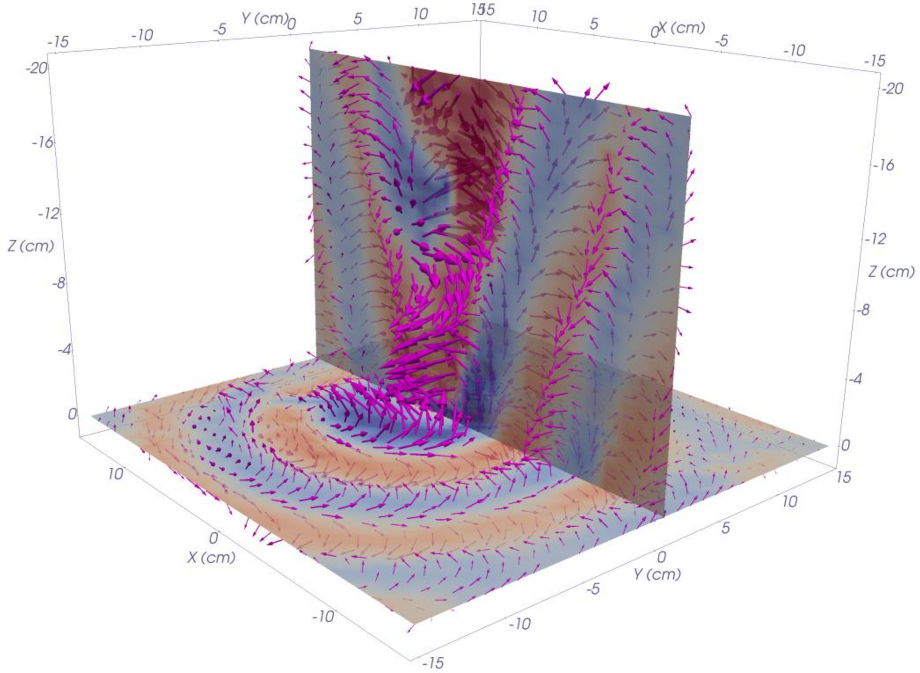
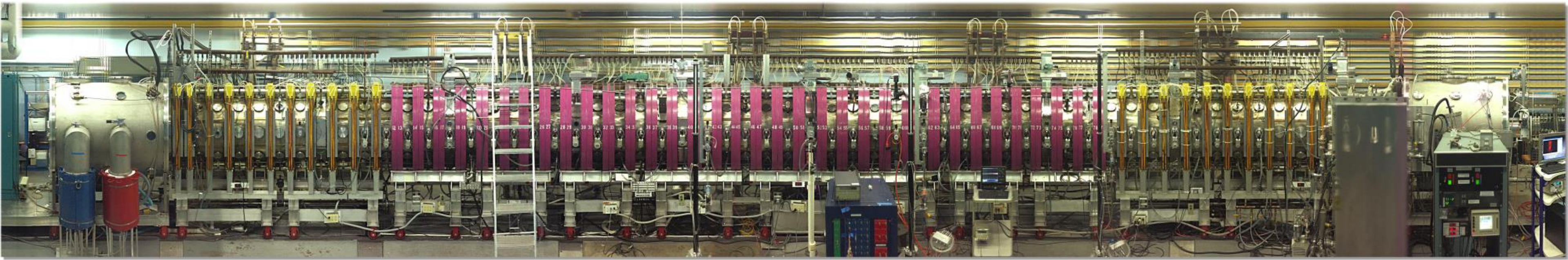
Plasma2020 Decadal Survey Meeting 2
Irvine, California
January 10-11, 2019

Perspectives on connections between experimental plasma physics and space/ astrophysical plasma physics



Prof. Jacob Bortnik
Atmospheric & Oceanic Sciences Dept., UCLA



Outline

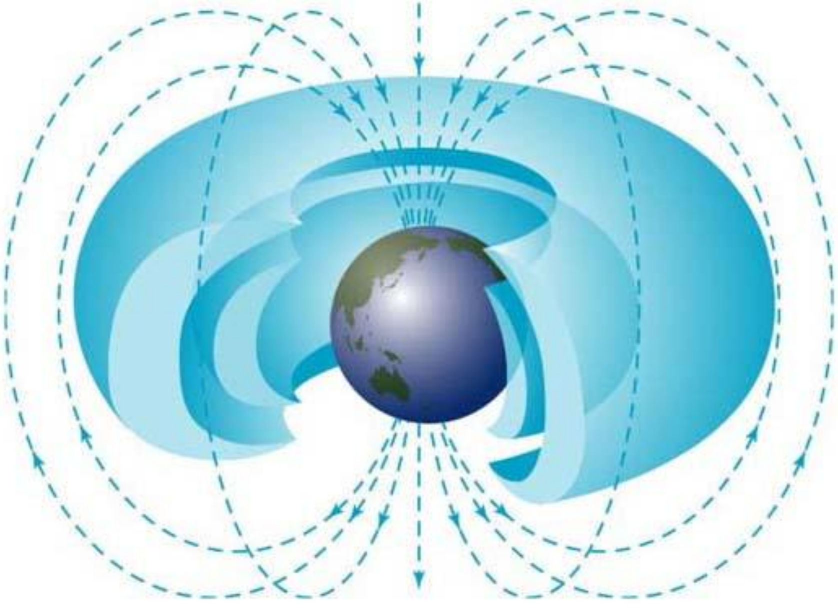
1. A brief history
    - Scientific context/motivation
    - Lab/space work at the Bortnik group at UCLA
    - A few key results
2. Where we are now
    - Current projects and results
3. Where (I think) we’re going
    - US standing in international research;
    - Role of universities; research opportunities

