Electron acceleration by Alfven waves in the magnetosphere

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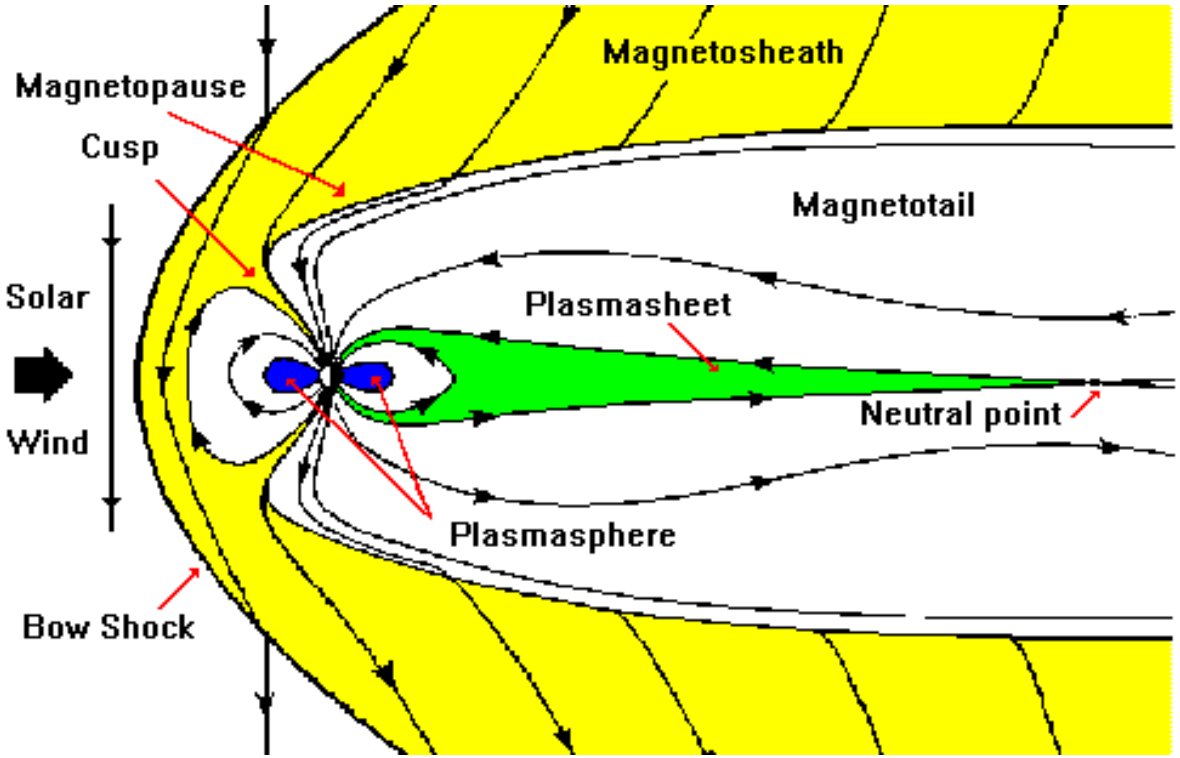
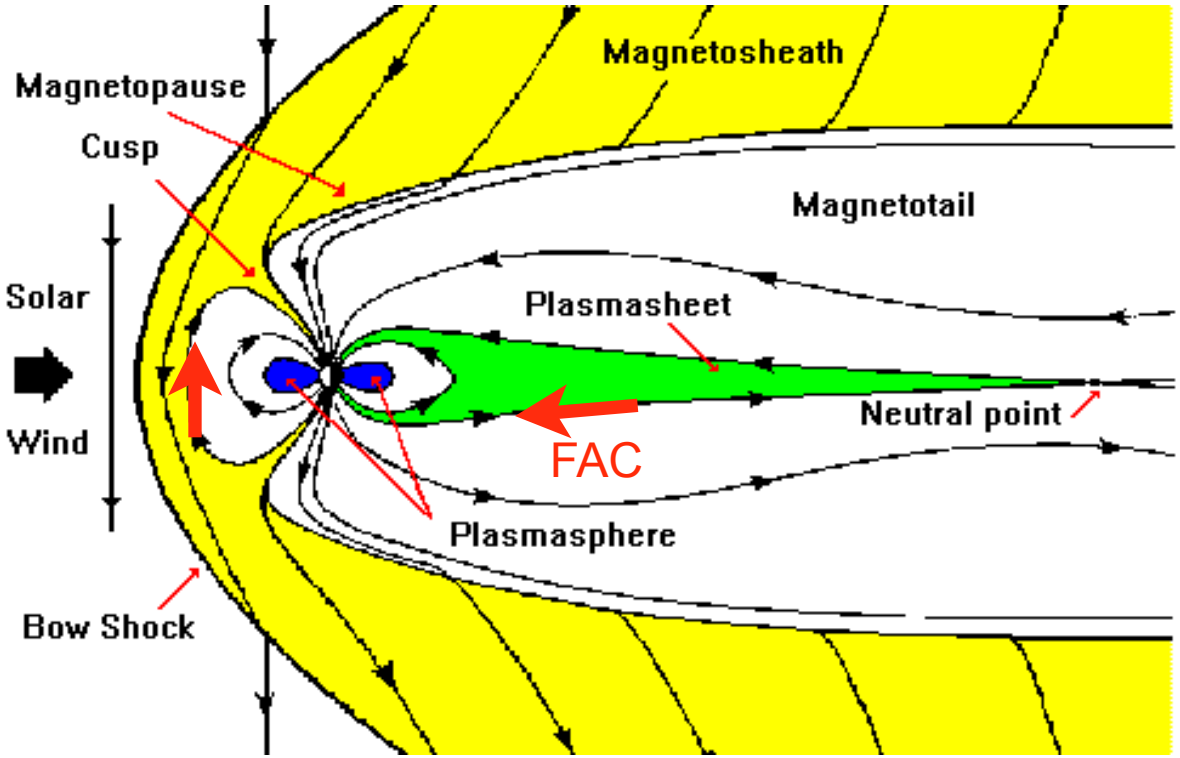
(image courtesy of NASA)

Magnetosphere-Ionosphere Coupling



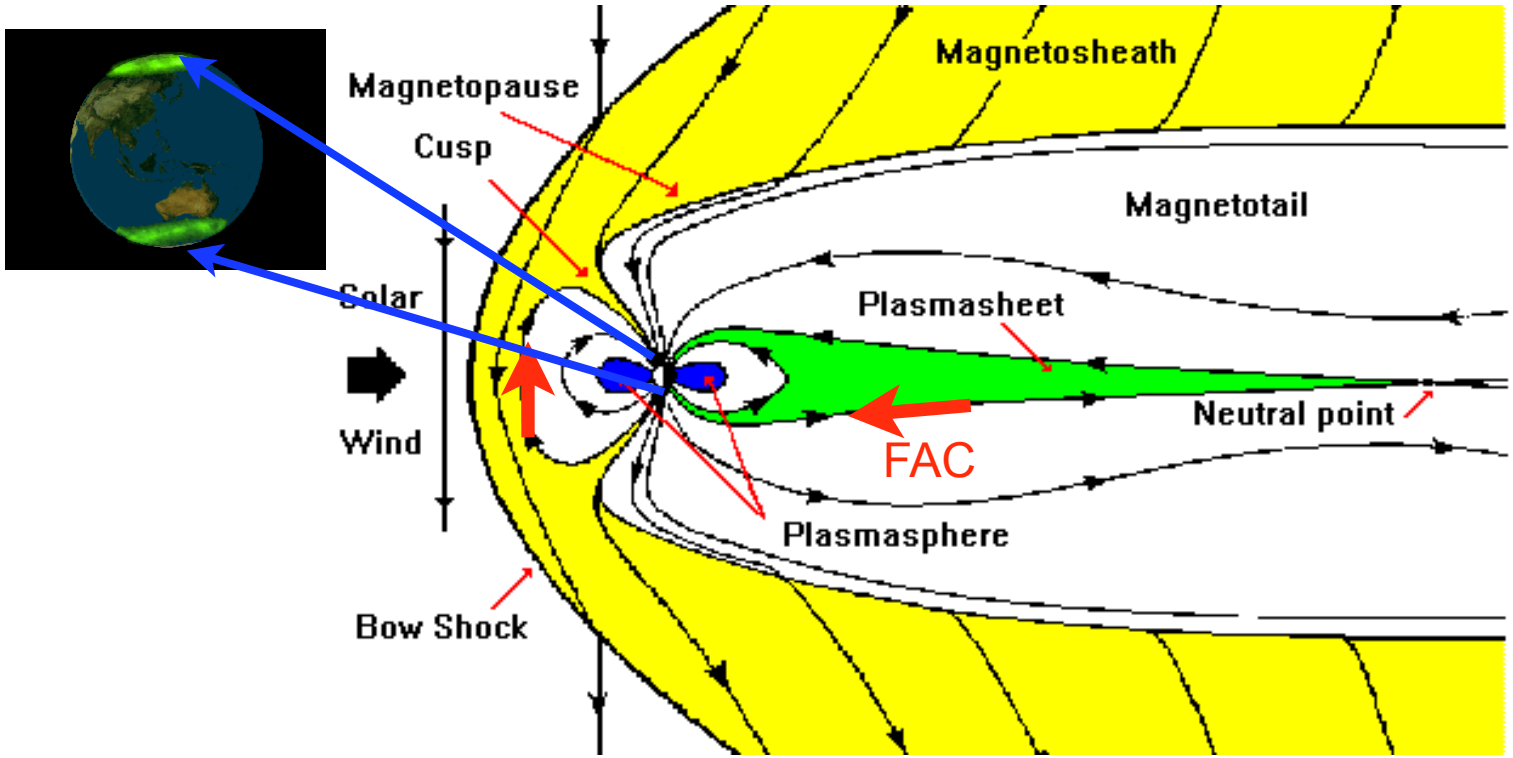
Magnetosphere-Ionosphere Coupling

Magnetospheric configuration changes drive Field Aligned Currents (FAC)



