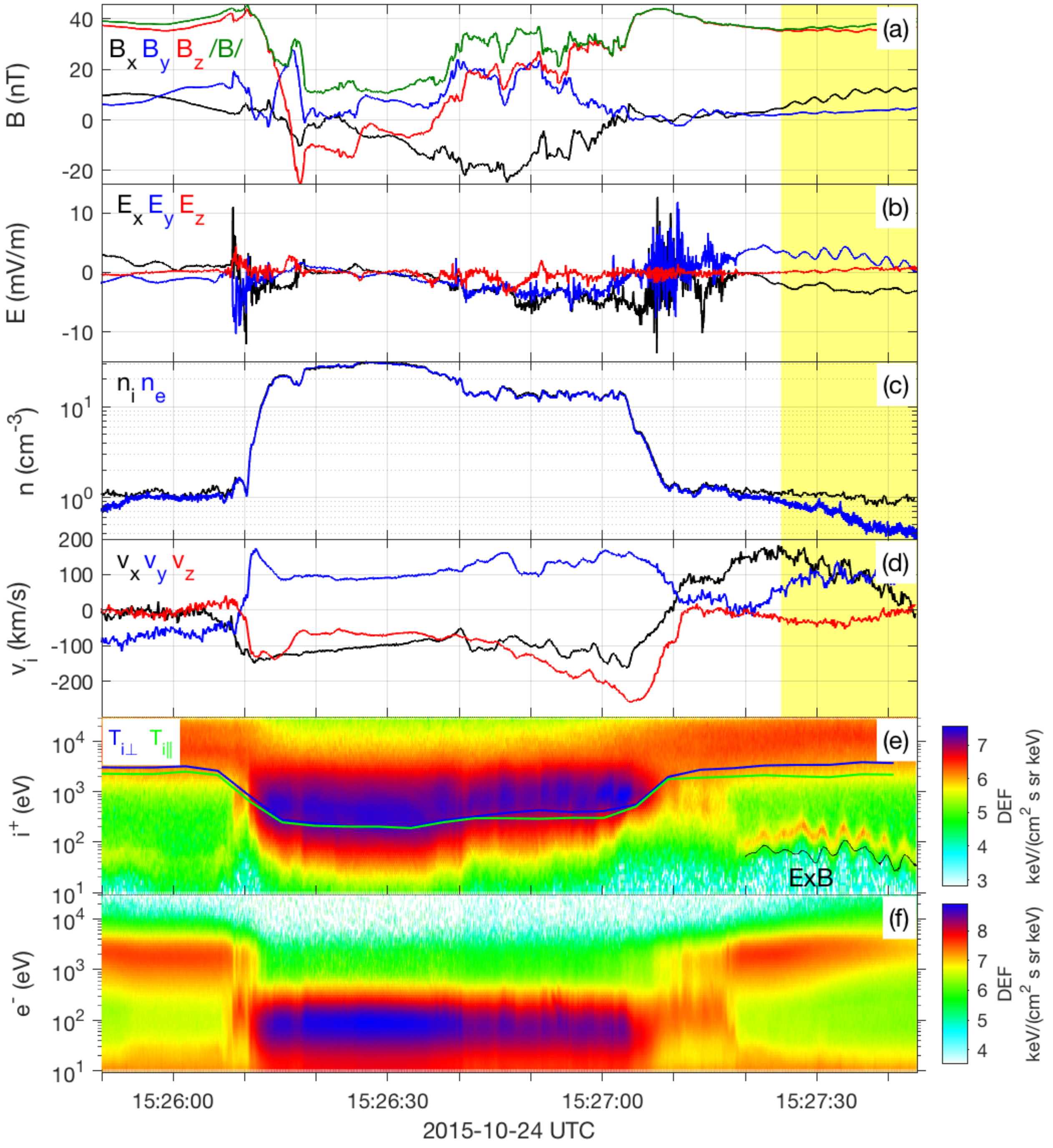
Cold ion dynamics and interaction with EMIC waves near the Earth's magnetopause

Sergio Toledo-Redondo, Justin Lee, Sarah K Vines, Drew L Turner, Robert Allen, Wenya Li, Scott Boardsen, Mats Andre, Stephen A Fuselier, Benoit Lavraud, Daniel Gershman, Adolfo Viñas, Olivier Lecontel, Barbara Giles, and James L Burch