1. A brief history

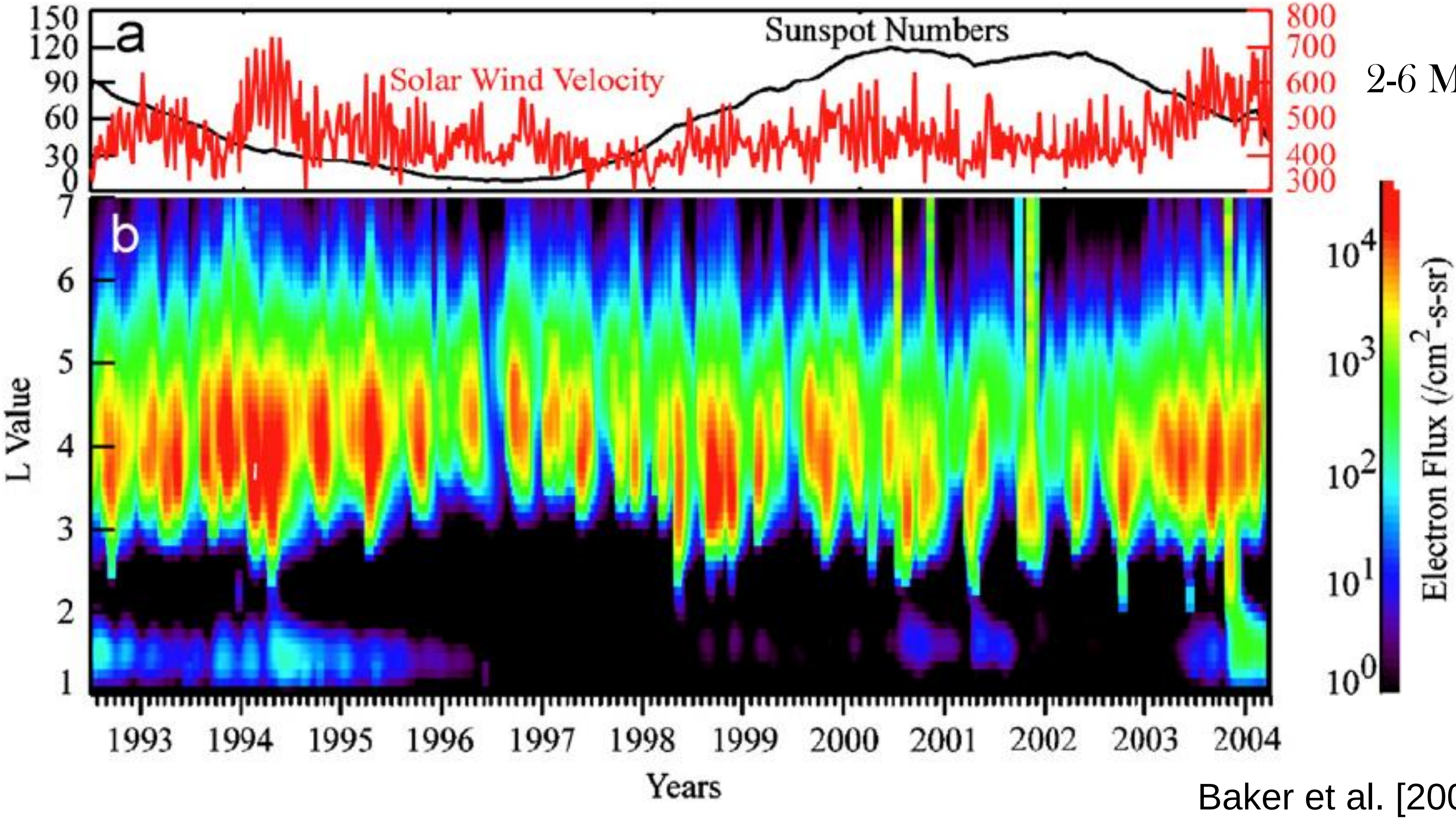
Scientific context/motivation

Explorer 1 launch:
Jan. 31st 1958

- High energy >1 MeV (“killer”) electrons
- Satellite & astronaut hazard
- Occur in 2 zones



Variability of the outer radiation belt

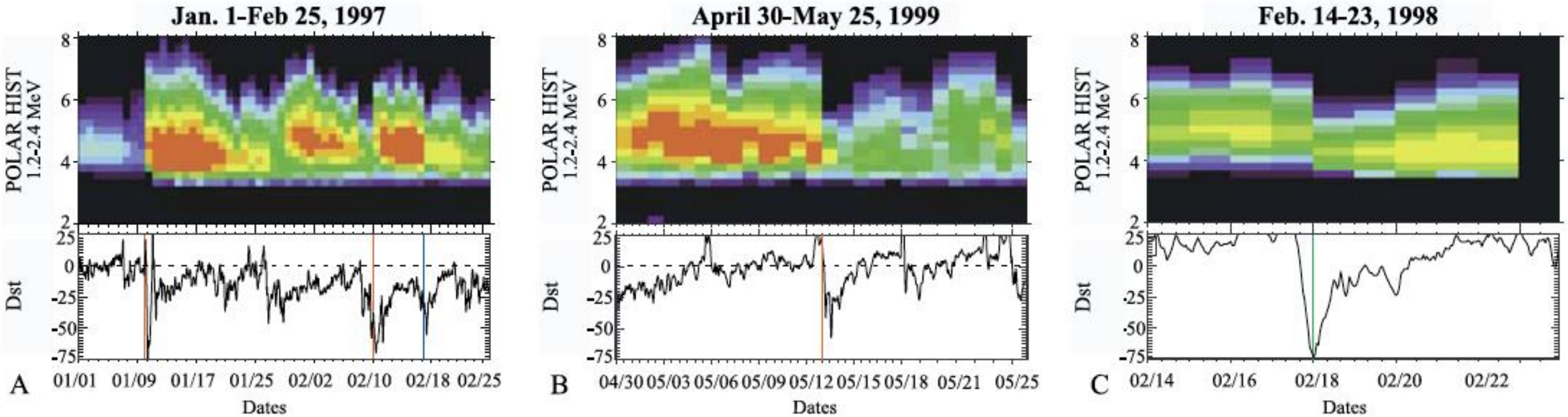


2-6 MeV

Baker et al. [2008]

Outer radiation belt exhibits variability, several orders of magnitude, timescale ~minutes.

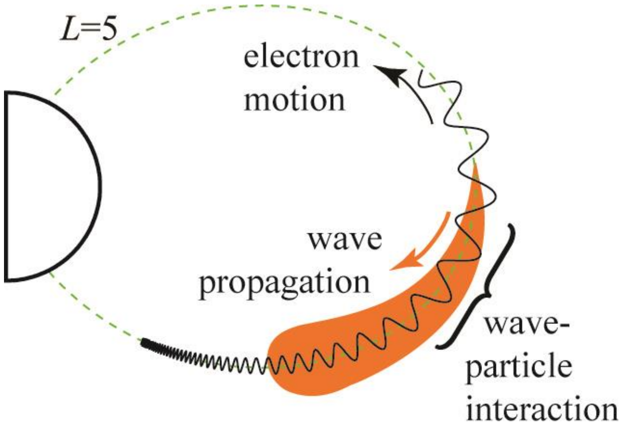
Predictability of outer belt fluxes



Reeves et al. [2003]

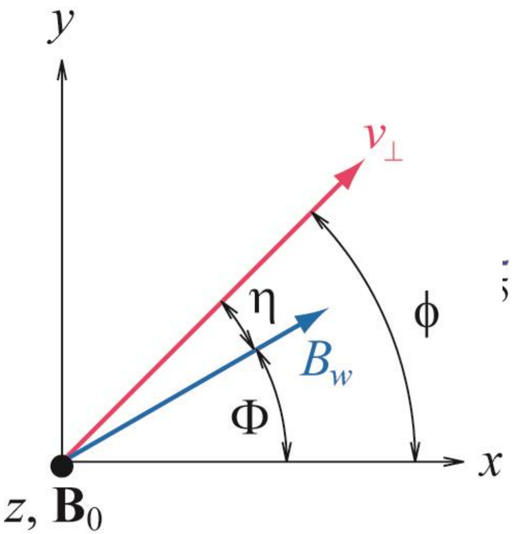
- Similar sized storms can produce net increase (53%), decrease (19%), or no change (28%). “*Equally intense post-storm fluxes can be produced out of nearly any pre-existing population*”
- Delicate balance between acceleration and loss, both enhanced during storm-time, “*like subtraction of two large numbers*”.

