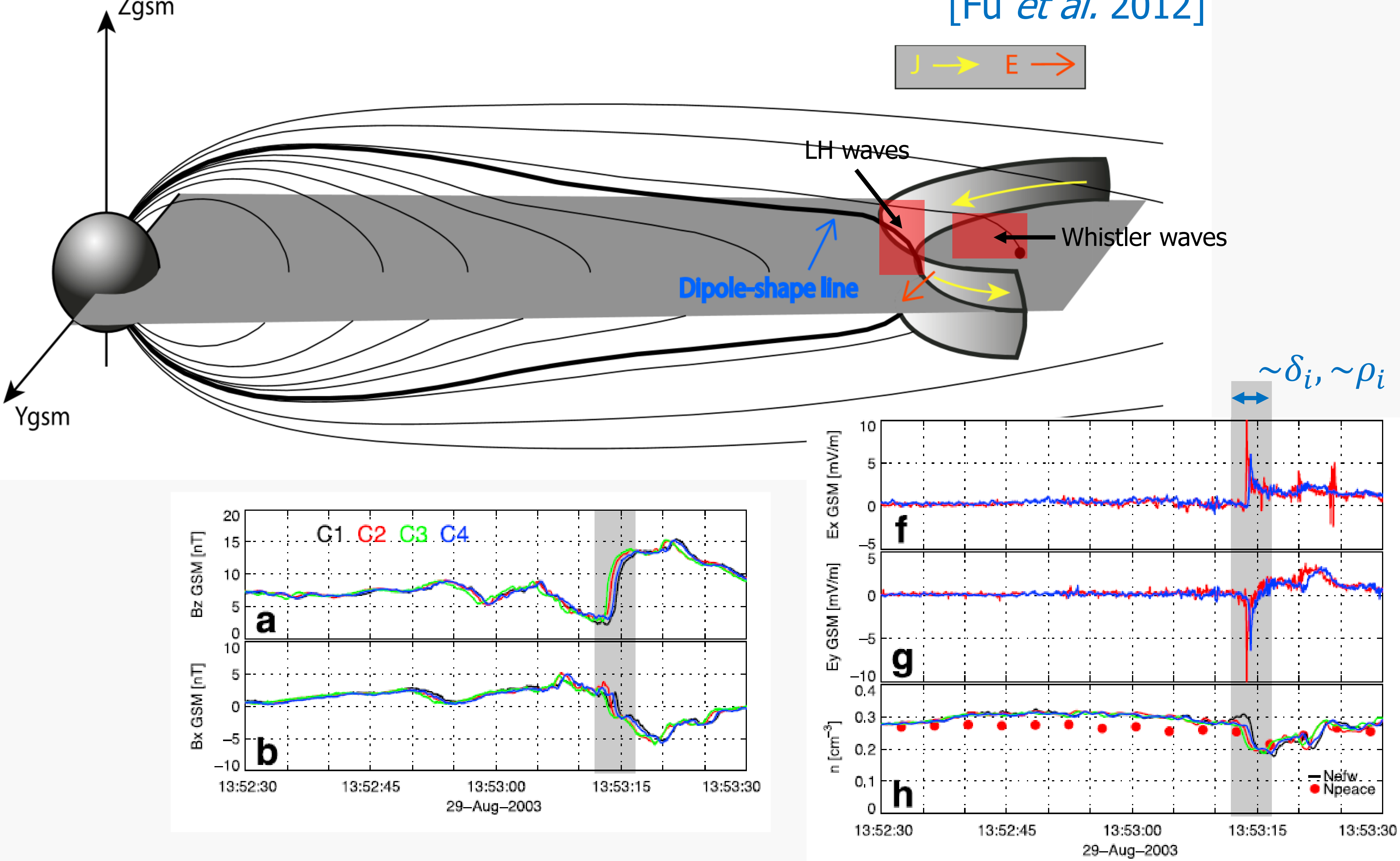
Broadband Electrostatic Noise



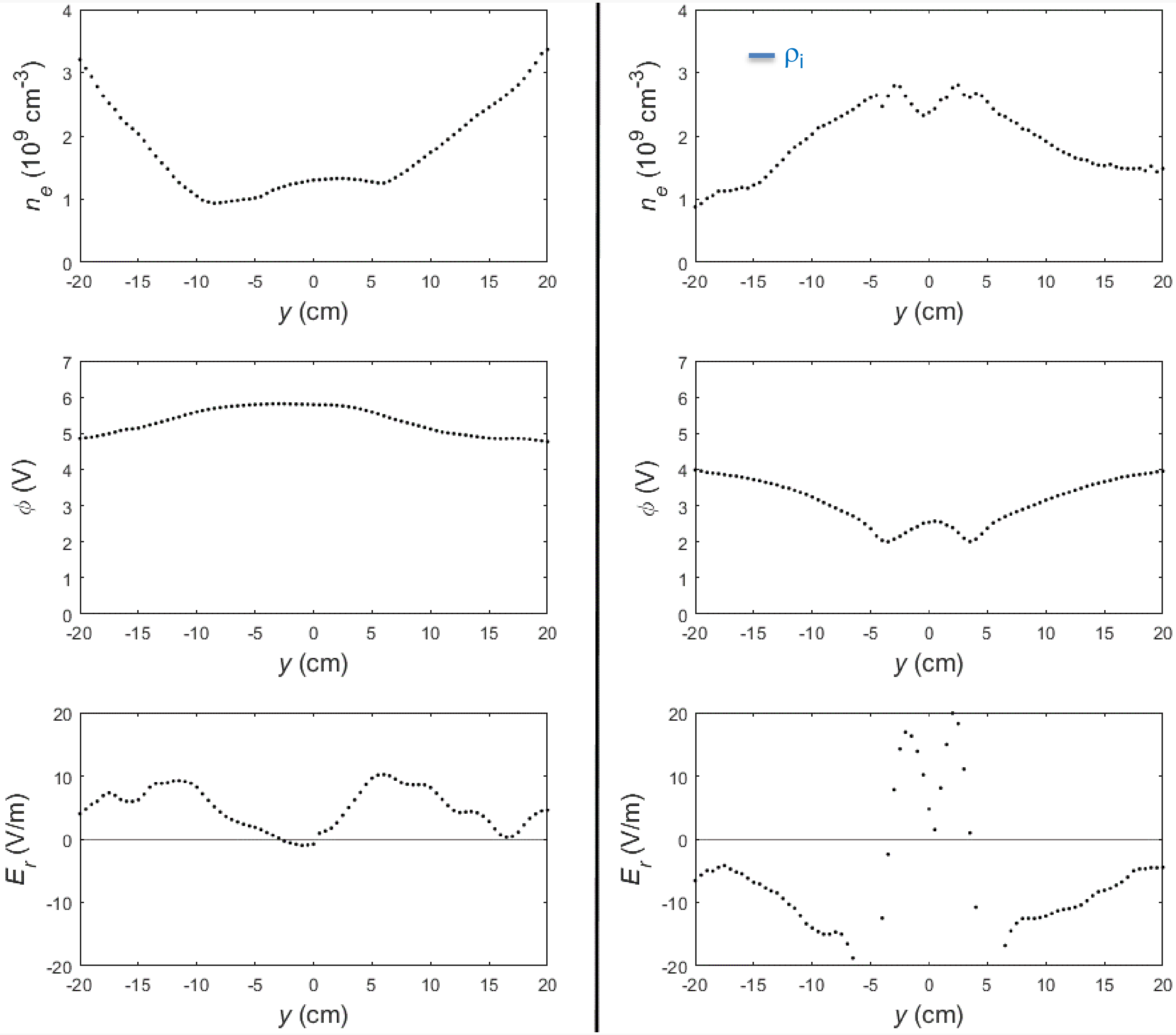
Dubois *et al.*, *JGR*, **119**, 5624 (2014)

In Situ Observations of Dipolarization Fronts

