Cold electron impact on parallel-propagating whistler chorus waves

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Background and motivation

- Cold electrons = below 100eV ⇒ "hidden population" due to spacecraft charging.
- Recently, Roytershteyn et al. [1, 2] identified secondary instabilities that involve direct energy exchange between the cold plasma and parallel propagating chorus waves, suggesting that cold plasma heating could significantly damp parallel propagating whistler waves.
- We aim to quantify this energy exchange via quasilinear theory.
- We also speculate that the electrostatic drift-driven instabilities between cold electrons and ions may contribute to the discrepancy between simulated and observed energies of parallel-propagating whistler waves.

How do cold electrons impact the whistler anisotropy instability?

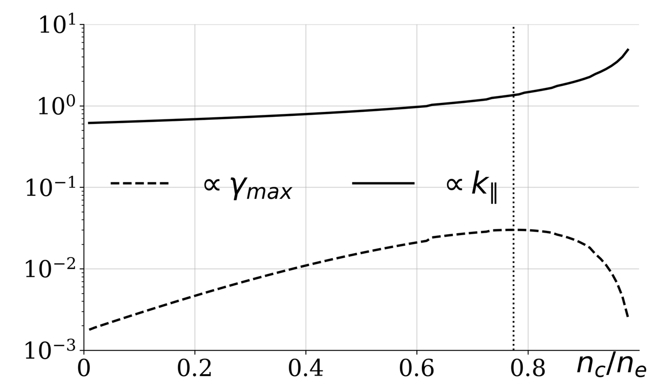
- What causes the instability? hot electron anisotropy (source of "free energy")

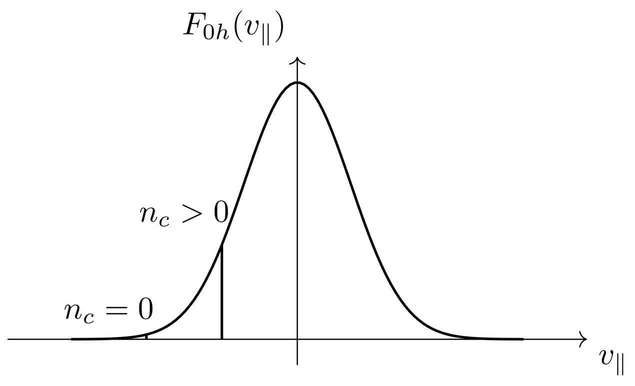
$$A_h := \frac{T_{\perp h}}{T_{\parallel h}} - 1 > 0$$

- Resonance for parallel propagating whistler waves

$$v_\parallel^{\text{res}} = \frac{\omega - |\Omega_{ce}|}{k_\parallel}$$

- As $\frac{n_c}{n_e}\uparrow$ then $k_\parallel \uparrow$, and $v_\parallel^{\text{res}}\downarrow$, allowing a larger portion of the hot electron distribution to resonate with the wave leading to $\gamma_{\max}\uparrow$ [3].
- As $\frac{n_c}{n_e}\uparrow$ then $\beta_{\parallel h}^{\text{critical}}\downarrow \Rightarrow$ parallel-propagating whistler.





Beyond linear theory ⇒ quasilinear theory (QLT)

- Parallel propagating whistler instability QLT [4]:

$$\partial_t F_{0h}(\vec v, t) = \nabla_{\vec v}\cdot\left[\mathcal{D}(\vec v, k_\parallel, t, \vec B_W)\cdot\nabla_{\vec v}F_{0h}(\vec v, t)\right] \quad (1)$$

$$\partial_t|\vec B_W(k_\parallel, t)|^2 = 2\gamma(k_\parallel, t)|\delta\vec B(k_\parallel, t)|^2 \quad (2)$$