Magnetosphere-Ionosphere Coupling

FACs carry electron flux into ionosphere



Electron flux interacts with atmospheric gases to produce aurora

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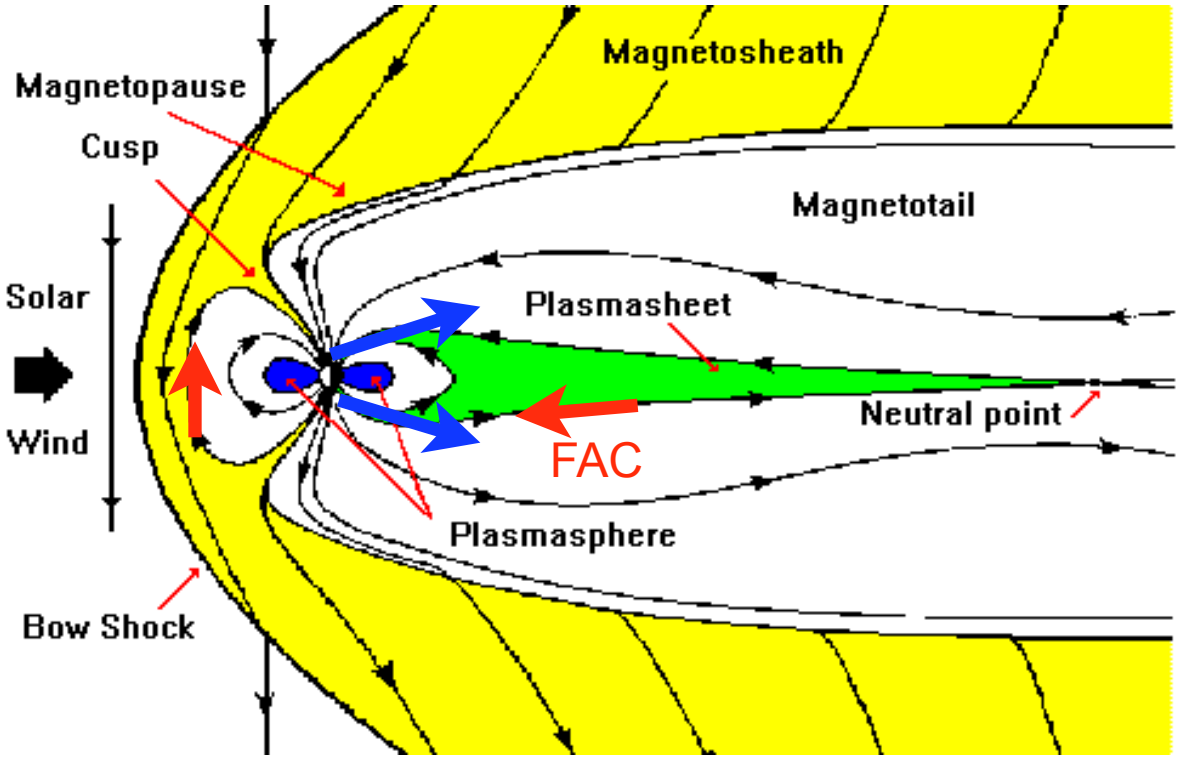
Magnetosphere-Ionosphere Coupling

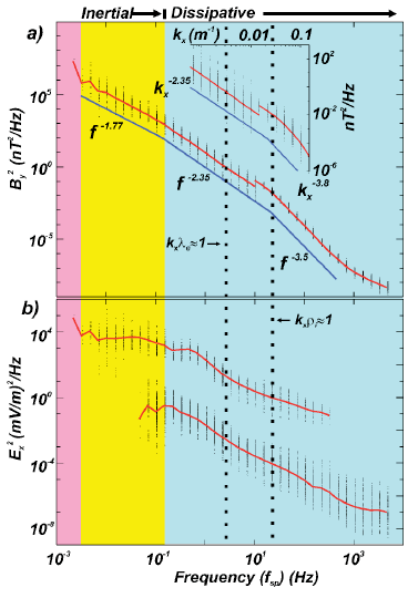
Poynting and Electron flux also drive outflow of heavy ions



Which alters the magnetospheric configuration

Auroral Morphology

- Monoenergetic Aurora are associated with
  - quasi-static global Field Aligned Currents
  - Low frequency Alfven waves
- Broadband Aurora are associated with
  - kinetic scale Alfven waves ($\lambda_\perp \sim c/\omega_{pe}$, ρ_s or ρ_i)
  - and can drive substantial outflow
- Diffuse Aurora
  - EMIC and whistler waves (radiation belts).



Chaston et al., 2008

Fundamental Questions:

- How and where are e^- accelerated to carry FACs?
- How does wave energy reach dispersive scales?
- How do auroral arcs form?
- What is feedback on global system?

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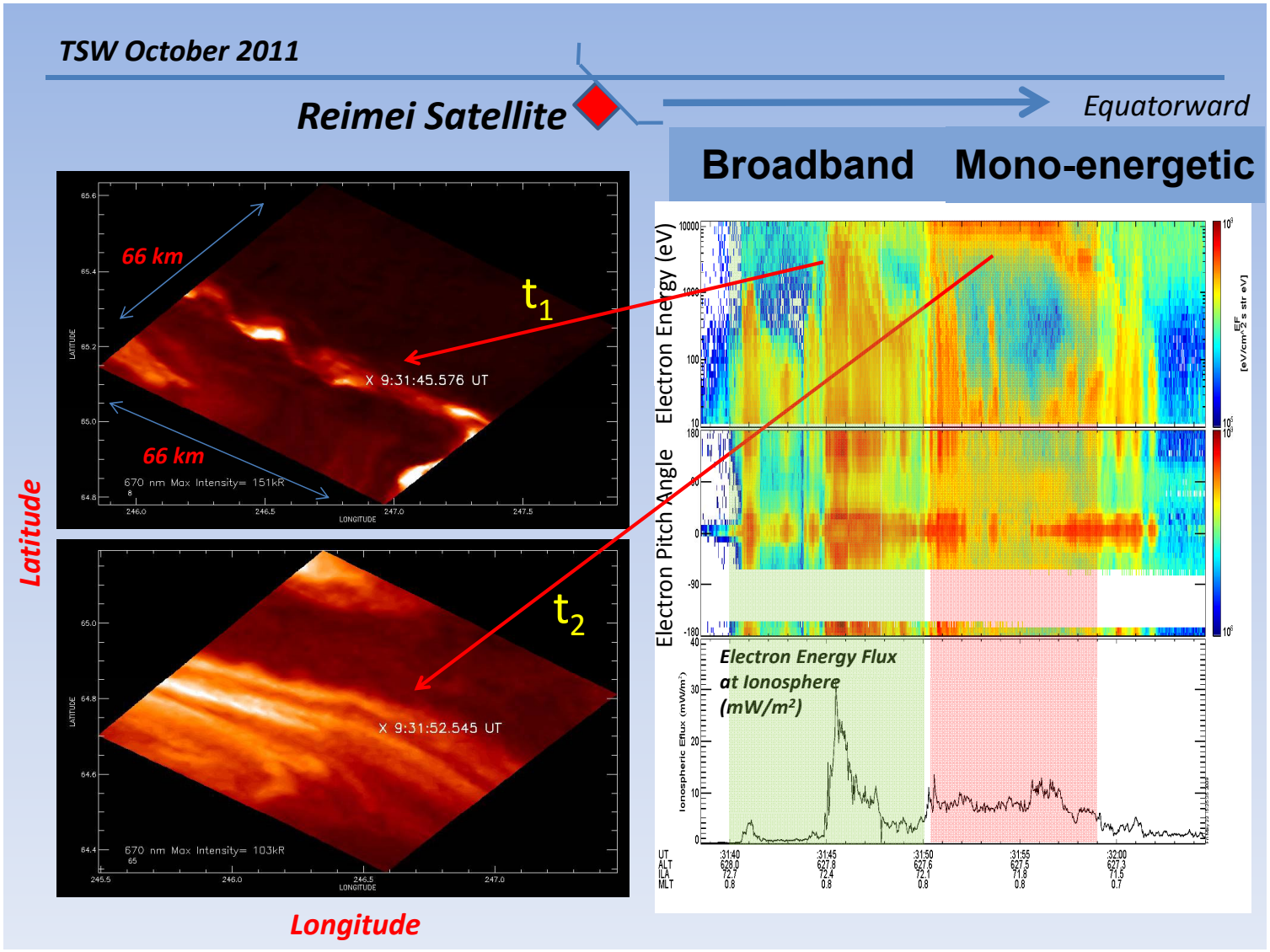
Characteristics of Monoenergetic and Broadband Aurora