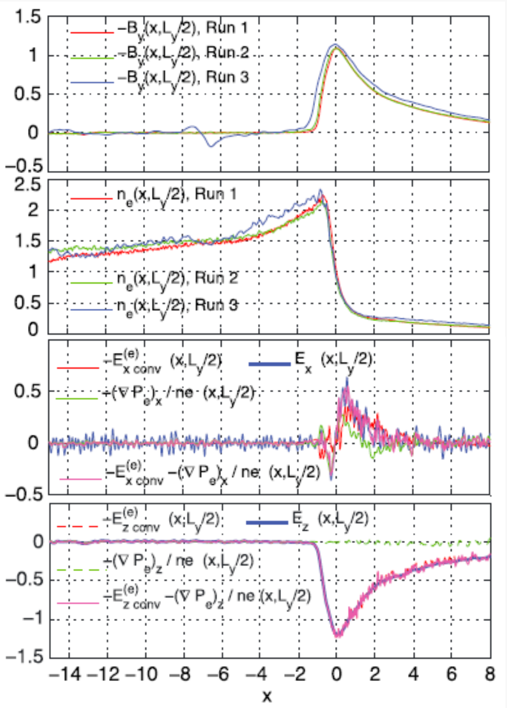
[Fu *et al.* 2012]



Self-consistent E-field Generation Observed in Lab



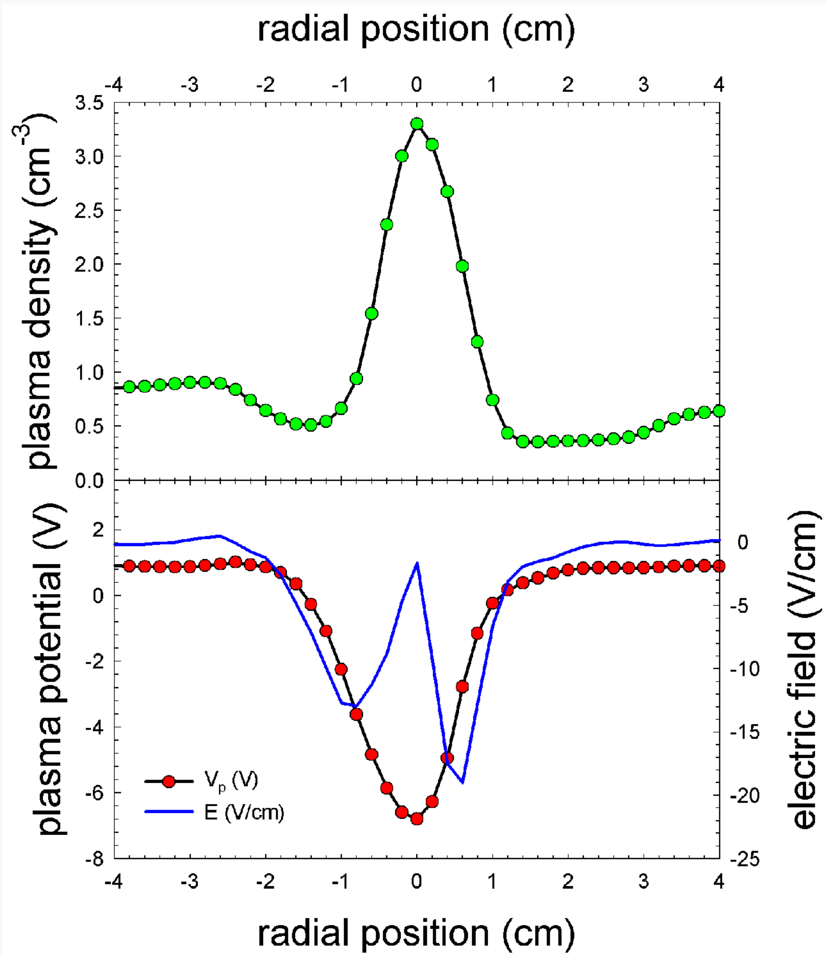
- B = 65 G
- ρ_i = 2.2 cm
- ρ_e = 0.09 cm