+ dispersion relation depending on $\frac{n_c}{n_e}, \dots$

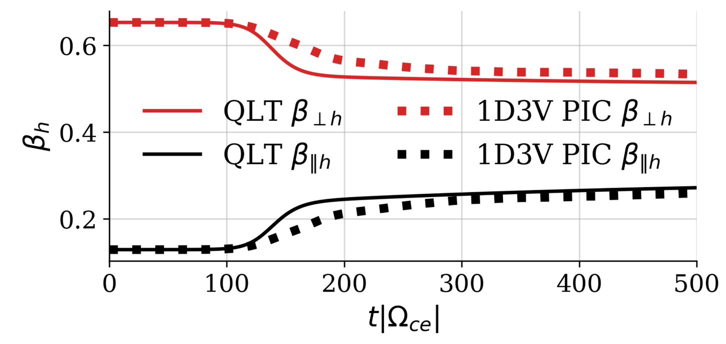
- We assume $F_{0h}(\vec v, t)$ is bi-Maxwellian for all times:

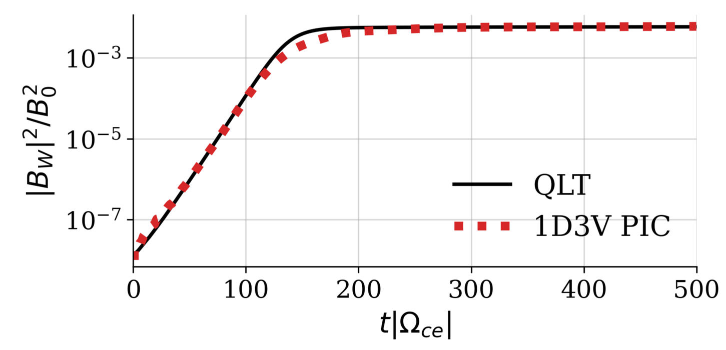
$$F_{0h} \propto \exp\left(-\frac{m_e}{2}\left[\frac{v_\parallel^2}{T_{\parallel h}(t)} + \frac{v_\perp^2}{T_{\perp h}(t)}\right]\right) \quad (3)$$

and take moments of Eq. (1)

$$\frac{\mathrm{d}T_{\perp h}}{\mathrm{d}t} = \mathcal{F}_{\perp h}\left(k_\parallel, \omega, A_h, \delta\vec B\right) \quad (4)$$