(Courtesy C. Chaston)

Mono-energetic Aurora and low frequency Alfven waves

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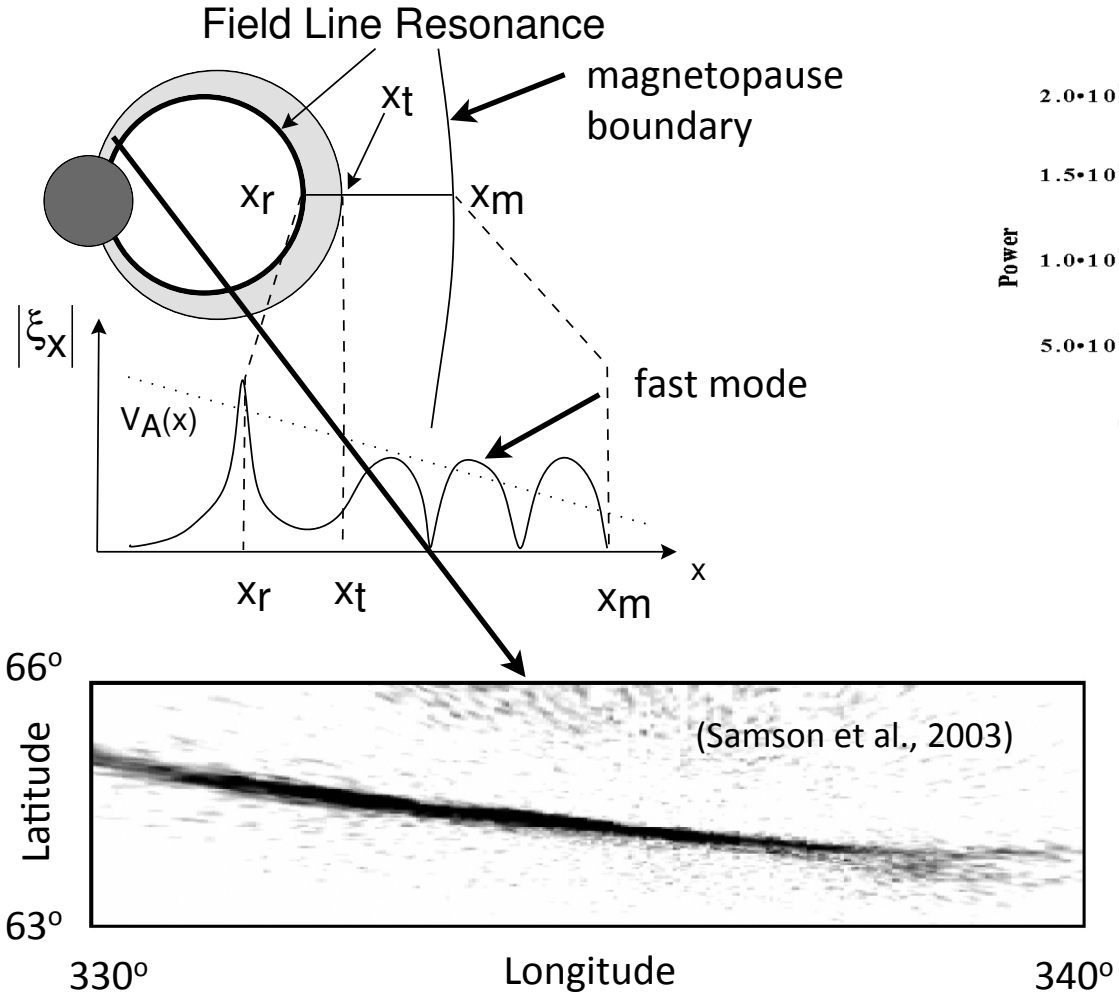
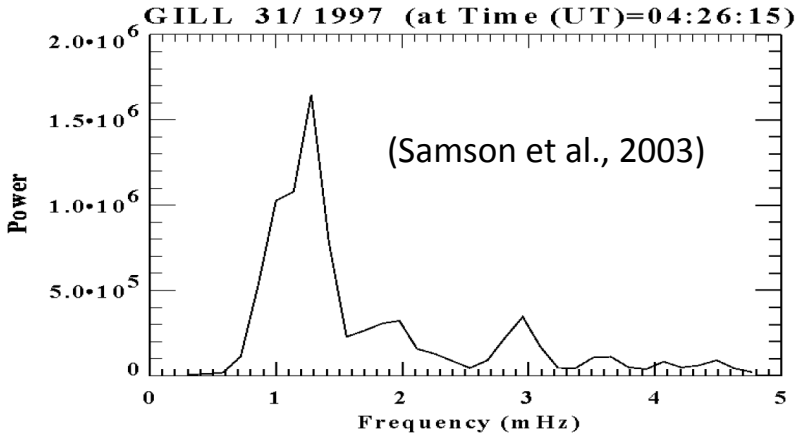
Field Line Resonances (standing Alfven waves) and auroral arcs

FLRs can be generated by mode conversion from fast mode





(mHz frequency wave)

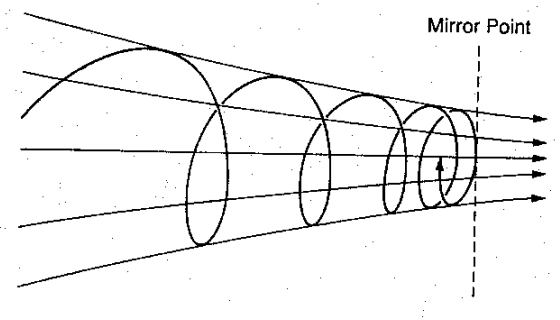
Long extended arc in azimuthal direction (out of page)

What generates $E_{||}$ in Alfven waves?

- Dispersive wave effects - (e.g. Wei et al., 1994; Streltsov and Lotko 1996; Bhattacharjee, et al. 1999; Wright et al., 2002).

- Anomalous resistivity (Lysak and Dum, 1983; Lotko et al., 1998).

- Mirror force effects (Rankin et al., 1999).



Need $E_{||}$ to accelerate trapped electrons to carry $j_{||}$

Questions: Can we generate sufficient $E_{||}$ due to mirror force effects in a self-consistent kinetic simulation to accelerate electrons to keV energies? What are signatures of acceleration?

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2D hybrid MHD-kinetic electron model

(Damiano et al., Phys. Plasmas, 14, 062904, 2007)

Cold Plasma MHD equations

Momentum equation

$$\mu_o \rho_o \frac{\partial u_\phi}{\partial t} = \frac{B_o}{h_{||} h_\phi}\left[\frac{\partial}{\partial x_{||}}(h_\phi b_\phi)\right]$$

Faraday's Law

$$\frac{\partial b_\phi}{\partial t} = \frac{-1}{h_{||} h_\perp}\left[\frac{\partial}{\partial x_{||}}(h_\perp E_\perp) - \frac{\partial}{\partial x_\perp}(h_{||} E_{||})\right]$$

Perpendicular Ohm's law

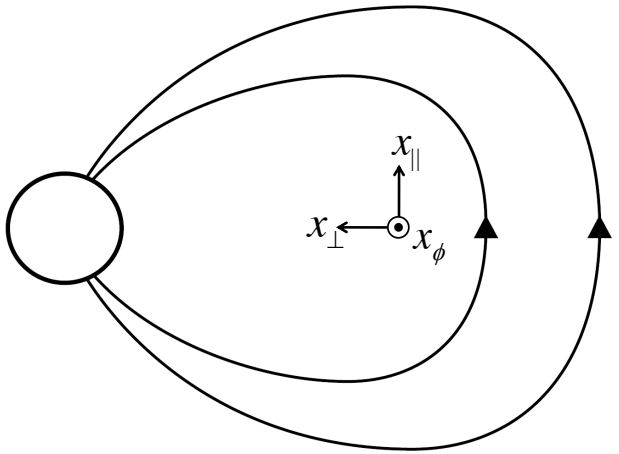
$$E_\perp = -u_\phi B_o$$

Guiding center equations

$$m_e \frac{dv_{||}}{dt} = -eE_{||} - \boxed{\mu_m \nabla_{||} B_o}$$

$$h_{||} \frac{dx_{||}}{dt} = v_{||}$$

mirror force term



coupling via $E_{||}$ (Gen. Ohm's Law including moments of e^- distribution function)

Particle/field interpolation done using standard PIC techniques.