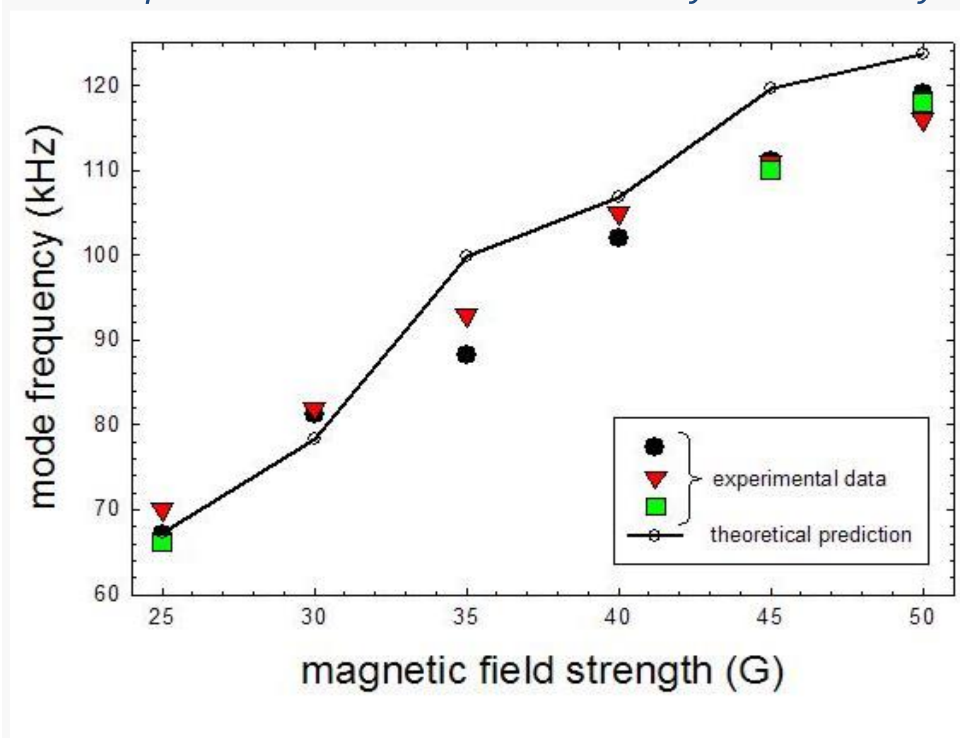
[Divin *et al.* 2015]

Laboratory Experiments Verified EIH Instability

NRL PPD

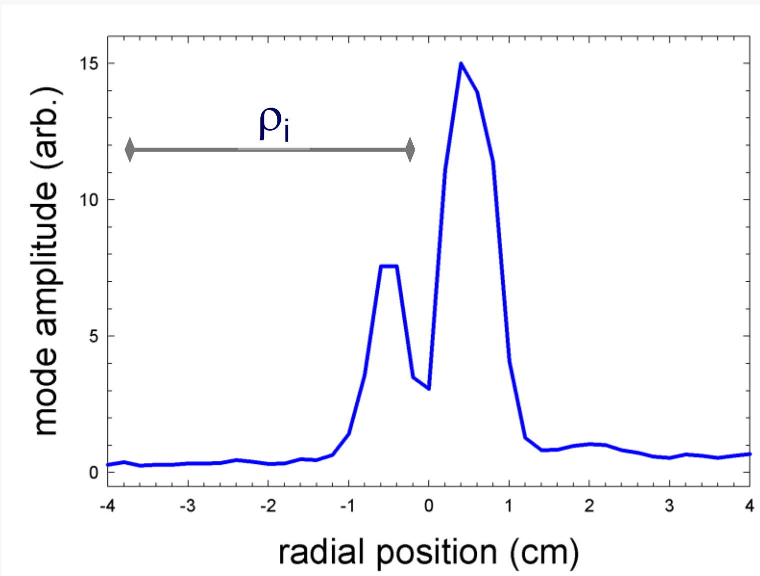


Comparison of experimental data with theoretical predictions for the Electron-Ion Hybrid Instability