Wave-particle interaction equations



$$\frac{d\mathrm{p}}{dt} = q\left(\mathrm{E}_w + \frac{\mathrm{p}}{m_e\gamma}\times\left[\mathrm{B}_0(/) + \mathrm{B}_w\right]\right)$$

Example simple case: field aligned wave, non-relativistic particles



wave

$$\frac{dv_\parallel}{dt} = \boxed{\left(\frac{qB_w}{m}\right)} v_\perp \boxed{\sin\eta} - \boxed{\frac{v_\perp^2}{2B}\frac{\partial B}{\partial z}}$$

adiabatic

$$\frac{dv_\perp}{dt} = -\boxed{\left(\frac{qB_w}{m}\right)}\left(v_\parallel + \frac{\omega}{k}\right) v_\perp \boxed{\sin\eta} + \boxed{\frac{v_\perp v_\parallel}{2B}\frac{\partial B}{\partial z}}$$

$$\boxed{\frac{d\eta}{dt} = \Omega - \omega - kv_\parallel}$$

phase

When are nonlinear effects important?

"restoring" force

"driving" force

$$\frac{d^2\eta}{dt^2} + \boxed{k\left(\frac{qB_w}{m}\right)} v_\perp \sin\eta = \boxed{\left[\frac{3}{2} + \frac{\Omega-\omega}{2\Omega}\tan^2\alpha\right] v_\parallel \frac{\partial\Omega}{\partial z}}$$

$$\frac{d^2\eta}{dt^2} = \omega_t^2\left(\sin\eta + S\right) \approx 0$$

$$\boxed{\rho \approx \left(\frac{B^w}{dB_0/dz}\right)\left(\frac{2\Omega}{v}\right)\Gamma}$$

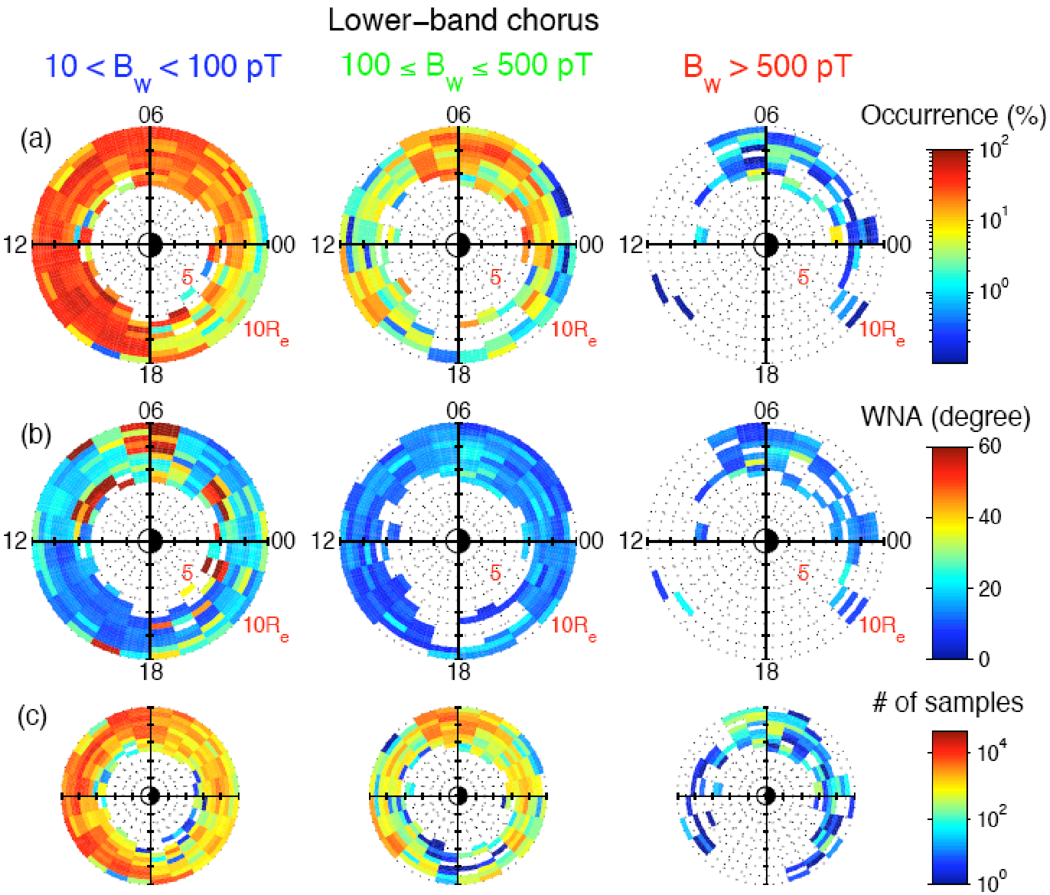
$$\Gamma = \begin{cases} \left(1 - \dfrac{\omega}{\Omega}\right)\dfrac{\sin\alpha}{3\cos^2\alpha}, & \alpha < 60^\circ \\ \dfrac{1}{\sin\alpha}, & \alpha > 60^\circ \end{cases}$$

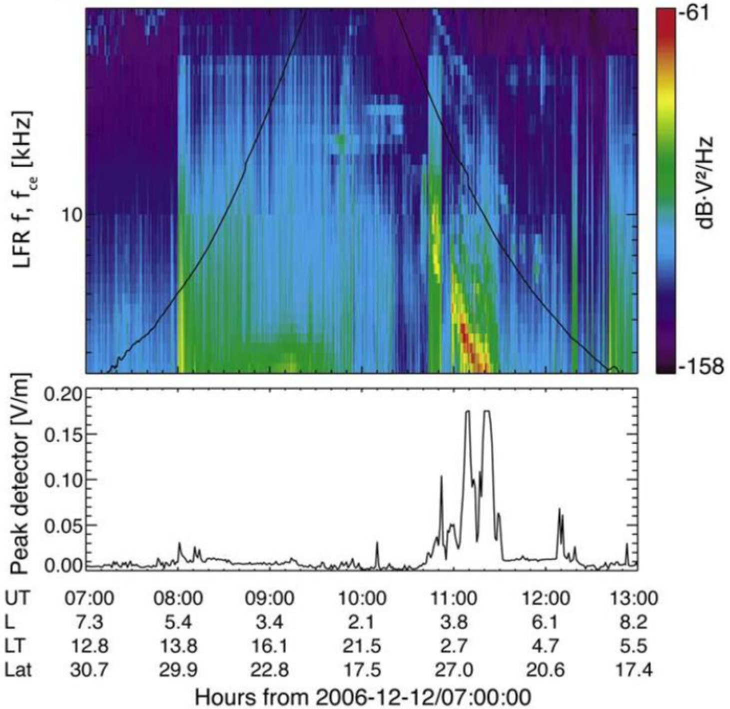
Conditions for NL:

- Waves are "large" amplitude
- Inhomogeneity is "low", i.e., near the equator
- Pitch angles are medium-high

Large amplitude whistler waves

Li et al. [2011], Burst mode observations from THEMIS: Large amplitude chorus is ubiquitous, midnight-dawn, predominantly small wave normal angles





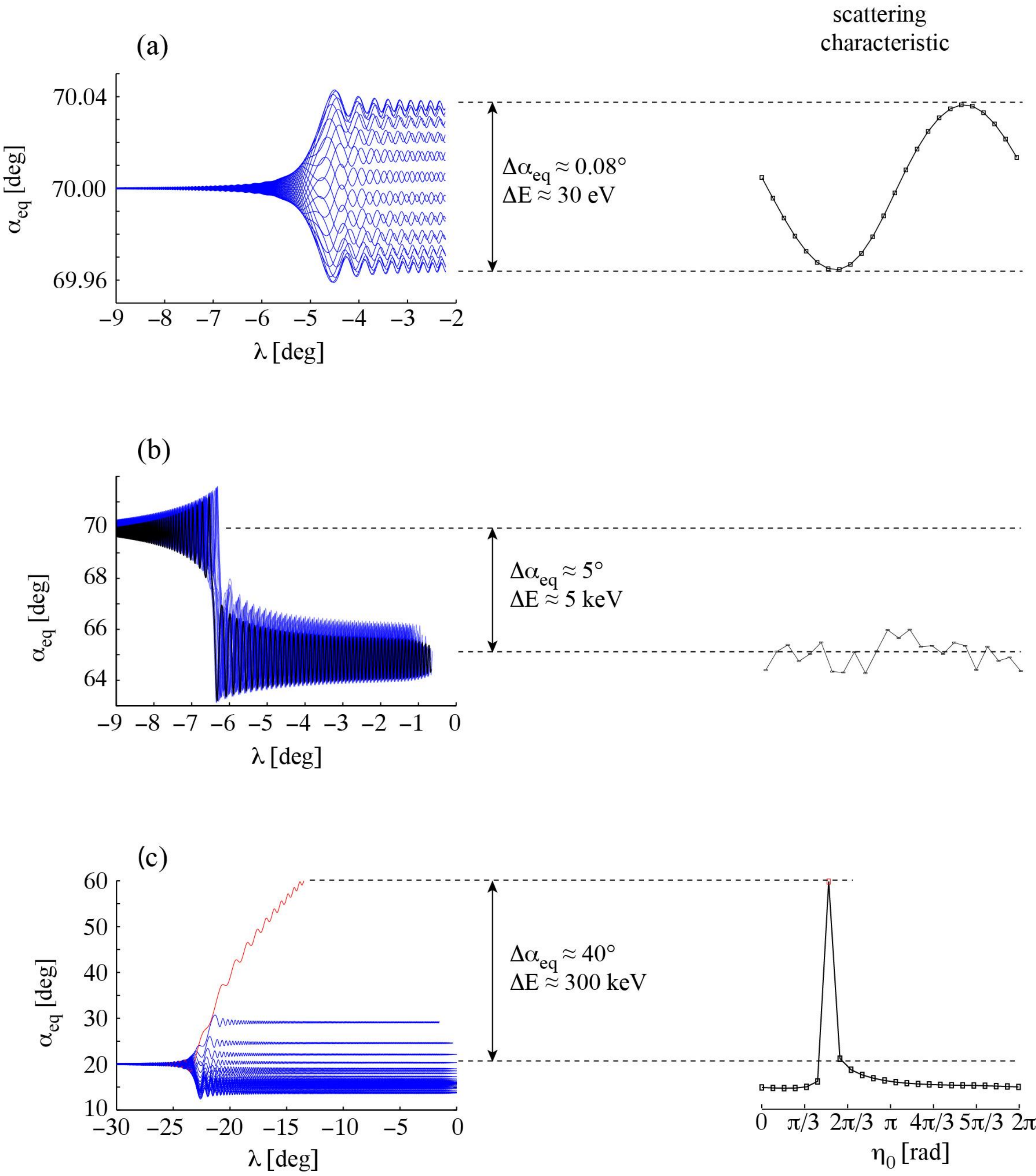
Cattell et al. [2008], First reports of large amplitude chorus, STEREO B
~ 240 mV/m, ~ 0.5-2 nT
Monotonic & coherent (f~0.2 f_{ce}, ~2 kHz)
Oblique (ψ~ 45° - 60°), Transient
L~3.5 – 4.8, MLT~2 – 3:45, Lat ~ 21° - 26°, AE ~800 nT