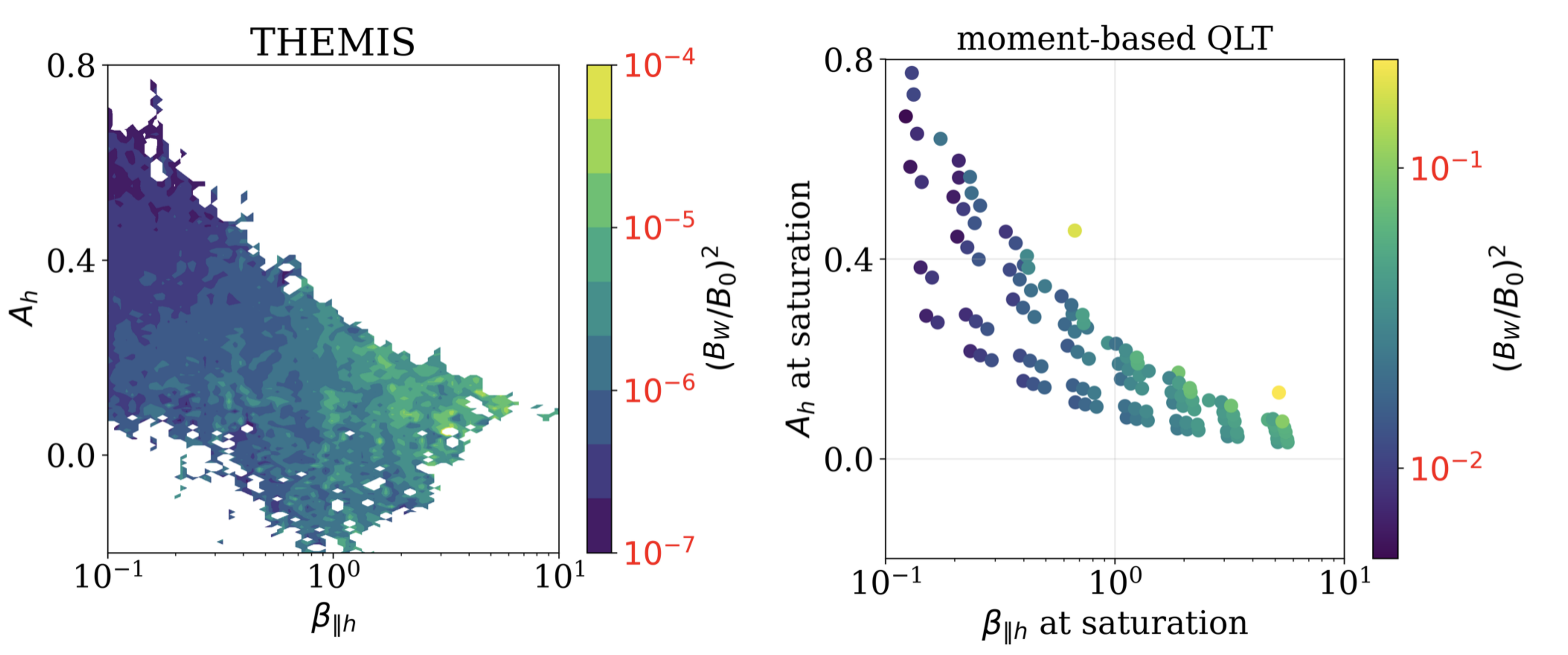
$$\frac{\mathrm{d}T_{\parallel h}}{\mathrm{d}t} = \mathcal{F}_{\parallel h}\left(k_\parallel, \omega, A_h, \delta\vec B\right) \quad (5)$$





Parametric setup:
$\frac{n_c}{n_e} = 0.8$ $\frac{\omega_{pe}}{|\Omega_{ce}|} = 4$ $T_{\parallel h}(t=0) = 2\text{keV}$
$A_h(t=0) = 4$ $A_{c/i}(t=0) = 0$ $T_{c/i}(t=0) = 10\text{eV}$

THEMIS vs. QLT whistler wave magnetic energies



Why do the normalized wave energies differ by a few orders of magnitude?