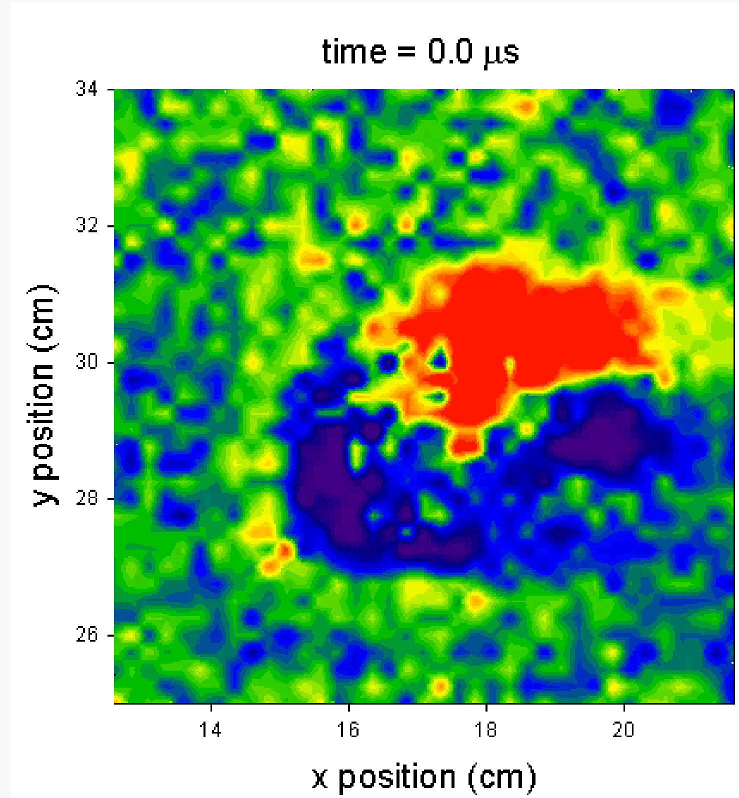


Sheared transverse flows drive lower hybrid waves

EIH Instability Experimental Verification



Amatucci et al, Phys. Plasmas. (2003)

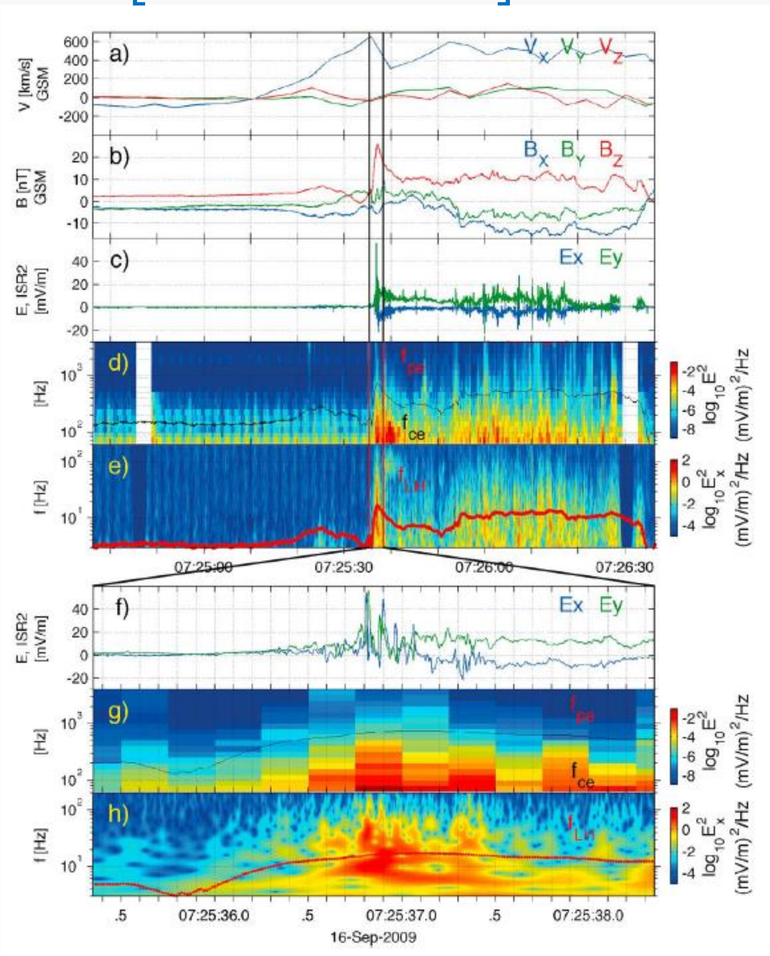


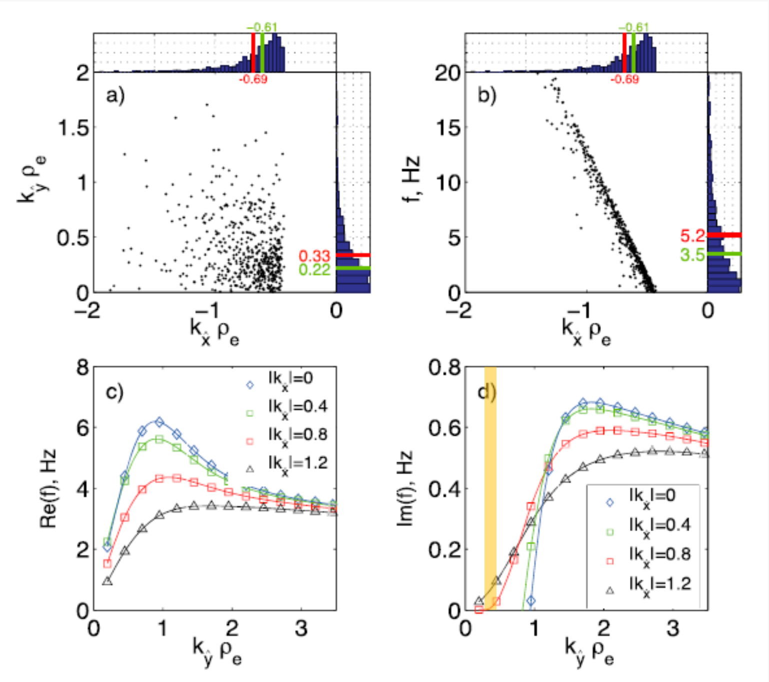
lower hybrid eigenmode <u>localized</u> to the shear layer as in DF