Three representative cases

(a) small amplitude wave

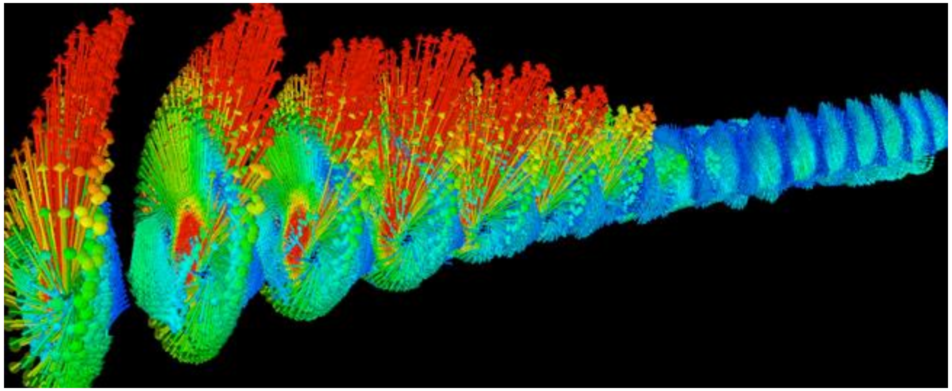
(b) Large amplitude waves

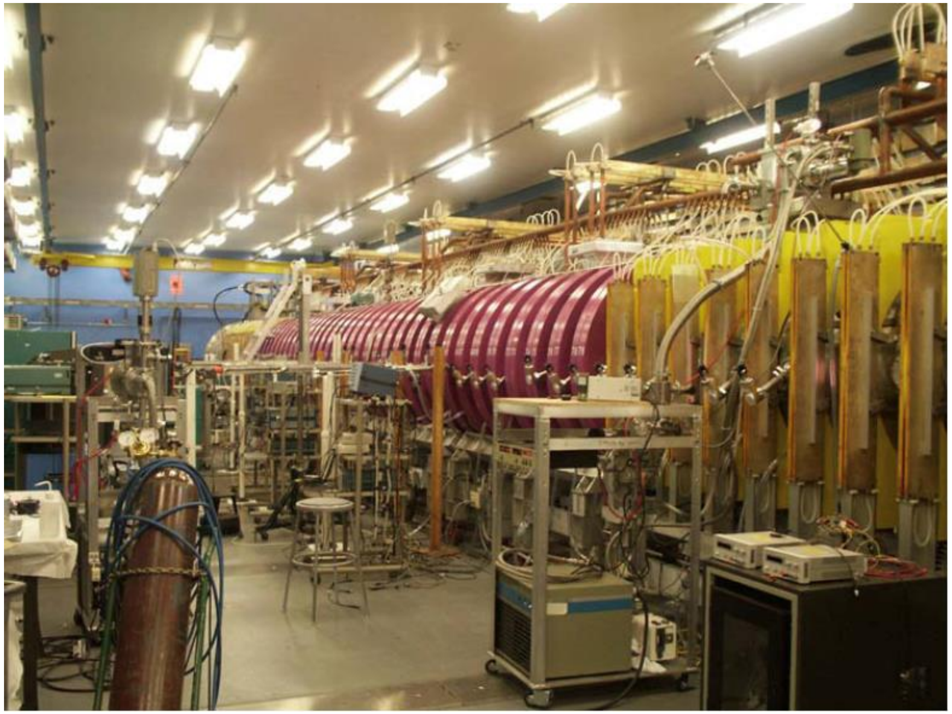
(c) Large amplitude, oblique, off-equatorial resonance



Bortnik, J., R. M. Thorne, and U. S. Inan (2008), Nonlinear interaction of energetic electrons with large amplitude chorus, Geophys. Res. Lett., 35, L21102, doi:10.1029/2008GL035500.

Large Plasma Device at UCLA





- Operated under Basic Plasma Science Facility (NSF/DOE)
- 18m long, 60 cm diam
- **B** up to 3.5 kG (0.35 T) 10 independent power supplies
- Plasma by diode switch ~1 MW, Ne>2x10^{12} cm^{-3}, Te=6-15 eV
- 450 radial ports, computer controlled scanning probes
- 20 kHz-200 MHz wave generator with 20 kW tuned RF amplifier

History of our Lab-space work at UCLA

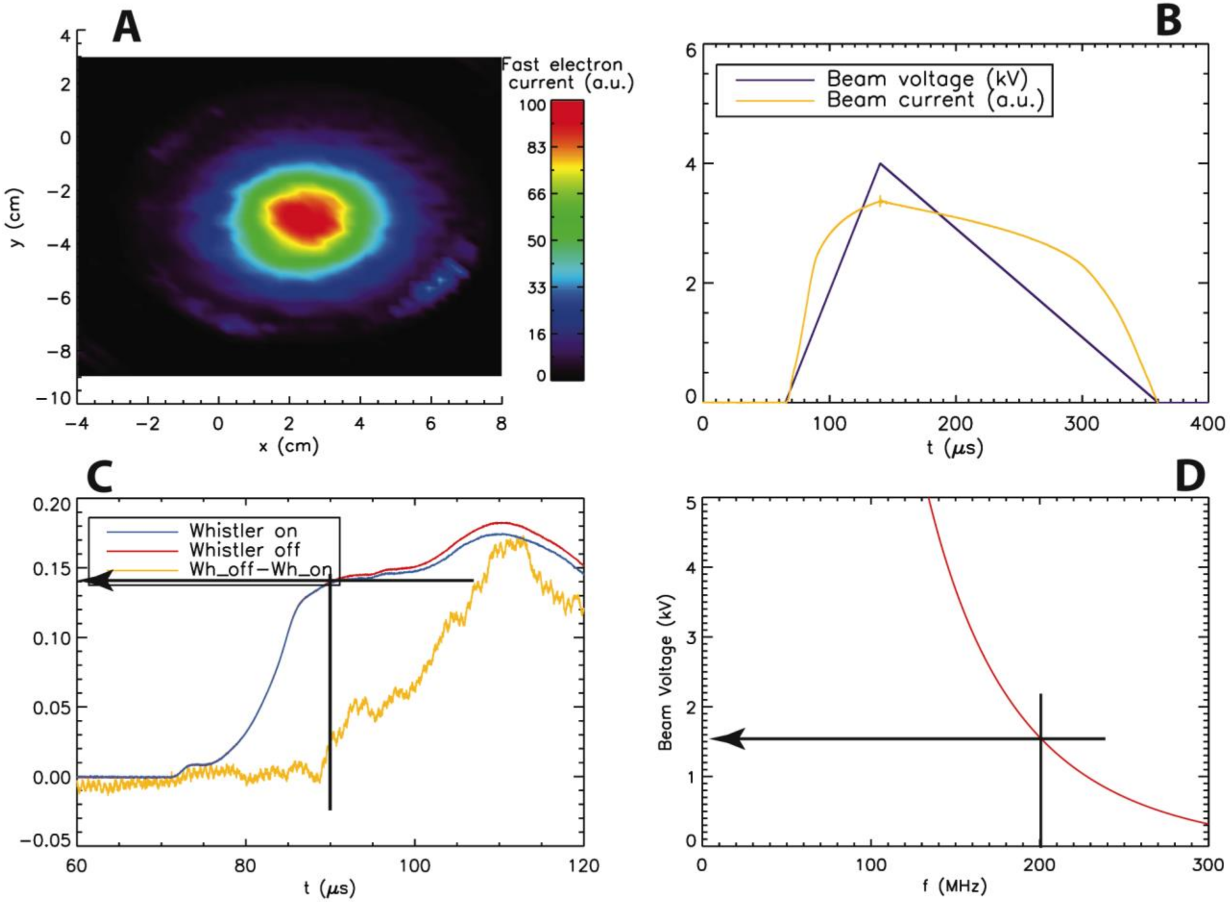
1. ATM-0903802 “Nonlinear wave-particle interactions”
    - NSF/DOE Partnership in basic plasma science and engineering (with ARRA stimulus)
    - Duration: 7/15/2009-6/30/2012 (+NCTE)
2. DE-SC0010578 “Nonlinear wave-particle interactions and excitation of whistlers”
    - NSF/DOE Partnership in basic plasma science and engineering
    - Duration: 09/01/2013-08/31/2016 (+NCTE)
3. NNX16AG21G “The relation of laboratory-generated whistler-mode waves and whistler-mode chorus waves in space”
    - NASA/HTIDeS (Heliophysics Technology & Instrument Development for Science)
    - Duration: 07/01/2016-06/30/2019 (current)

PRL **112,** 145006 (2014) PHYSICAL REVIEW LETTERS week ending 11 APRIL 2014

Direct Detection of Resonant Electron Pitch Angle Scattering by Whistler Waves in a Laboratory Plasma

B. Van Compernolle,[1,*] J. Bortnik,[2] P. Pribyl,[1] W. Gekelman,[1] M. Nakamoto,[1] X. Tao,[2] and R. M. Thorne[2]
[1]*Department of Physics, University of California, Los Angeles, California 90095, USA*
[2]*Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, California 90095, USA*

(Received 9 August 2013; published 10 April 2014)