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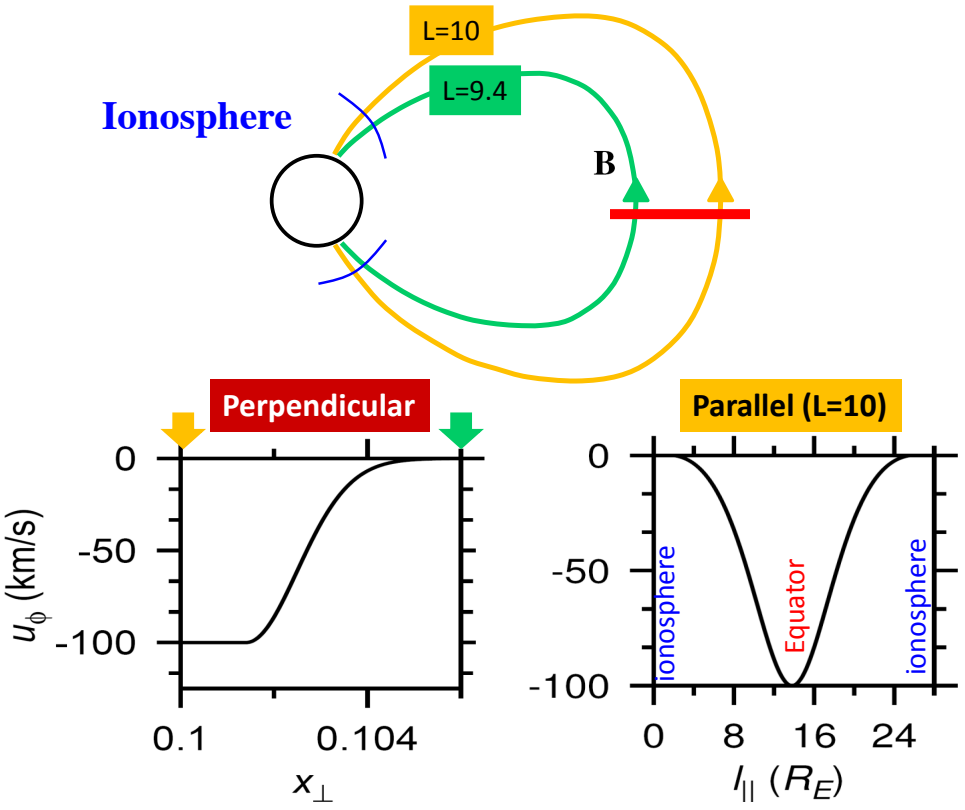
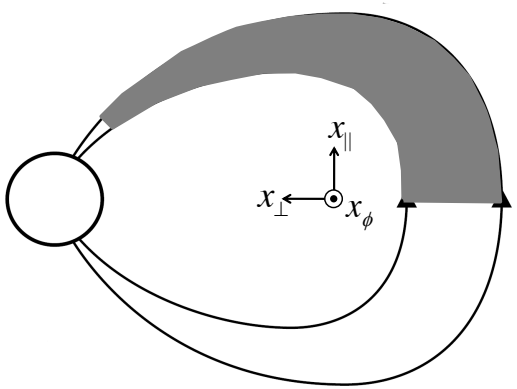
Initial Perturbation



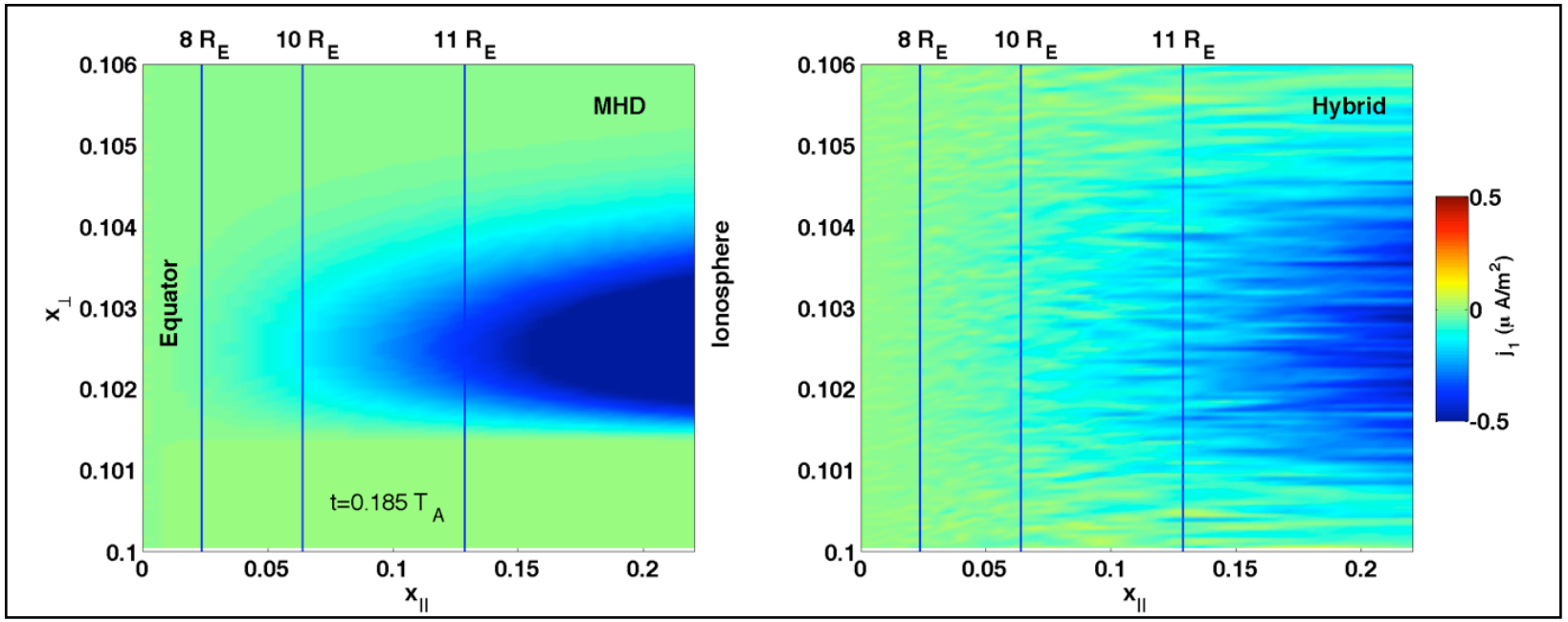
Half-Gaussian results in only region of upward FAC

Ionospheric boundary at altitude of 1 Re

Field Aligned Current Density



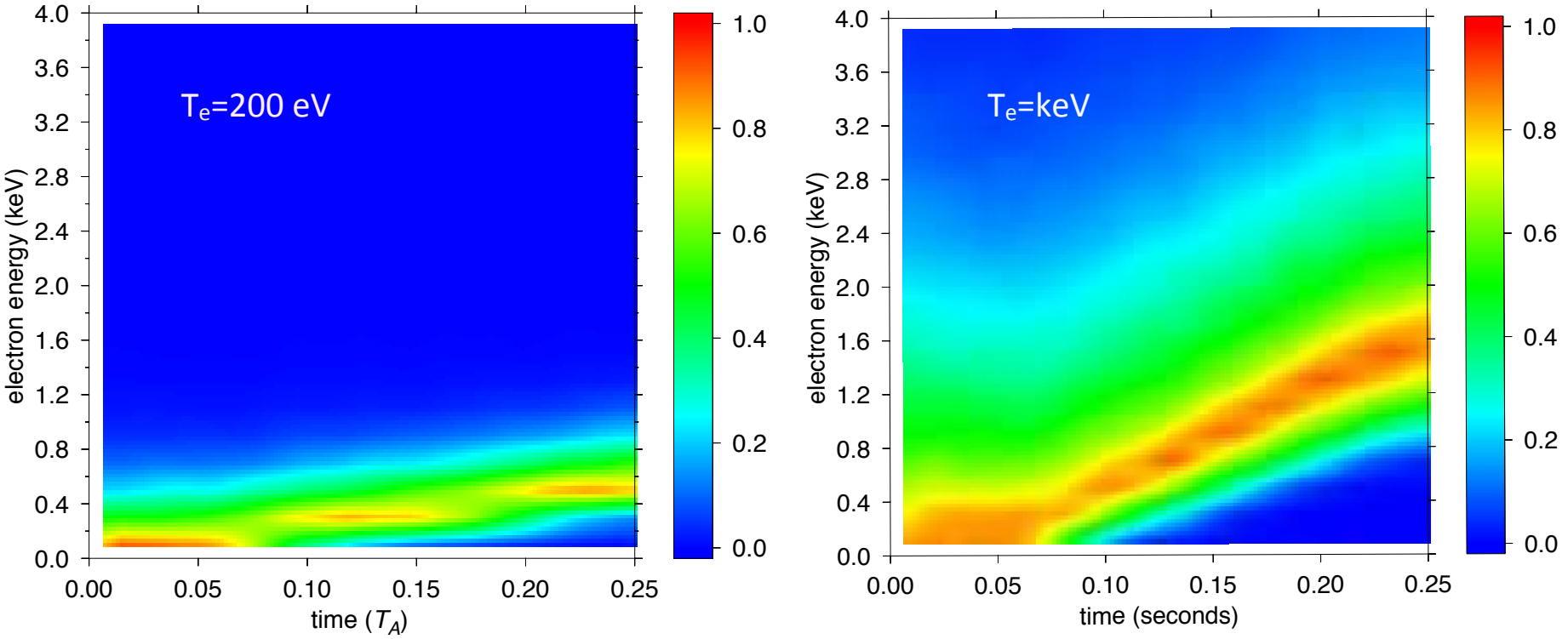
Plot northern hemisphere in dipolar coordinates