Amatucci et al, Phys. Plasmas. (2003)

Divin *et al.* Identified Lower Hybrid Drift Instability as Source of Observed Lower Hybrid Waves

[Divin *et al.* 2015]





- $(k_{\hat{x}}\rho_e, k_{\hat{y}}\rho_e) \sim (-0.6, 0.3)$
- LHDI modes should be damped

Eigenmode has no single k_x to Doppler shift

Reanalysis Shows that Sheared Flows Can Drive Observed Lower Hybrid Waves

Relevant Parameters

Density	$n = 3.8 \times 10^5\ \mathrm{m^{-3}}$
Magnetic Field	$B_z = 26\ \mathrm{nT}$
Ion Diamagnetic Drift	$V_{Di} = 1.9 \times 10^5\ \mathrm{m/s}$
Electric Field	$E_x = -20\ \mathrm{mV/m}$
E×B Drift	$v_E = 1.7 \times 10^6\ \mathrm{m/s}$
Electric Field Gradient Scale Length	$L_E = 54\ \mathrm{km}$
Wave Vector in E×B Direction	$k_y = 3 \times 10^{-5}\ \mathrm{m^{-1}}$

Analysis Results

- LHDI: $k_y \rho_e \sim 1$
- EIH: $k_y L_E \sim 1$

$$k_y \rho_e = 0.2 \text{ vs } k_y L_E = 1.1$$

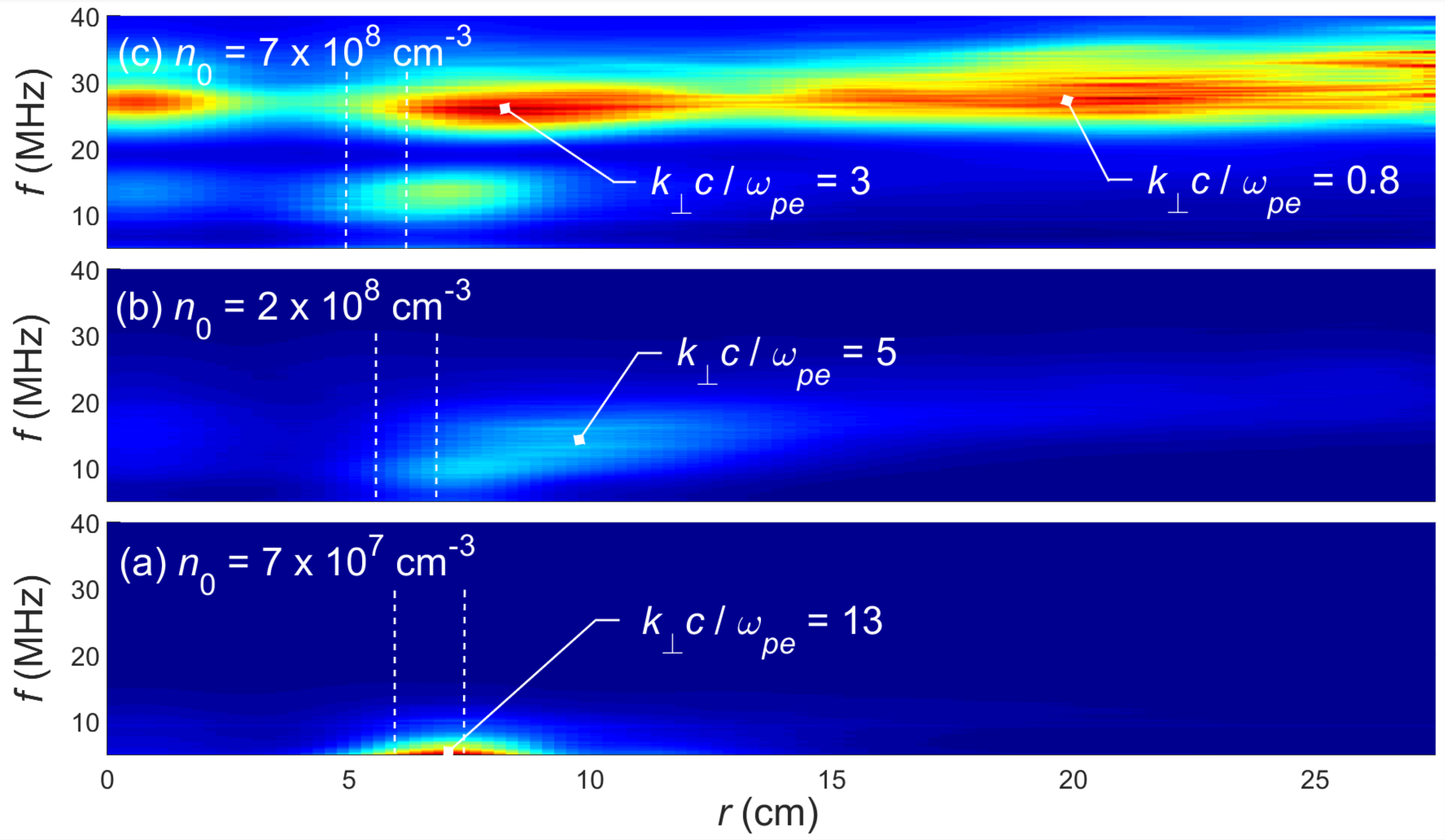
$$\Delta = -9.3$$

- Propagates in E×B direction

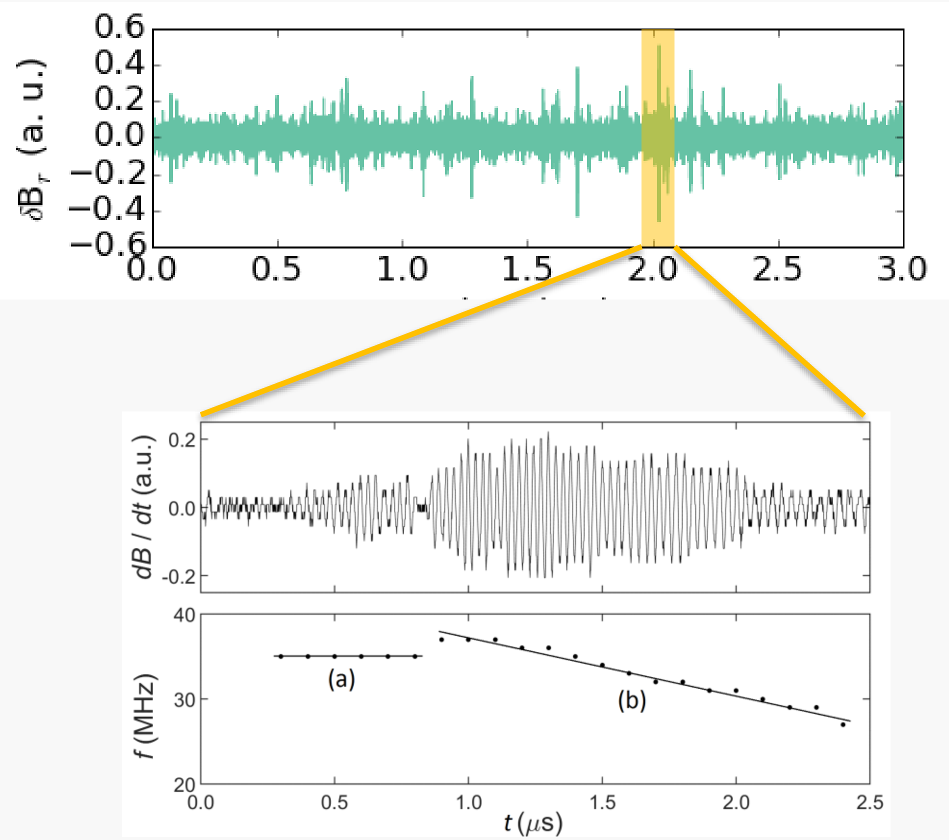
Conditions above threshold for EIH and wavelength is consistent.

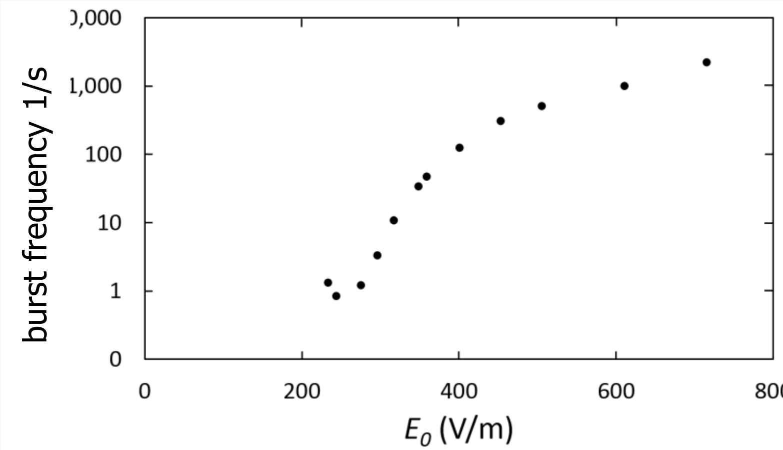
Whistler Waves Can Also Be Driven by Sheared Flows