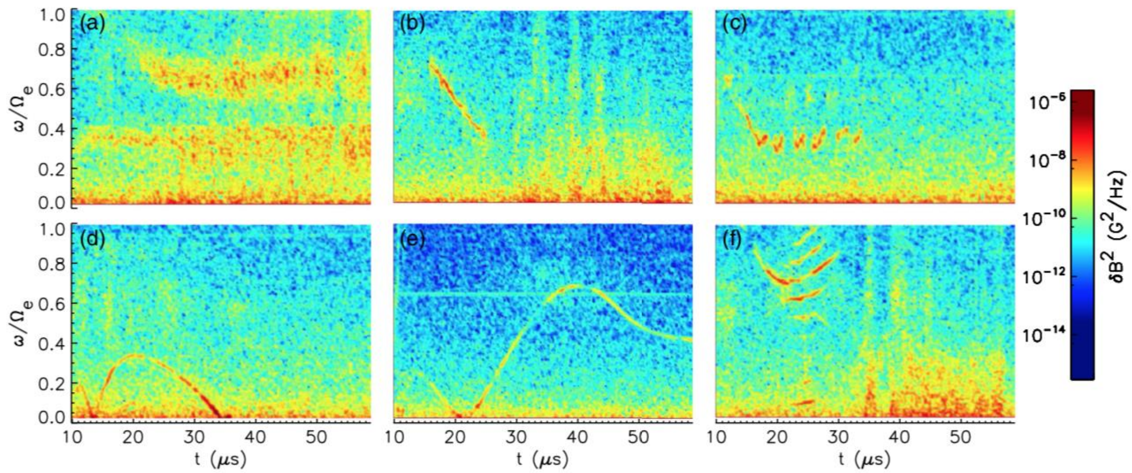
First direct detection of resonant electrons by whistler waves

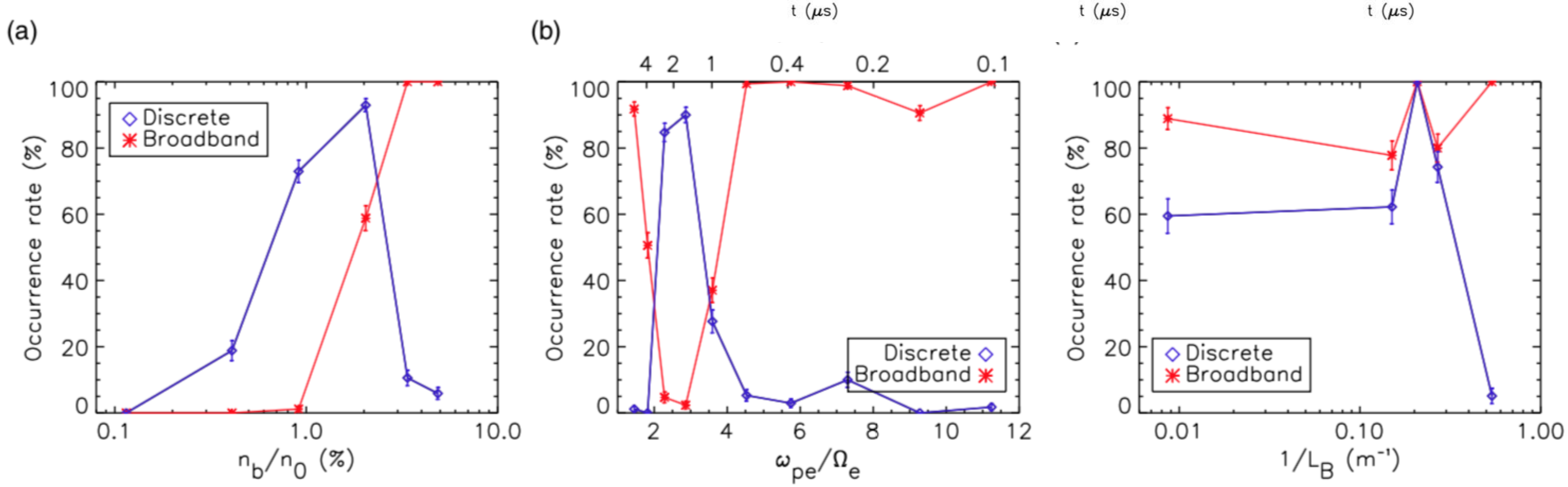
PRL **114,** 245002 (2015) PHYSICAL REVIEW LETTERS week ending 19 JUNE 2015

Excitation of Chirping Whistler Waves in a Laboratory Plasma

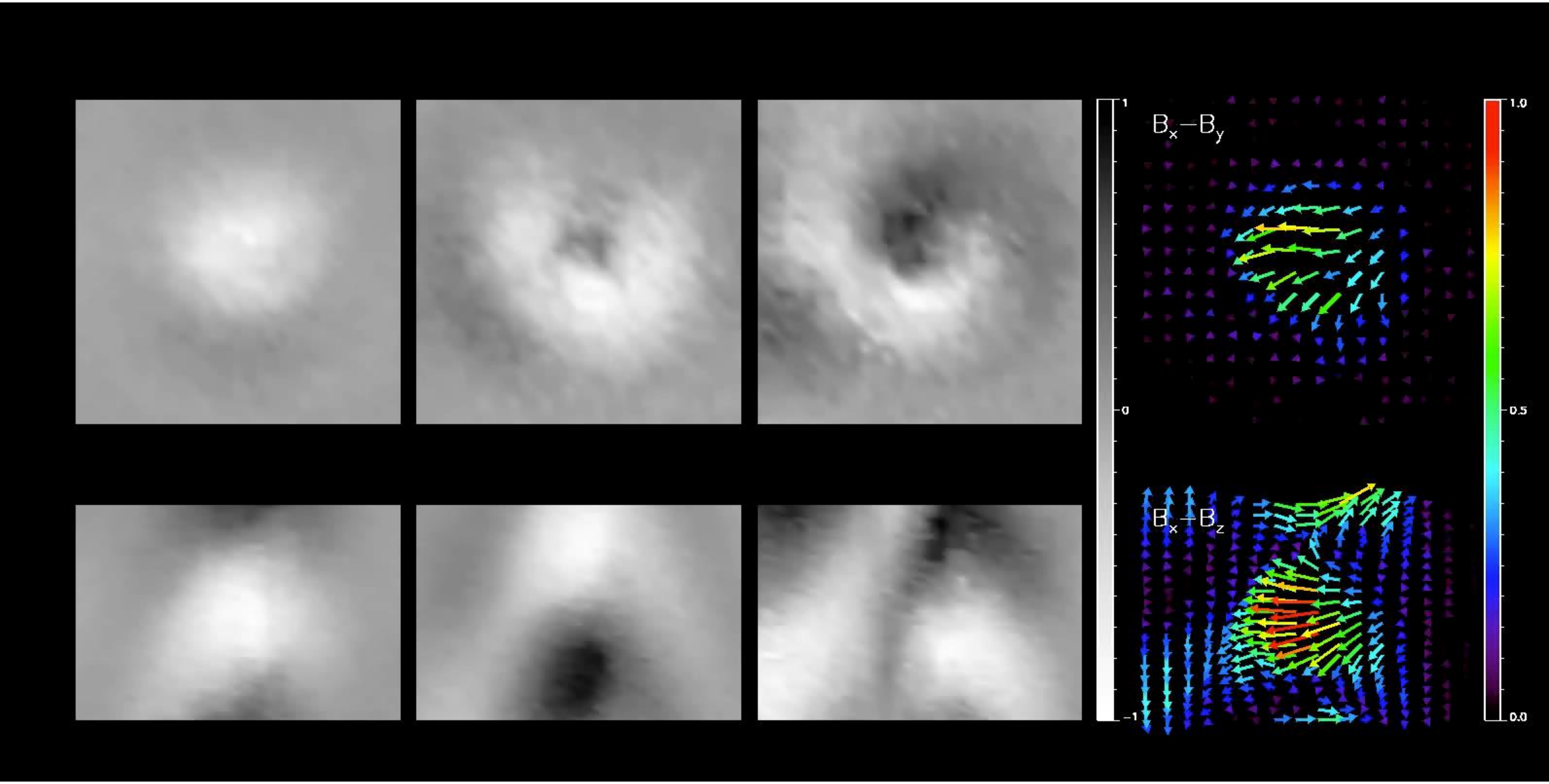
B. Van Compernolle,[1,*] X. An,[2] J. Bortnik,[2] R. M. Thorne,[2] P. Pribyl,[1] and W. Gekelman[1]
[1]*Department of Physics, University of California, Los Angeles, California 90095, USA*
[2]*Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, California 90095, USA*
(Received 3 March 2015; published 17 June 2015)