Feedback in hybrid model →

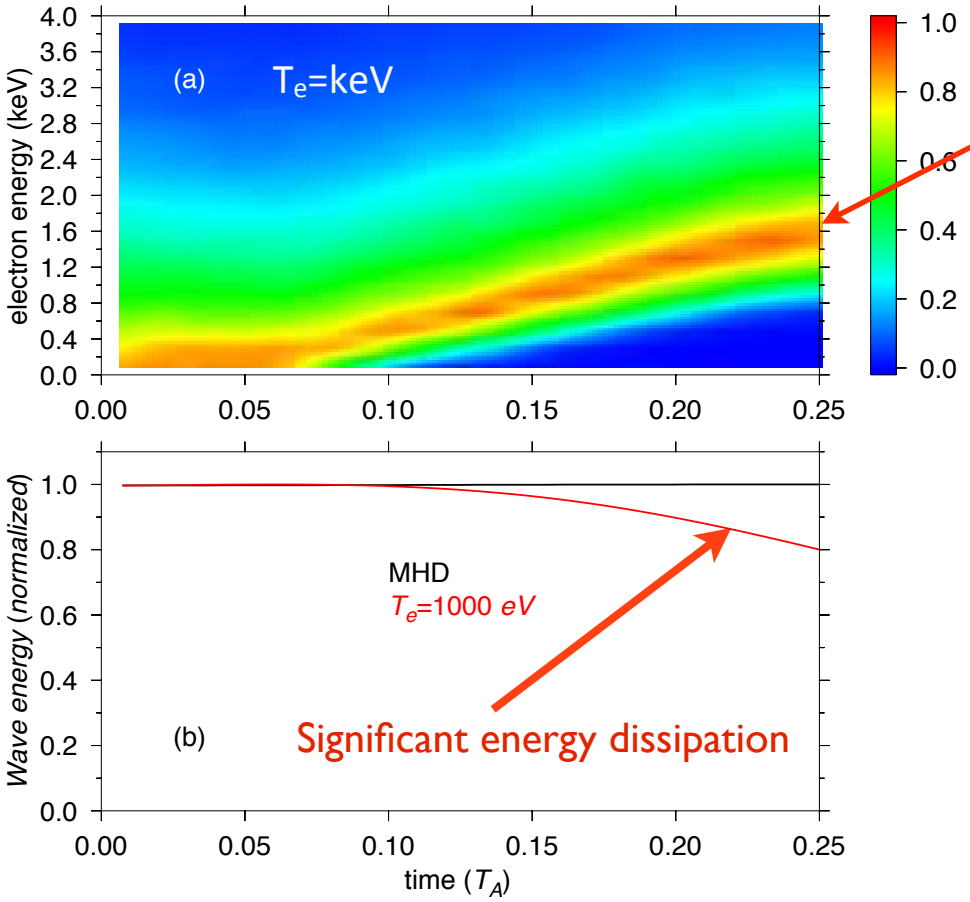
- Perpendicular dispersion ($S_{\perp}$=-$E_{||}b_{\phi}$)
- Cross scale coupling

Mirror force effects can accelerate electrons to keV energies

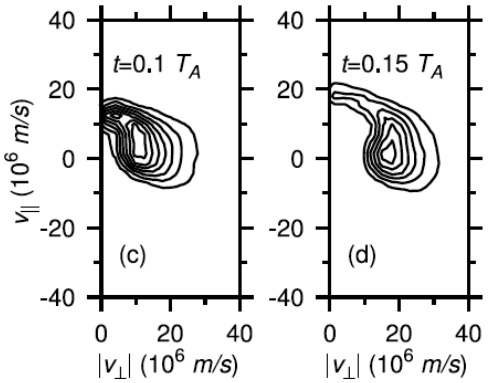


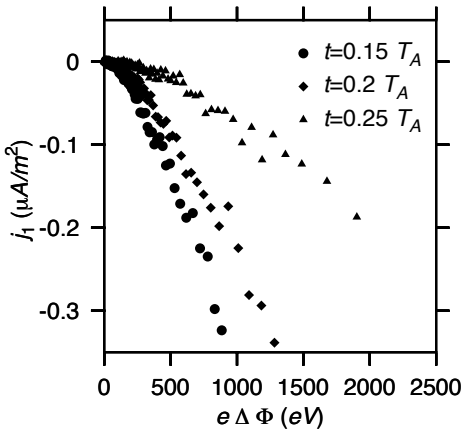
Larger T_e -> increased mirror force trapping -> remaining current carriers must be accelerated to higher velocity.

Electron acceleration is a large sink of wave energy



mono-energetic beam





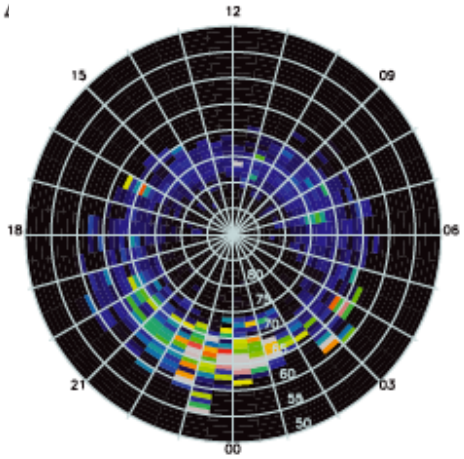
Un-driven resonance would completely damp in < 2 T_A -> same magnitude as Ohmic dissipation in ionospheric currents.

Broadband Aurora and Dispersive Alfven waves

Motivation - Understanding formation of Broadband Aurora

Broadband e^- precipitation correlated with Alfvenic Poynting flux.

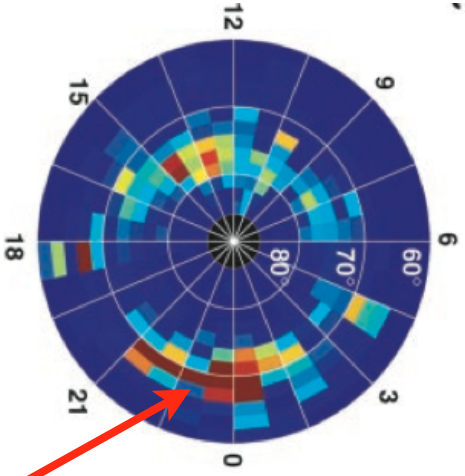
Broadband electron energy flux



(Wing et al., 2013)

Sun

Downward Alfvenic Poynting flux



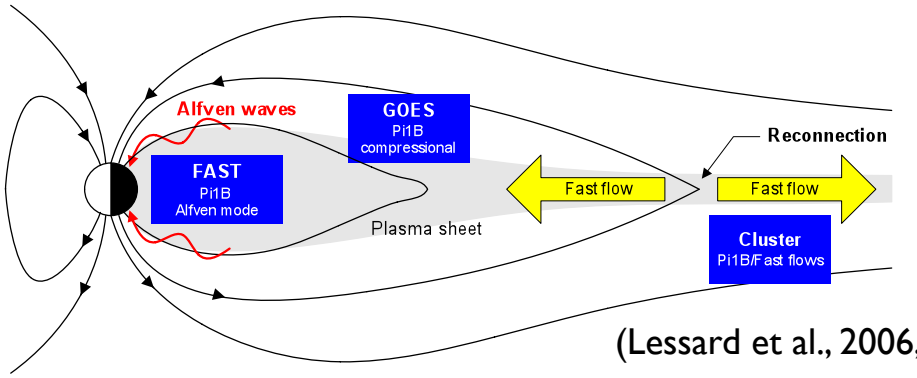
(Keiling et al., 2003)

Poynting flux associated with ~Hz frequency dispersive Alfven waves ($\lambda_{||} \sim R_E$, $\lambda_{\perp} \sim \lambda_e, \rho_s, \rho_i$).

Motivation - Substorm onset and Broadand Aurora

Broadband aurora increase rapidly at onset (e.g. Wing et al., 2013).

Is dispersive scale structuring imposed at onset site or after?