NRL PPD

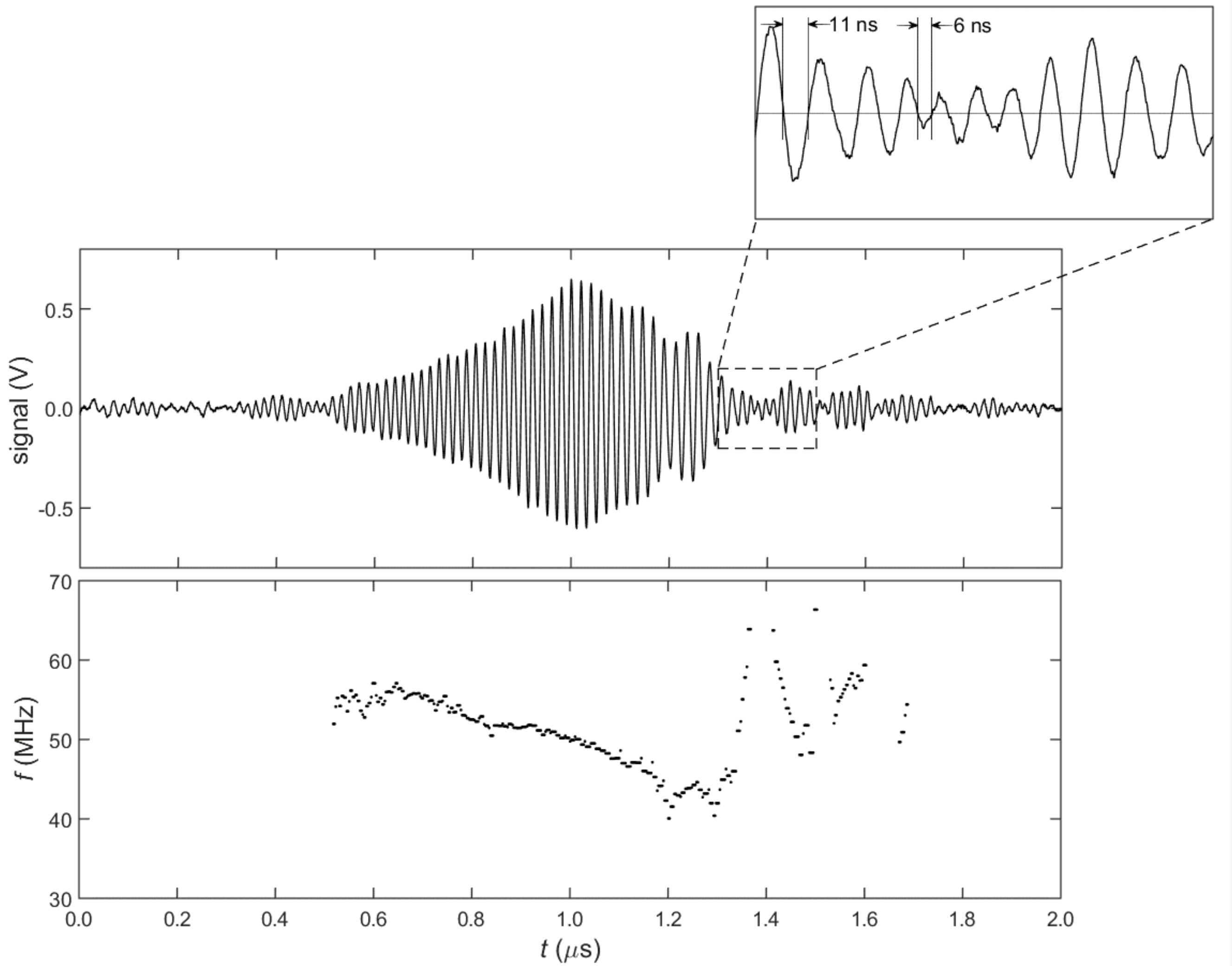


Whistler Waves Are Bursty, Chirping Waves



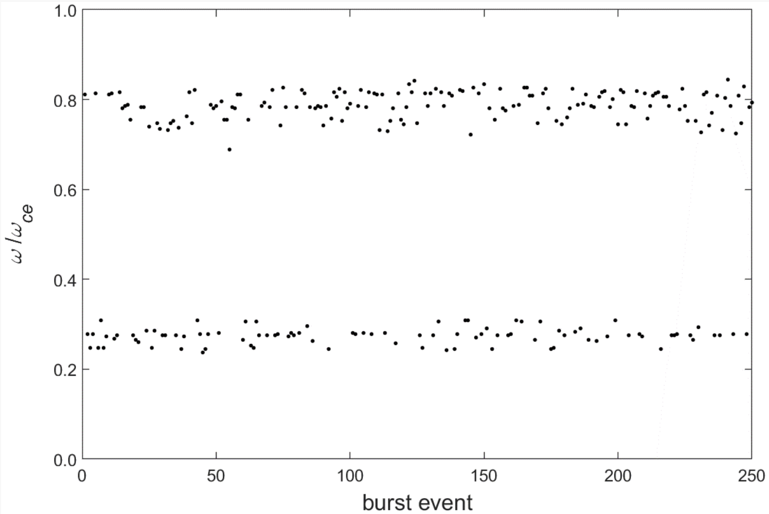


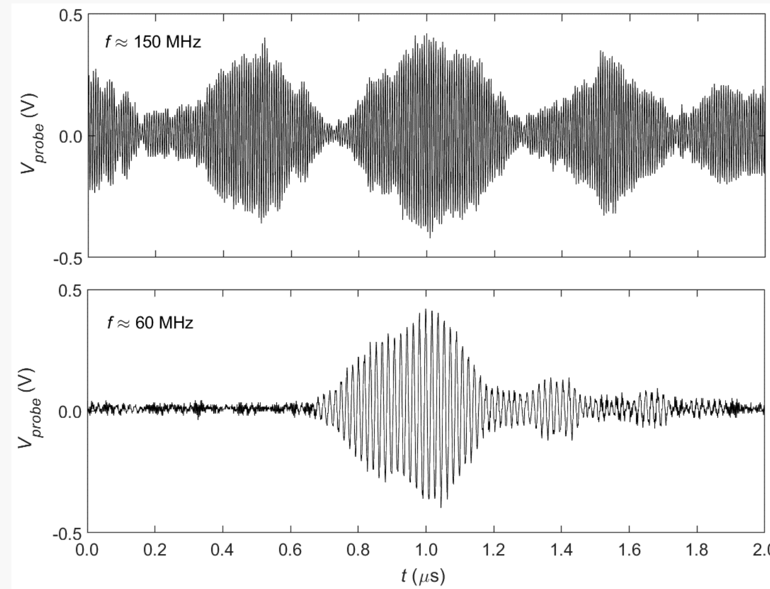
Whistler Waves Exhibit Characteristics Consistent with Particle Trapping