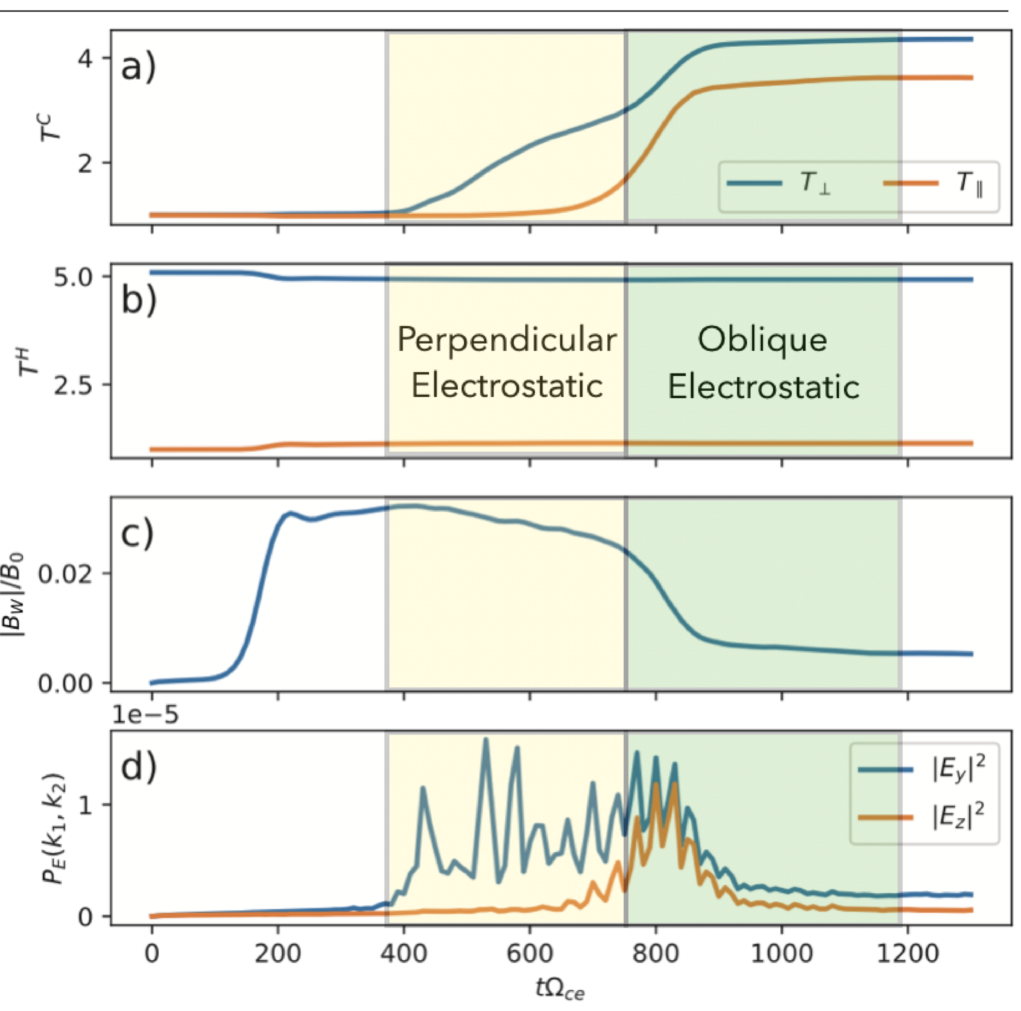
Secondary instabilities as a source of whistler wave damping

- Whistler waves excite electrostatic waves through drift-type secondary instabilities ⇒ heating the cold populations and damping the primary whistler waves.
- Primary whistler as the driver

$$\delta E_\perp(t) := |\delta E(t)|\exp(i\omega_0 t)$$
$$\delta B_\perp(t) := i|\delta B(t)|\exp(i\omega_0 t)$$
$$\vec B_0 := B_0\hat z$$

$$\boxed{V_{\perp s}(t) = \frac{-iq_s}{m_s}\frac{|\delta E(t)|}{\omega_0 + \Omega_{cs}}\exp(i\omega_0 t)}$$