Abstract

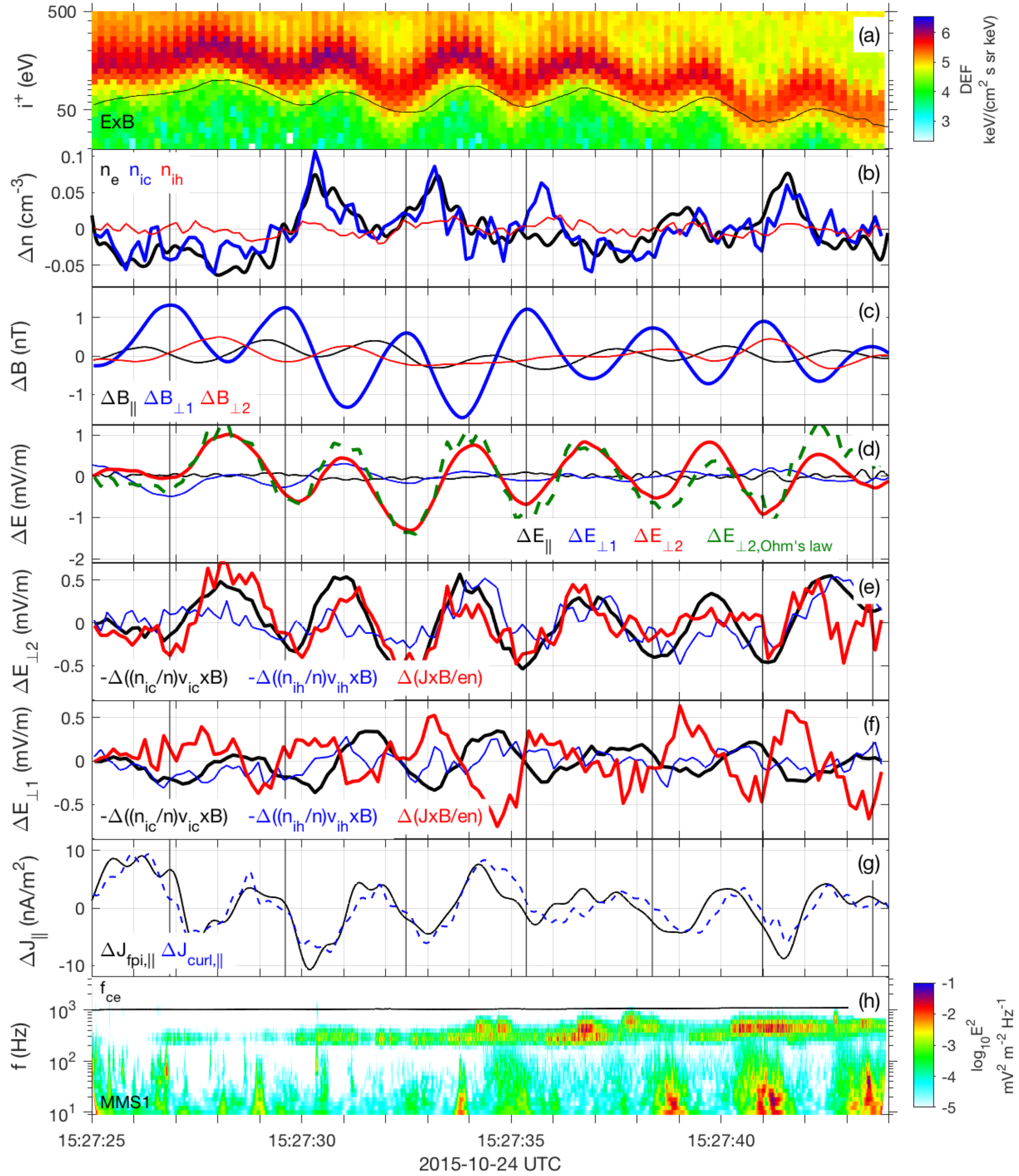
The Earth's magnetosphere is constantly supplied by plasma coming from the solar wind and from the ionosphere. The ionospheric supply is typically cold and contains heavy ions, which can be often found in most parts of the magnetosphere.

Electromagnetic Ion Cyclotron (EMIC) waves occur in the outer magnetosphere, often in association with ionospheric ions, and serve as a coupling mechanism to the ionosphere and inner magnetosphere. Using the MMS spacecraft, we investigate the dynamics of these waves when ionospheric ions are present, and resolve their motion and energy exchange with the electromagnetic fields below the ion scale. We find that ring current ions and ionospheric ions have different dynamics inside an EMIC wave packet near the magnetopause, affecting the dispersion relation of the wave. We compare the observations to linear dispersion theory, and find excellent agreement between both. Cold ions are accelerated and drain energy from the wave packet, and modify the intrinsic properties such as the wave normal angle and the polarization of the wave.



EVENT OVERVIEW

- Observation of low-frequency wave ($f \sim f_{ci}$) adjacent to reconnecting dayside magnetopause.
- Presence of cold ions of ionospheric origin.
- Fluctuations in B, E, vi, Ei
- Temperature anisotropy (ring current ions), probably due to magnetosphere compression, as free source of wave energy.