Growing chorus waves in the lab

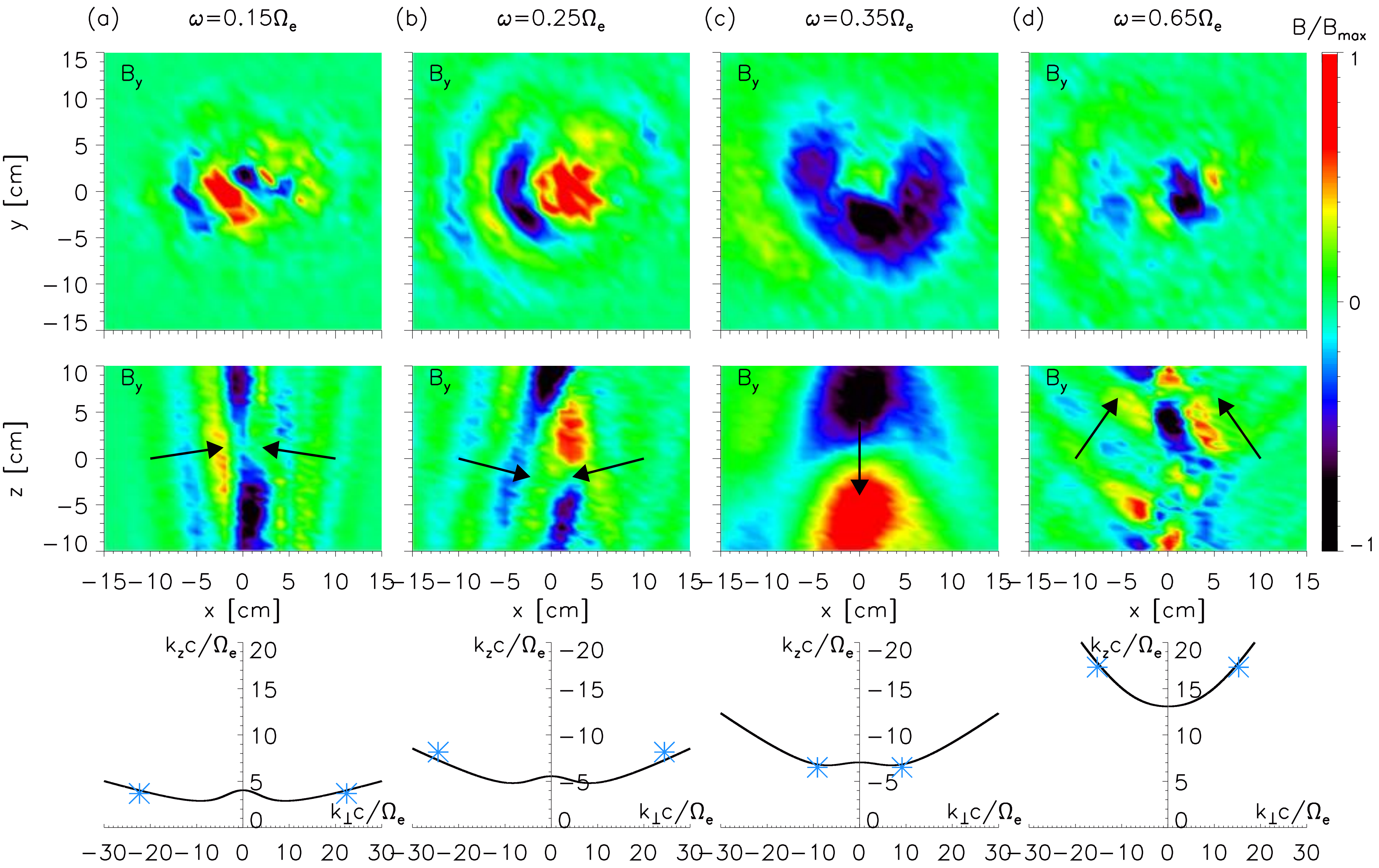




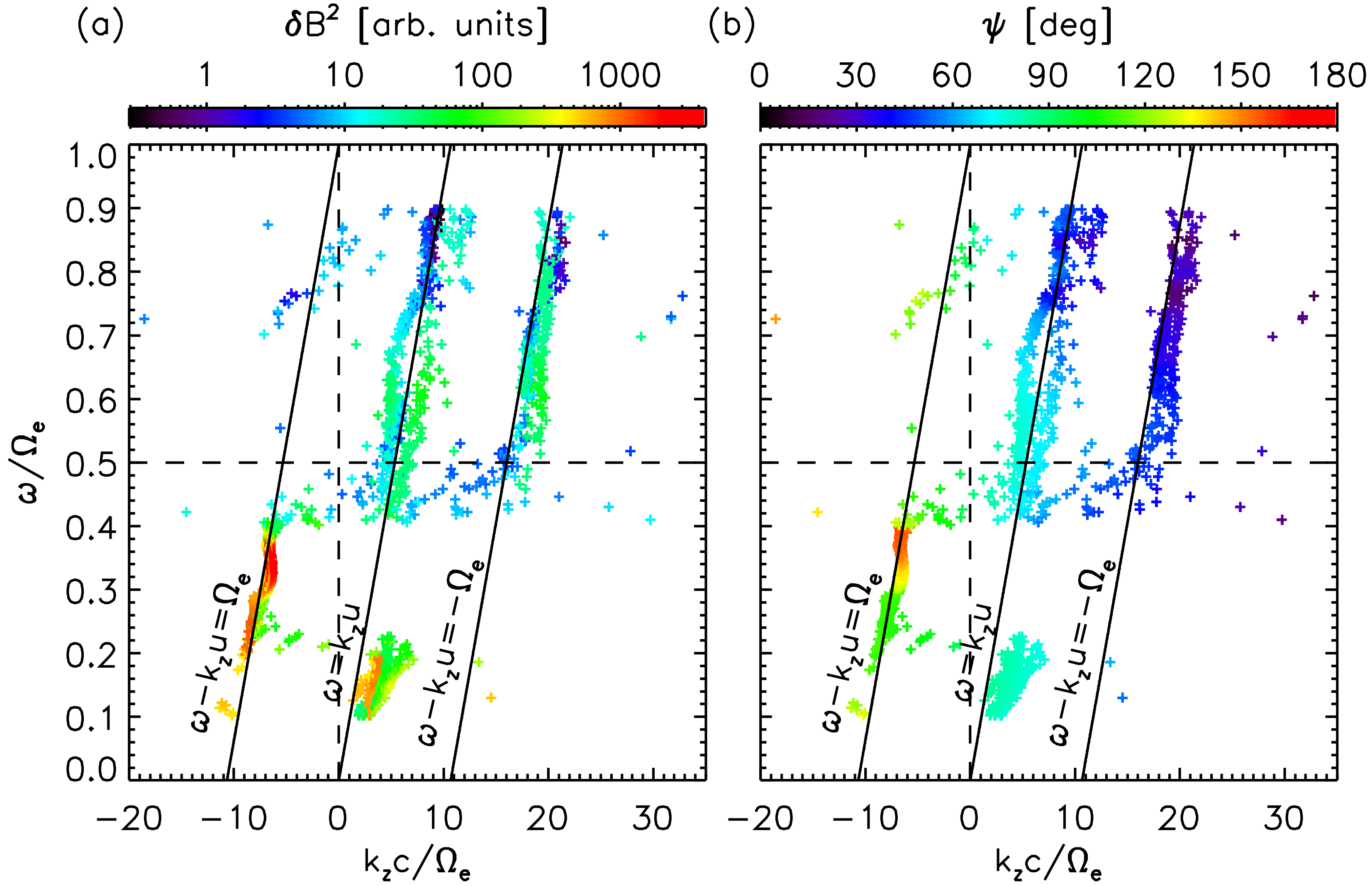
Excitation of whistler waves in the Large Plasma Device: $0.35f_{ce}$



Growing chorus waves in the lab

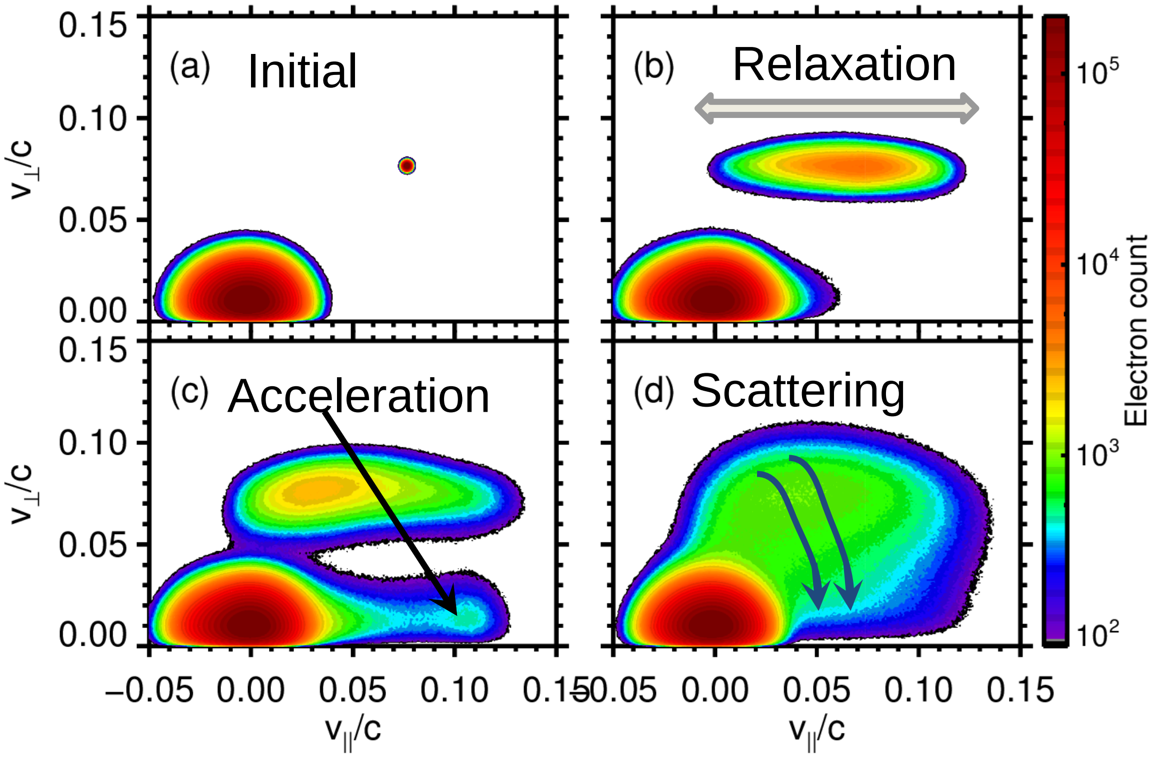


Resonant excitation!