(Lessard et al., 2006, 2011)

Breaking of fast flows is one observed source of KAWs

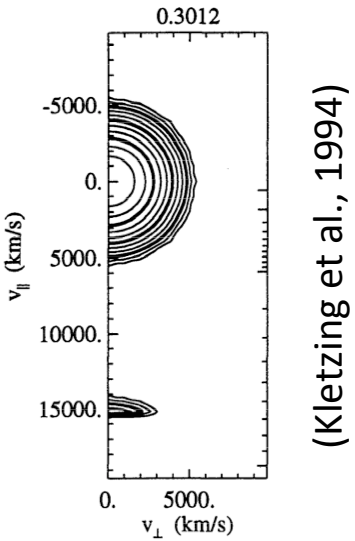
Wave observations (e.g. Lessard et al., 2006, Chi et al., 2009) used to evaluate onset timing and location.

Understanding transit time of waves to ionosphere is important to help connect optical signatures to driving mechanism.

Characteristics of wave-particle interactions depend on location

Path along field line is a highly variable plasma environment

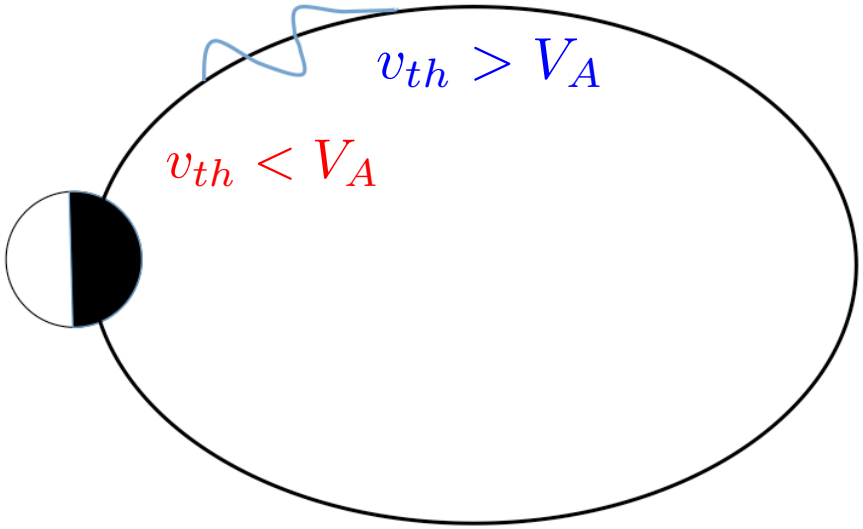
IAW regime



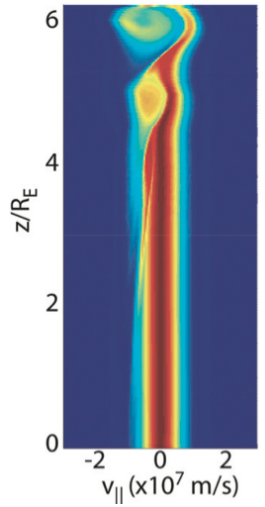
(Kletzing et al., 1994)

Fermi acceleration

Alfven wave



KAW regime



(Watt and Rankin, 2010)

Particle trapping

- Location/mechanism for acceleration not clearly established.
- Means by which energy reaches dispersive scales not known.
- Studies to date, informative but are mostly 1D or local.
- Limited exploration of ρ_i effects (T_i/T_e ~ 7 in plasma sheet).

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Hybrid gyrofluid-kinetic electron model in curvilinear coordinates

Cold Plasma MHD equations

Modified Momentum equation

$$\mu_o \rho_o \frac{\partial \tilde{u}_\phi}{\partial t} = \frac{B_o}{h_{||} h_\phi}\left[\frac{\partial}{\partial x_{||}}(h_\phi b_\phi)\right]$$

where $\tilde{u}_\phi = (1 - 1.25\rho_i^2 \nabla_\perp^2) u_\phi$

Faraday's Law

$$\frac{\partial b_\phi}{\partial t} = \frac{-1}{h_{||} h_\perp}\left[\frac{\partial}{\partial x_{||}}(h_\perp E_\perp) - \frac{\partial}{\partial x_\perp}(h_{||} E_{||})\right]$$

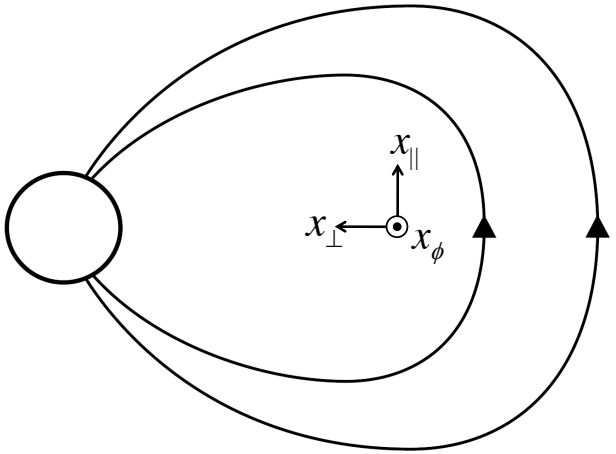
Modified Perpendicular Ohm's law

$$E_\perp = -B_o(\tilde{u}_\phi - \rho_i^2 \nabla_\perp^2 \tilde{u}_\phi)$$

Guiding center equations

$$m_e \frac{dv_{||}}{dt} = -eE_{||} - \mu_m \nabla_{||} B_o$$

$$h_{||} \frac{dx_{||}}{dt} = v_{||}$$



coupling via $E_{||}$ (Gen. Ohm's Law including moments of e^- distribution function)

(Damiano et al., Phys. Plasmas, 14, 062904, 2007, Cheng and Johnson, 1999, Damiano et al., 2015)

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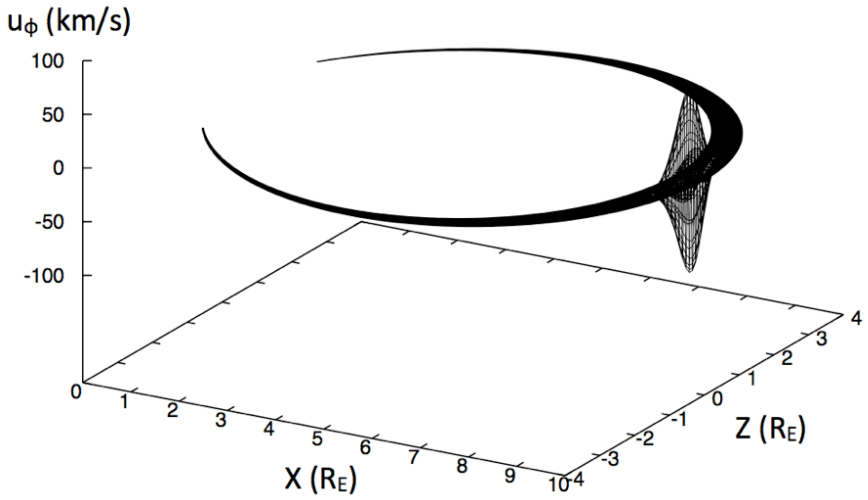
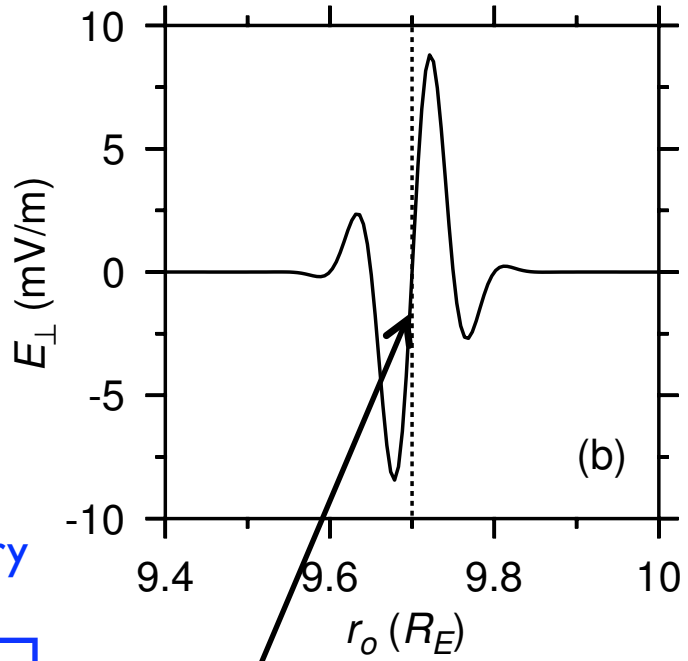
Kinetic Alfven wave pulse – initial perturbation example

Initialize KAW perturbation in the plasma sheet



perpendicular $E_\perp$ profile at equator



Identical pulses propagate to each field-aligned boundary (at 1 R_E altitude above Earth surface).

$$\frac{k_\perp}{k_{||}} \sim 10$$

$\lambda_\perp \sim 0.1\ R_E$

Field line of maximum upward current

Two simulation cases:

1) T_i=0, T_e=100 eV

2) T_i=1 keV, T_e=100 eV

$$\frac{k_\perp}{k_{||}} \sim 10 - 100 \quad \text{(Chaston et al., 2014)}$$

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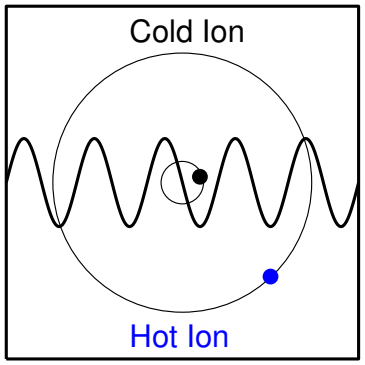
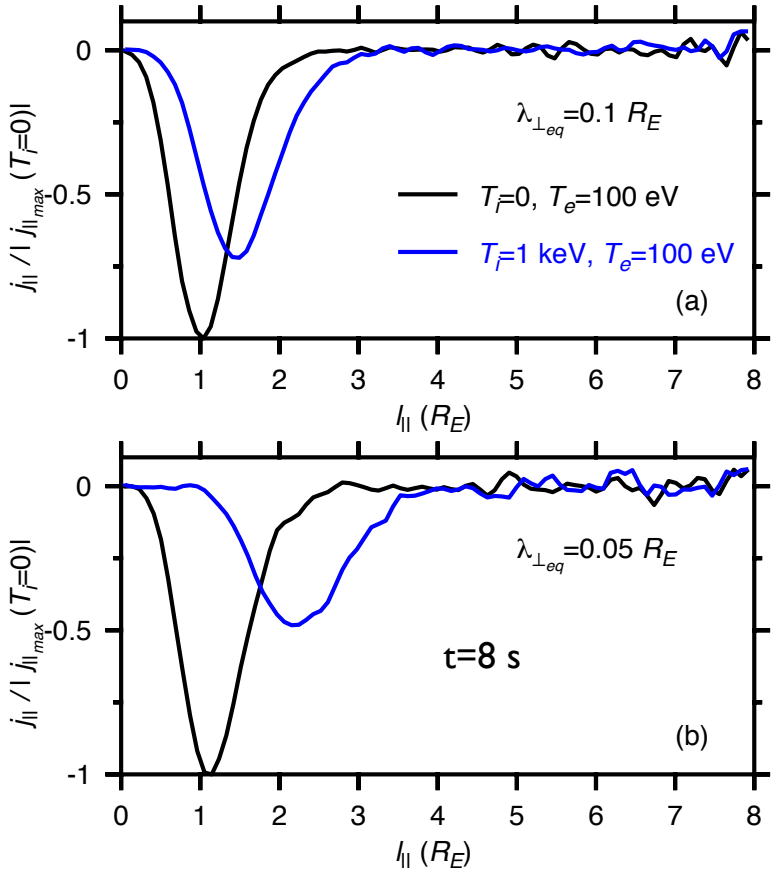
Increased phase speed, but reduced coupling

$$\omega = k_{||} V_A \sqrt{1 + k_\perp^2 \rho_i^2 (1 + \frac{T_e}{T_i})}$$

In plasma sheet, $T_e/T_i \sim 1/7$
(Baumjohann et al., 1987)



(e.g. Tatsuno et al., 2009)



$k_\perp \rho_i \sim 1$

$k_\perp \rho_i \sim 2$

Also evident in 2 fluid analysis
(e.g. Chaston et al., 2003)

$$\frac{E_{||}}{E_\perp} = \frac{-k_{||} k_\perp \rho_s^2}{(1 + k_\perp^2 \rho_i^2)}$$

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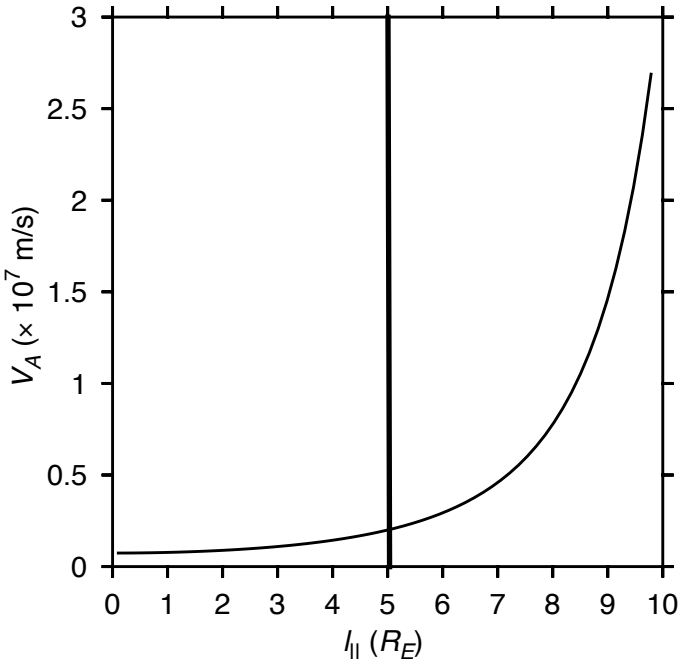
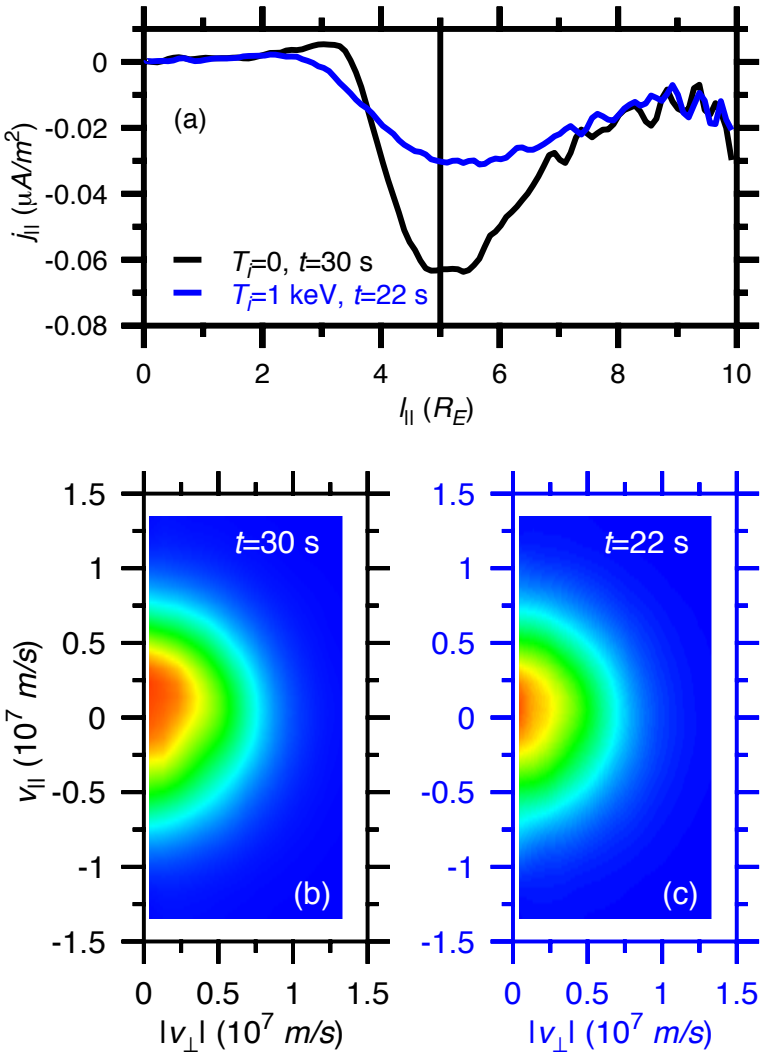
Electron distribution function evolution



$$\frac{\omega}{k_{||}} = V_A \sim 0.2 \times 10^7 m/s$$



Parallel elongation in distribution function is qualitatively consistent with observations (e.g. Wygant, 2000) and simulations (Watt and Rankin, 2009)