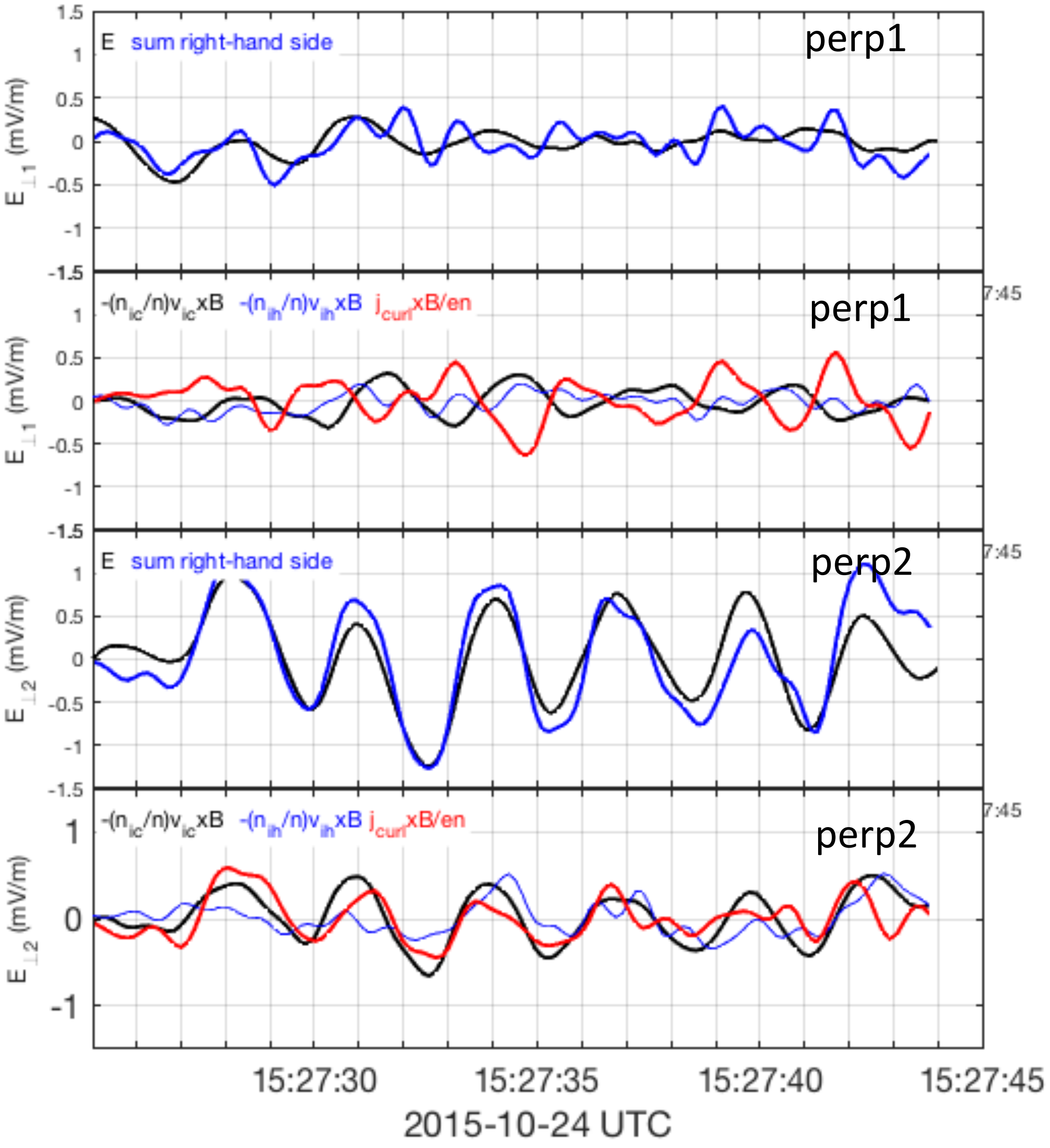


Fluctuation analysis

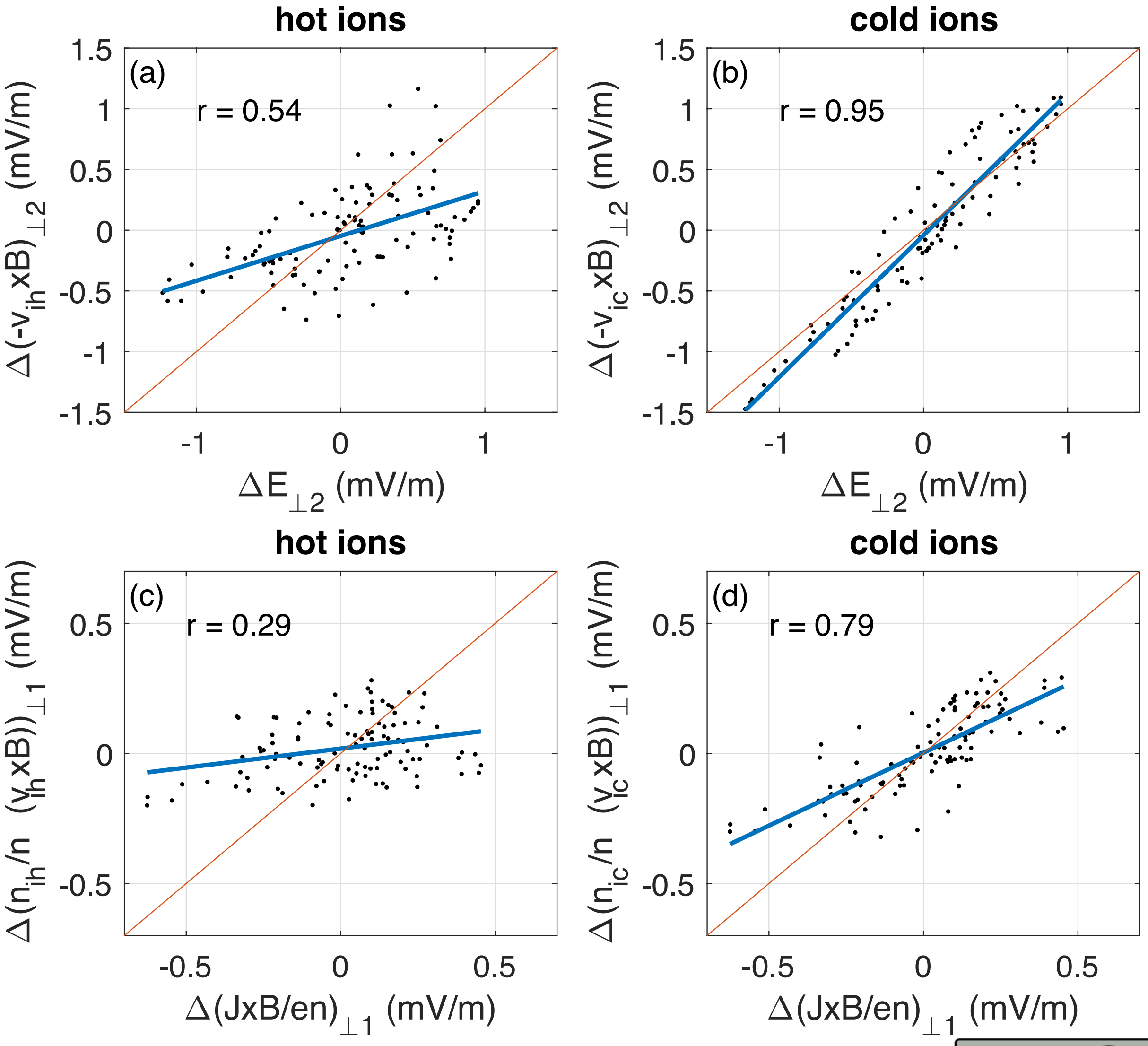
- (10-20%) density compressions of electrons and cold ions
- Almost linear polarization in B and E, (RHP)
- RMS(dE/dB)=750 km/s ~ v_A --> consistent with Alfvén Branch
- Ohm's law calculated for fluctuations (BPF 0.1fci – 5fci)
- E ~ JxB/en – v_{ic}xB(n_{ic}/n) in perp 2 direction
- JxB/en ~ vicxB(n_{ic}/n) in perp 1 direction → linear polarization.
- div(P_e)/en very noisy (n ~ 1 cc).
- Trigger of whistlers associated with B and n compressions, + Lower hybrid waves (?)

$$\mathbf{E} = -\frac{n_{ic}}{n}\mathbf{v_{ic}} \times \mathbf{B} - \frac{n_{ih}}{n}\mathbf{v_{ih}} \times \mathbf{B} + \frac{1}{en}\mathbf{J} \times \mathbf{B} - \frac{1}{en}\nabla \cdot \mathbf{P_e},$$

E field fluctuations and Ohm's law analysis



$$\mathbf{E} = -\frac{n_{ic}}{n}(\mathbf{v_{ic}}\times\mathbf{B}) - \frac{n_{ih}}{n}(\mathbf{v_{ih}}\times\mathbf{B}) + \frac{1}{en}\mathbf{j}\times\mathbf{B} - \frac{1}{en}\nabla\mathbf{P_e}$$



K vector determination using Bellan and 4sc time differencing

- $K_{4sc} \sim K_{bellan} = (1.9, 0.6, 5.6)\cdot 10^{-3}$ rad/km, wna~72°
- $f_{obs} = 0.35$ Hz, after doppler shift correction f_{wave}~0.26 Hz ~0.5 fci

Comparison of spatial scales:

$k\cdot d_i = 1.4$

$k\cdot \rho_{ih} = 1.9$

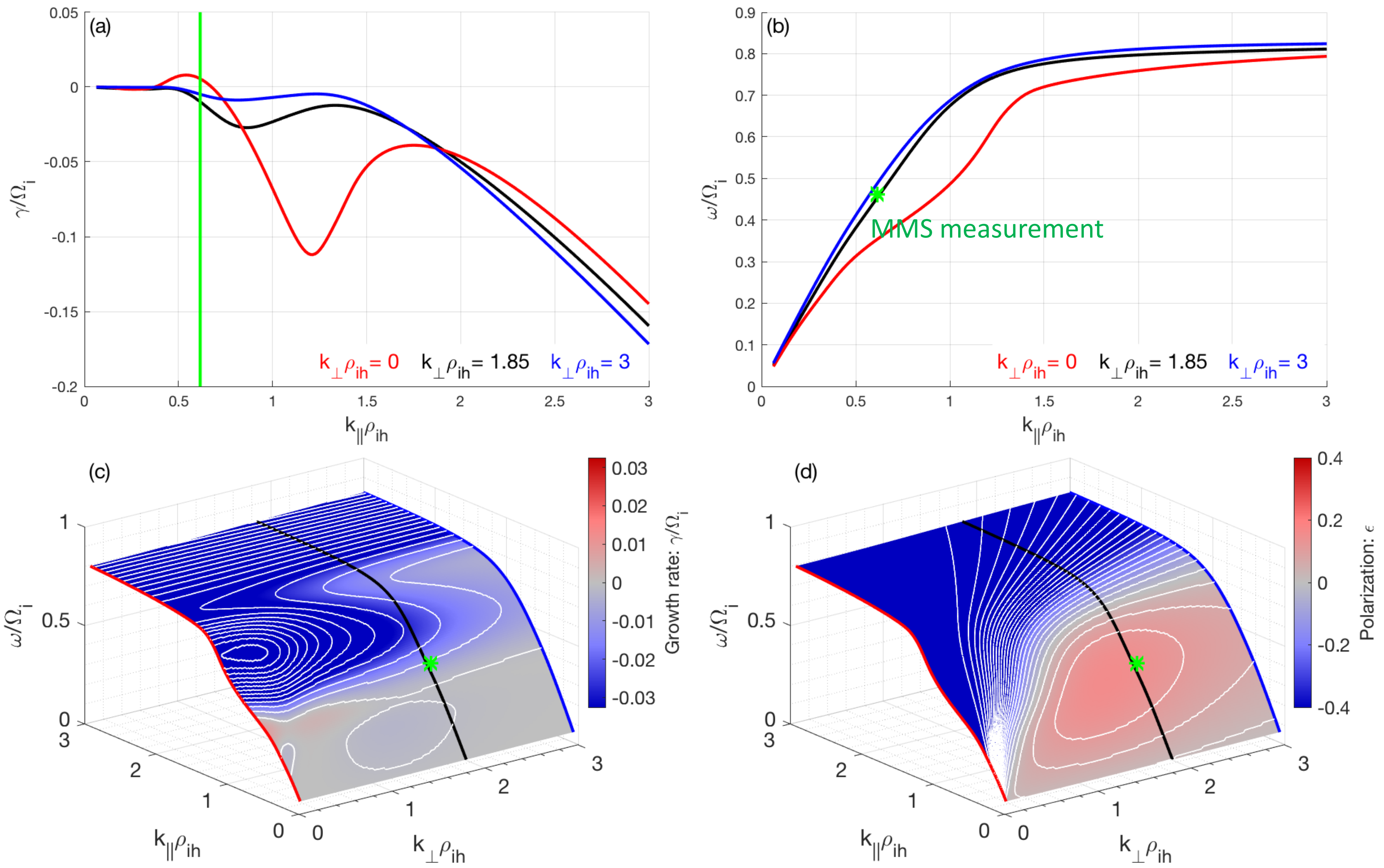
$k\cdot \rho_{ic} = 0.1$

K vector estimation

Bellan method and 4sc phase differencing:

Properties \ EMIC	With cold ions
$[k_{\|\|}, k_{per1}, k_{per2}]$ (1/km)	$[1.5\ -0.3\ 4.7]\cdot 10^{-3}$
λ (km)	[42,000 -21,000 **1,340**]
theta_k (degrees)	~70
ρ_{ic} (km)	**20**
ρ_{ih} (km)	**325**
d_i (km)	**227**
f_{EMIC}/f_{ci}	0.49