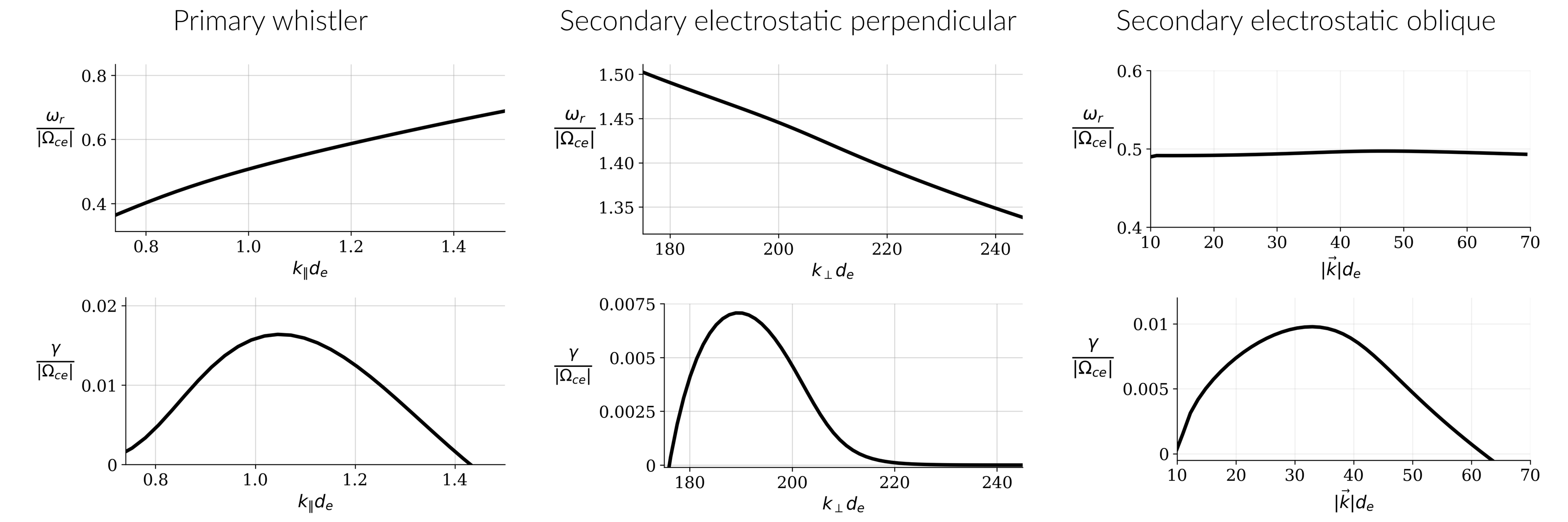
$|V_{\perp i}| \ll |V_{\perp c}| \sim \sqrt{T_c/m_e}$ and $|V_{\perp h}| \ll \sqrt{T_h/m_e}$



Credit: Figure 8 in [1] 3D3V PIC $\sim 10^6$ CPU hours.

Understanding the secondary instabilities via linear theory

Parametric setup: $\frac{n_c}{n_e} = 0.8$ $\frac{|V_{\perp c}(t=0)|}{d_e|\Omega_{ce}|} = 0.005$ $\frac{\omega_{pe}}{|\Omega_{ce}|} = 4$ $\frac{\omega_0}{|\Omega_{ce}|} = 0.5$ $k_{\parallel 0}d_e = 1$ $A_{c/i}(t=0) = 0$ $T_{c/i}(t=0) = 1\text{eV}$



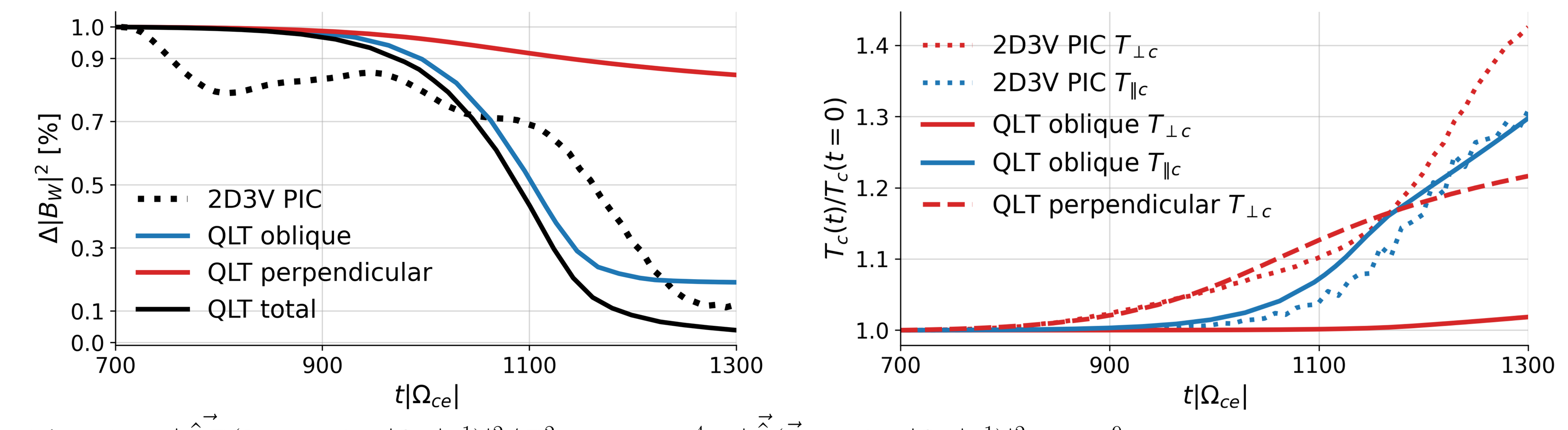
Understanding the secondary instabilities via QLT