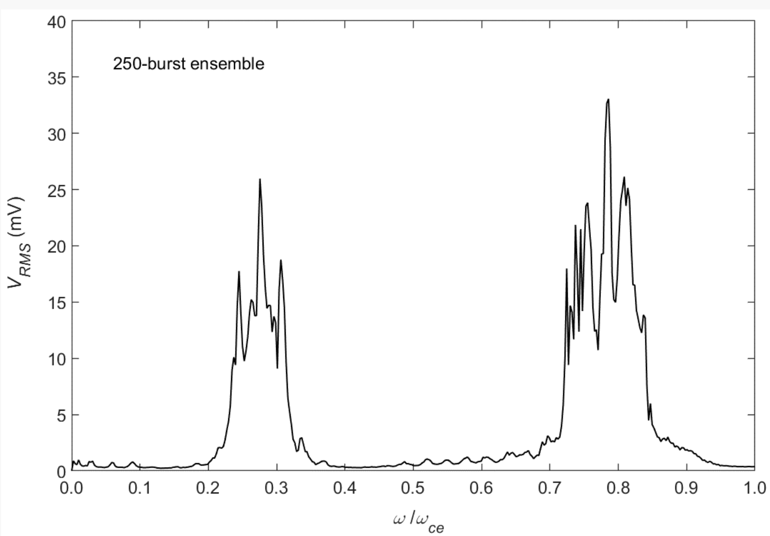


- $f < 0.5\ f_{ce}$
- $m = 1$
- $k_z \sim 10\ m^{-1}$
- $E_{res} \sim$ 1-10 keV

Velocity Shear-driven Whistler Waves in Lab Are Observed with an Upper and Lower Band







- Large amplitude bursts
- Chirp both up and down
- Lower band has faster chirp rates

Summary

- Dipolarization fronts provide a variety of sources of free energy to drive waves
- Laboratory experiments verified EIH instability theory
- Lab and theory results provide quantitative tests to determine source of waves
- Analysis demonstrates that sheared flows are capable of driving the observed lower hybrid waves
- Lab experiments demonstrate that electromagnetic whistler waves can also be driven by sheared flows
- Could observed whistler waves also be due to the EIH instability?

Begun a coordinated study between lab, theory, modeling, and space observations to study these waves at dipolarization fronts

Local Approximation Predicts Instability Threshold

$$\bar{\omega}^3 + \left(2\frac{\delta^2}{1+\delta^2}\frac{\bar{V}_0}{\bar{k}_y} - \bar{k}_y\bar{V}_0\right)\bar{\omega}^2 - \bar{\omega} + \bar{k}_y\bar{V}_0 = 0$$

$$\bar{\omega} = \frac{\omega}{\omega_{LH}}, \delta = \frac{\omega_{pe}}{\Omega_e}, \bar{V}_0 = \frac{v_E}{\omega_{LH}L_E}, \bar{k}_y = k_y L_E$$

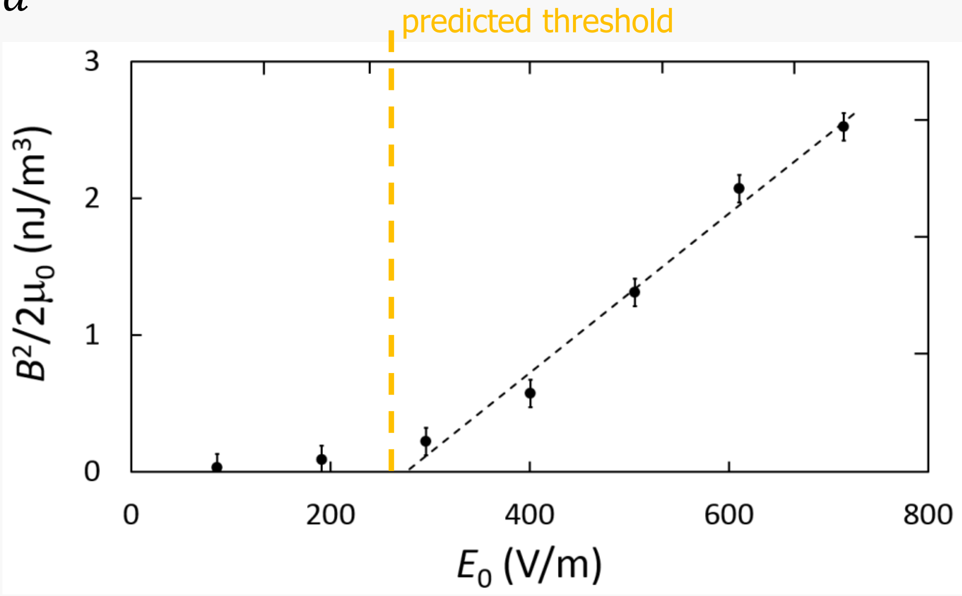
$$ax^3 + bx^2 + cx + d = 0$$

$$\Delta = 18abcd - 4b^3d + b^2c^2 - 4ac^3 - 27a^2d^2$$

Diamagnetic Drift Frequency: $\omega_{De,i} = kv_{De,i}$

Shear Frequency: $\omega_s = \frac{dv_E}{dx}$

If $\Delta < 0$, then 1 real solution and two complex conjugate solutions



Effects of Nonuniform B on EIH

- Increased growth rate
- No effect on wavelength