Comparison with dispersion solver including cold and hot proton population

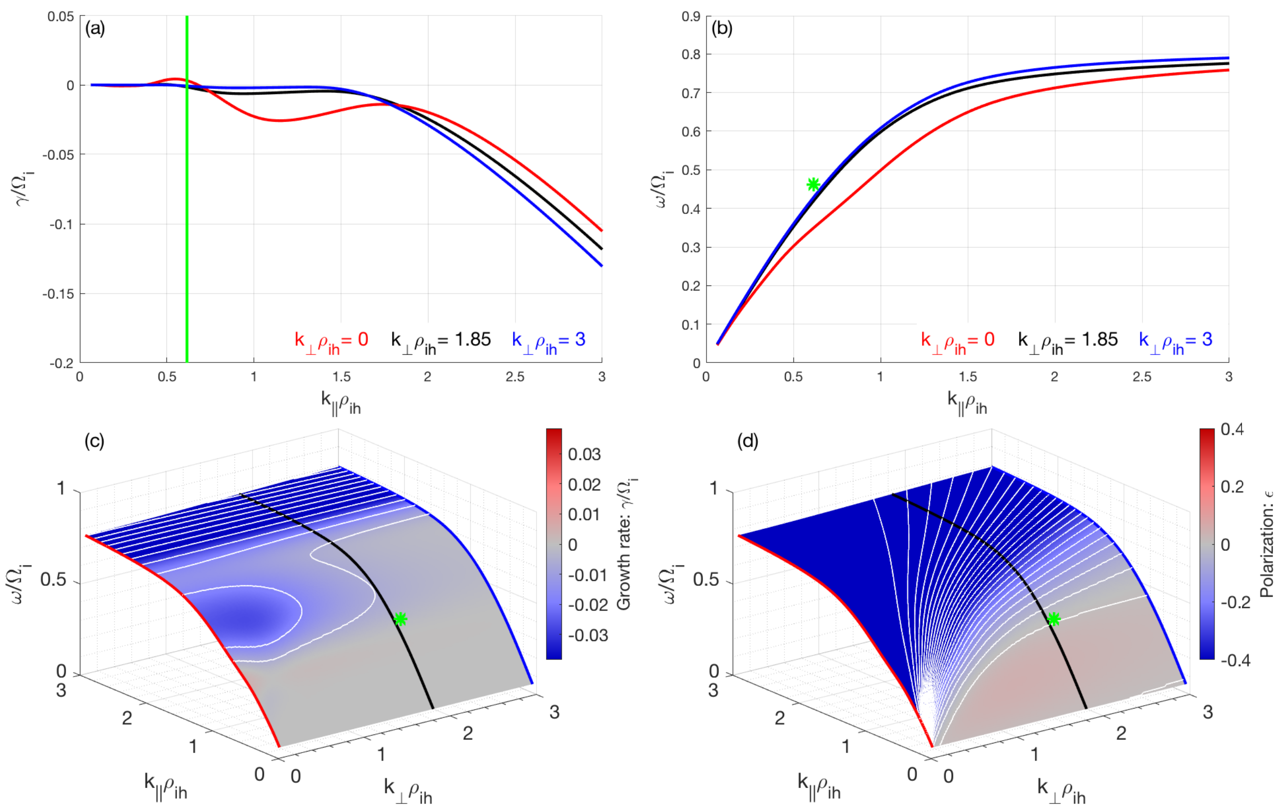


- Doppler-shifter observed frequency consistent with WHAMP prediction.
- Wave polarization also consistent (RHP, Re(iB_{perp1}/B_{perp2})~0.1
- Departed from positive growth rate due to oblique propagation.