- Electrostatic QLT equations in magnetized plasma [4]:

$$\partial_t F_{0c}(\vec v, t) = \frac{1}{v_\perp}\partial_{v_\perp}\left[v_\perp\left[\mathcal{D}_{\perp\perp}\partial_{v_\perp}F_{0c} + \mathcal{D}_{\perp\parallel}\partial_{v_\parallel}F_{0c}\right]\right] + \partial_{v_\parallel}\left[\mathcal{D}_{\perp\parallel}\partial_{v_\perp}F_{0c} + \mathcal{D}_{\parallel\parallel}\partial_{v_\parallel}F_{0c}\right] \quad (6)$$

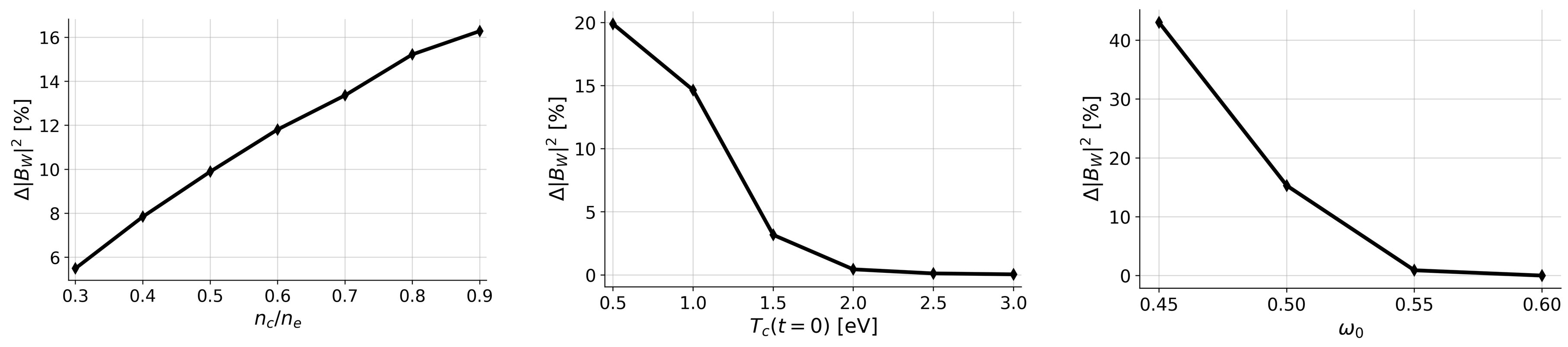
$$\begin{bmatrix}\mathcal{D}_{\perp\perp}\\ \mathcal{D}_{\perp\parallel}\\ \mathcal{D}_{\parallel\parallel}\end{bmatrix} := \frac{ie^2}{m_e^2}\sum_{n=-\infty}^{\infty}\int \mathrm{d}\vec k \frac{|\vec E(\vec k, t)|^2}{|\vec k|^2}\frac{J_n^2(k_\perp v_\perp/\Omega_{ce})}{\omega - k_\parallel v_\parallel - n\Omega_{ce}}\begin{bmatrix}\frac{n^2\Omega_{ce}^2}{v_\perp^2}\\ \frac{n\Omega_{ce}k_\parallel}{v_\perp}\\ k_\parallel^2\end{bmatrix} \quad (7)$$

- We assume $F_{0c}(\vec v, t)$ is bi-Maxwellian, see Eq. (3), and take moments of Eq. (6).
- We derive the whistler damping rate by conservation of energy.