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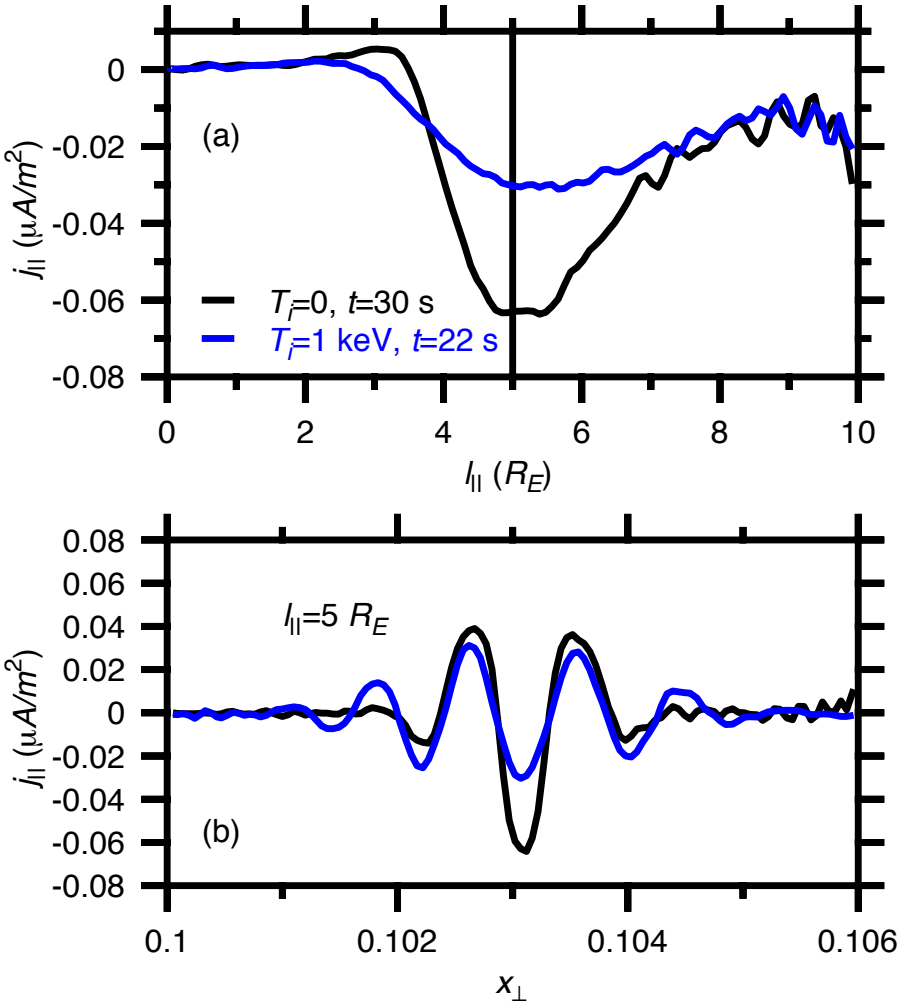
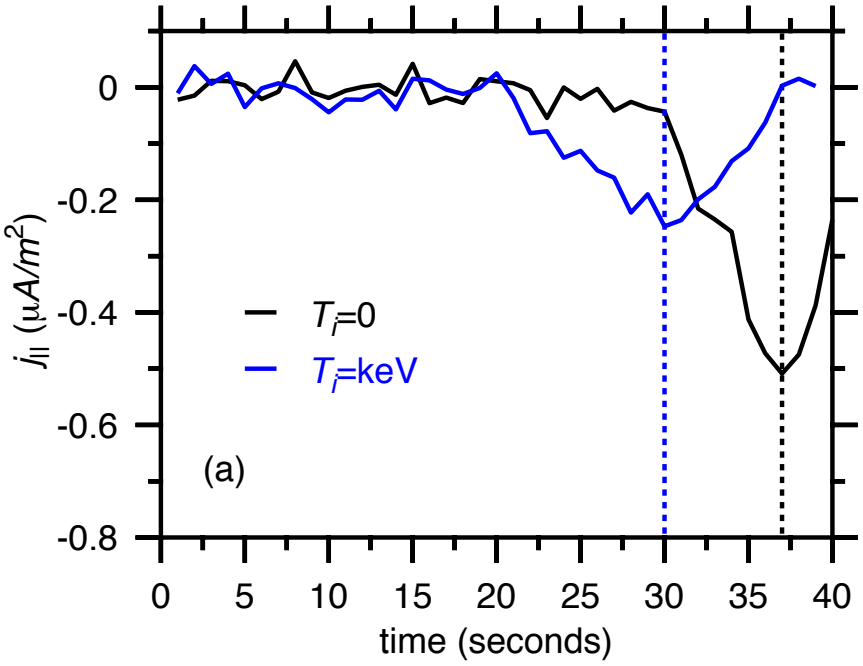
More perpendicular dispersion for increased T_i

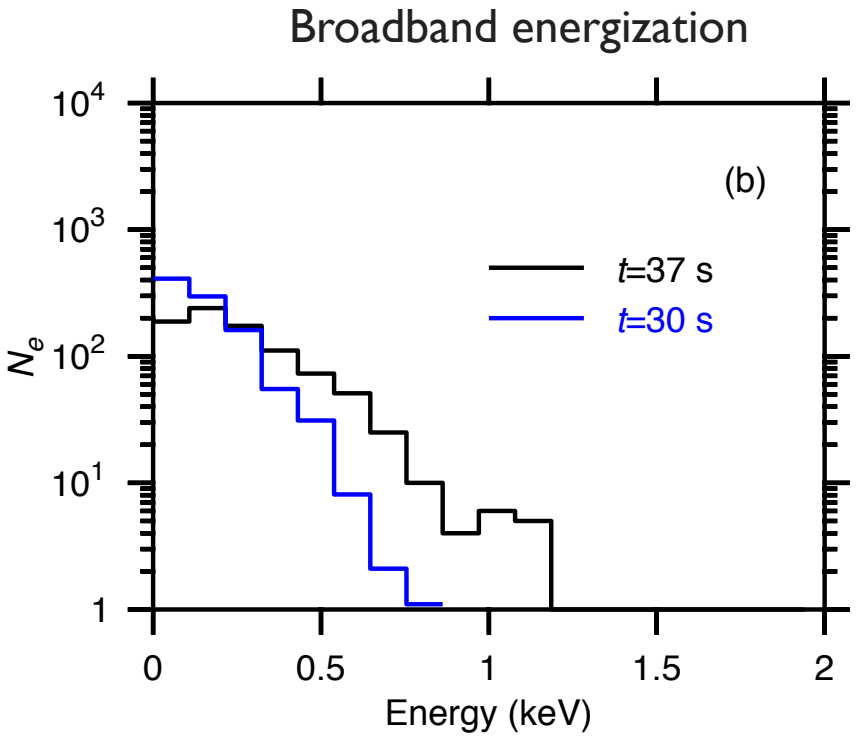


Superposition at same $l_{||}$=5 R_E, but different times

Ionospheric Evolution

ρ_i effects limit current and electron energization all along field line





Summary

- Mirror force effects in global scale Alfven waves self-consistently produce sufficient $\Delta\Phi_{||}$ to accelerate electrons to keV energies (consistent with observations).
- Electron acceleration is a significant sink of wave energy.
- Consistent with observations, electron acceleration in dispersive scale Alfven waves is broadband in nature
- ρ_i effects significantly shorten transit time of Alfven wave to the ionosphere but reduce the ability of the wave to energize electrons.
- $E_{||}$ effects (on all scales) cause a perpendicular dispersion of wave energy.

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Fundamental Questions:

- How and where are e^- accelerated to carry FACs?
- How does wave energy reach dispersive scales?
- How do auroral arcs form?
- What is feedback on global system?

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Future directions

- Broadband aurora - parameter study ($k_{\perp}$, $k_{||}$, $E_{\perp}$,T_i, T_e).
- ρ_i effects on Field Line Resonances - affects $E_{||}$ profile (Streltsov et al., 1998) - observed (Chaston et al., 2013).
- Fast mode dynamics and mode conversion (relevant to both Field Line Resonances and broadband aurora) - stretched tail topologies (MAG2D)
- Ionospheric coupling - (ionospheric dissipation, return currents, multi-period simulations -> auroral arc formation, evolution)
- Cross-scale coupling of wave energy [phase mixing, wave-wave coupling (nonlinear MHD/3D), wave particle interactions, ionospheric feedback].
- Nonlinear stationary inertial Alfven waves (nonlinear MHD).
- More systematic comparison with satellite observations (e.g FAST, Polar, Themis).
- More realistic driving.

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Extra Slides

Generalized Ohm's Law

$$\frac{\partial}{\partial x_\perp}\left[\frac{h_\phi}{h_{||}h_\perp}\left(\frac{\partial(h_{||}E_{||})}{\partial x_\perp}\right)\right]-\frac{h_{||}E_{||}}{\lambda_e^2} = \frac{\partial}{\partial x_\perp}\left(\frac{h_\phi}{h_{||}h_\perp}\frac{\partial}{\partial x_{||}}(h_\perp E_\perp)\right)$$

KAW

$$+ \; e\mu_o\frac{\partial}{\partial x_{||}}\int v_{||}^2 f_e d^3v$$

Mirror force terms

$$+ \; \mu_o\frac{e}{m_e}\frac{\partial B_o}{\partial x_{||}}\int \mu_m f_e d^3v$$

$$- \; 2\mu_o\frac{e}{m_e}\frac{\partial B_o}{\partial x_{||}}\int \frac{m_e v_{||}^2}{2B_o} f_e d^3v$$

Moments of electron distribution function determined from kinetic electrons using Particle-In-Cell (PIC) techniques.

(plus auxiliary Poisson's equation to enforce quasi-neutrality)

(*Damiano et al., Phys. Plasmas, 14, 062904, 2007*)