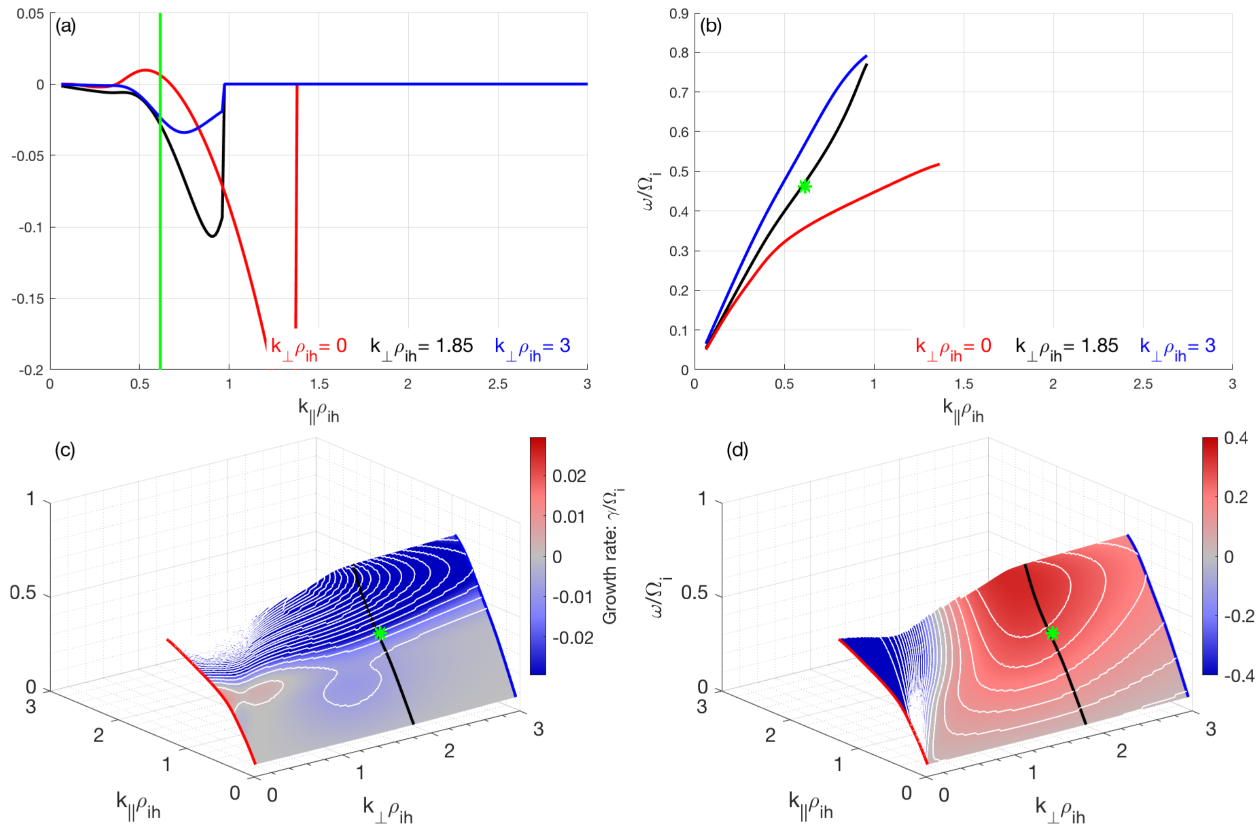
	hot ions			cold ions		
B_0 (nT)	n (cm^{-3})	$T_{\|}$ (eV)	$T_\perp/T_{\|}$	n (cm^{-3})	T (eV)	$T_\perp/T_{\|}$
37	0.5	4400	1.6	0.5	40	1

Polarization dependence on cold to hot ion density ratio for oblique angles

80% cold ions



20% cold ions



Main points

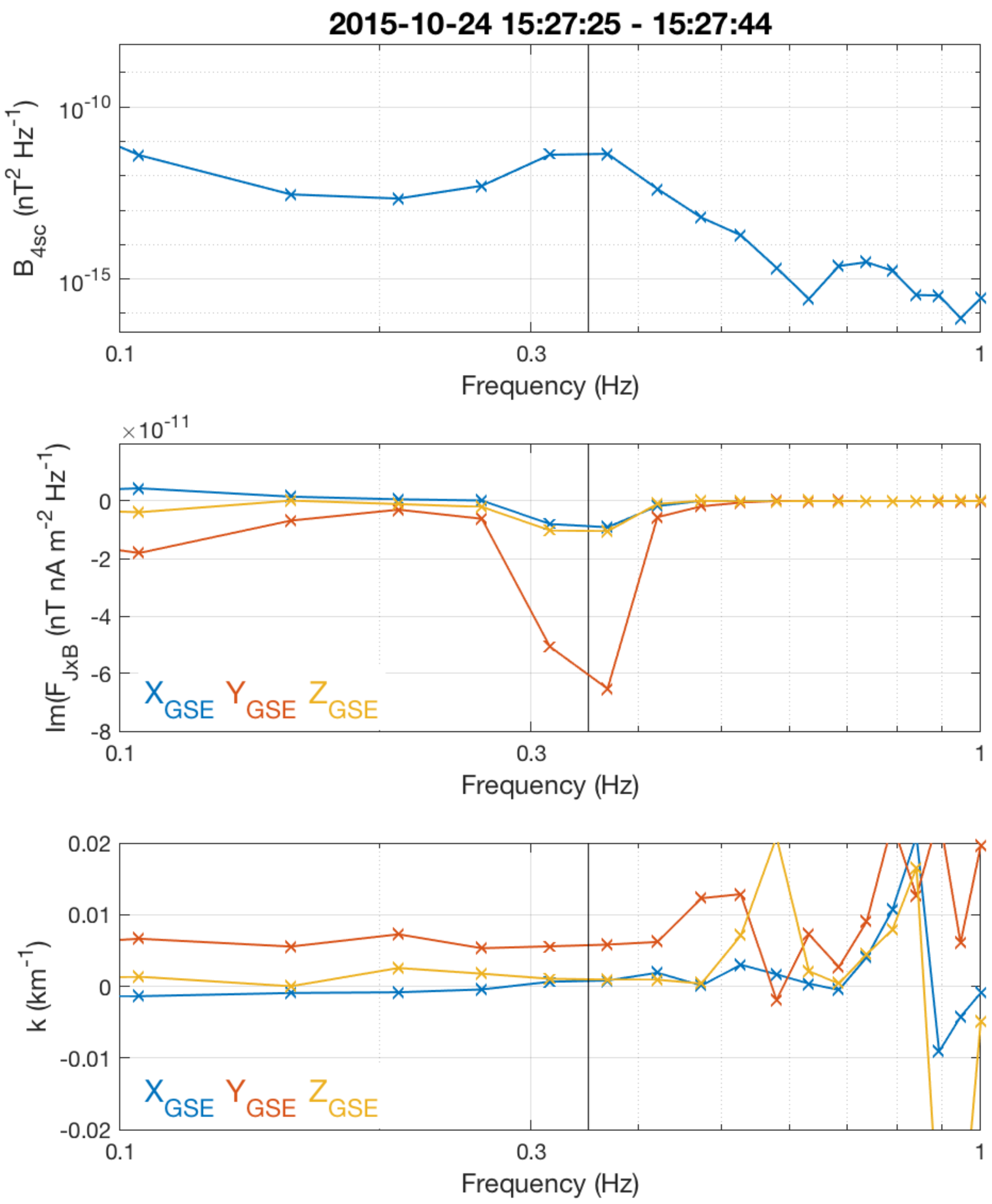
- EMIC wave travelling tangential (+YGSE) to the reconnecting magnetopause.