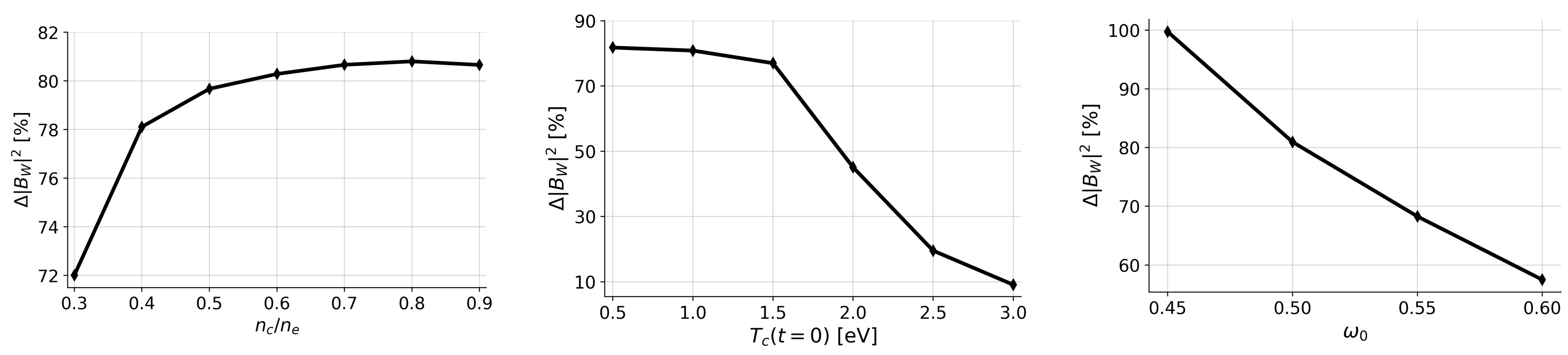


Parametric setup: $|\vec{\tilde B}(k_{\parallel 0}, t = 700|\Omega_{ce}|^{-1})|^2/B_0^2 = 4\times 10^{-4}$ $|\vec{\tilde E}(\vec k, t = 700|\Omega_{ce}|^{-1})|^2 = 10^{-9}$

Parametric dependence of secondary perpendicular waves as a damping source



Parametric dependence of secondary oblique waves as a damping source



Conclusions and future work

- Parallel propagating whistler waves are damped due to secondary drift-driven instabilities between cold electrons and ions.
- Both secondary instabilities weaken significantly as $T_c(t=0)\uparrow$. Changes in $\frac{n_c}{n_e}\in[0.6, 0.9]$ do not significantly impact the energy exchange.
- Open questions and future directions:
  1. How do observations of the secondary electrostatic waves compare to QLT?
  2. Are EMIC waves and cold ions susceptible to the same secondary instabilities?

Link to preprint

Acknowledgment

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References

[1] V. Roytershteyn and G. L. Delzanno. *Nonlinear coupling of whistler waves to oblique electrostatic turbulence enabled by cold plasma.* Physics of Plasmas, 28(4):042903, 04 2021.

[2] V. Roytershteyn, G. L. Delzanno, and J. Holmes. *Oblique instability of quasi-parallel whistler waves in the presence of cold and warm electron populations.* Frontiers in Astronomy and Space Sciences, 11, 2024.

[3] S. Cuperman and R. W. Landau. *On the enhancement of the whistler mode instability in the magnetosphere by cold plasma injection.* Journal of Geophysical Research, 79(1):128–134, 1974.

[4] C. F. Kennel and F. Engelmann. *Velocity Space Diffusion from Weak Plasma Turbulence in a Magnetic Field.* The Physics of Fluids, 9(12):2377–2388, 12 1966.