- Cold ions strongly magnetized ($v_{ic}xB = E$), hot ions weakly magnetized. Consistent with spatial scales $k \cdot d_i = 1.4$, $k \cdot \rho_{ih} = 1.9$, $k \cdot \rho_{ic} = 0.1$

- Cold ions accelerated in ordered, coherent fashion, no thermalization should take place. For hot ions, irreversible energy transfer (pitch angle scattering) should be possible. Interaction with delta E dependent on gyrophase of individual ions (not shown).

- Cold ion velocity term and Hall term dominate the balance of the Ohm's law. Fluctuations of JxB and $v_{ic}xB$ are in phase (anti-phase) in perp2 and perp1 directions. Polarization dependent on n_{ic}/n ratio.

THANKS

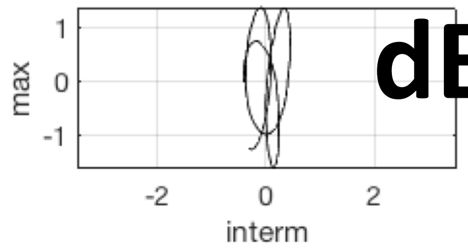


Supplemental material

- Results of Bellan method for determination of K vector.
- Results are consistent with MVA and 4sc phase timing of the wave.

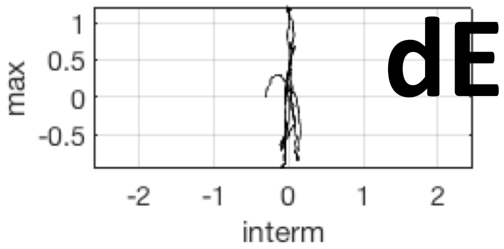
Bellan method and 4sc phase differencing:

Properties \ EMIC	With cold ions
$[k_{\|\|}, k_{per1}, k_{per2}]$ (1/km)	$[1.5\ -0.3\ 4.7]\cdot 10^{-3}$
λ (km)	[42,000 -21,000 1,340]
theta_k (degrees)	~70
ρ_{ic} (km)	20
ρ_{ih} (km)	325
f_{EMIC}/f_{ci}	0.49



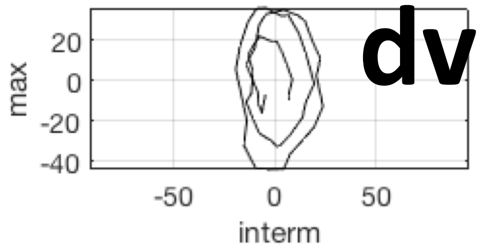
dB

perp1/perp2=13 ~linear
perp2/para=1.1



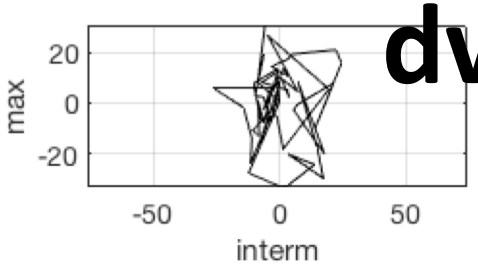
dE

perp2/perp1=12 ~linear
perp1/para=11



dv$_{ic}$

perp1/perp2=**3.9 elliptical**
perp2/para=24



dv$_{ih}$

perp1/perp2=2.4
perp2/para=1.6