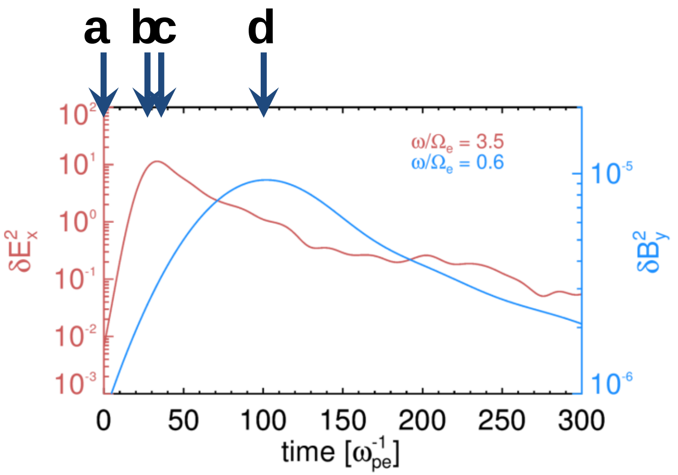


Evolution of the distribution function

The evolution of distribution function



(b) Beam relaxation by electrostatic beam-mode waves.
(c) Acceleration of core plasma by electrostatic beam-mode.
(d) Scattering by whistler waves.



2. Where we are now

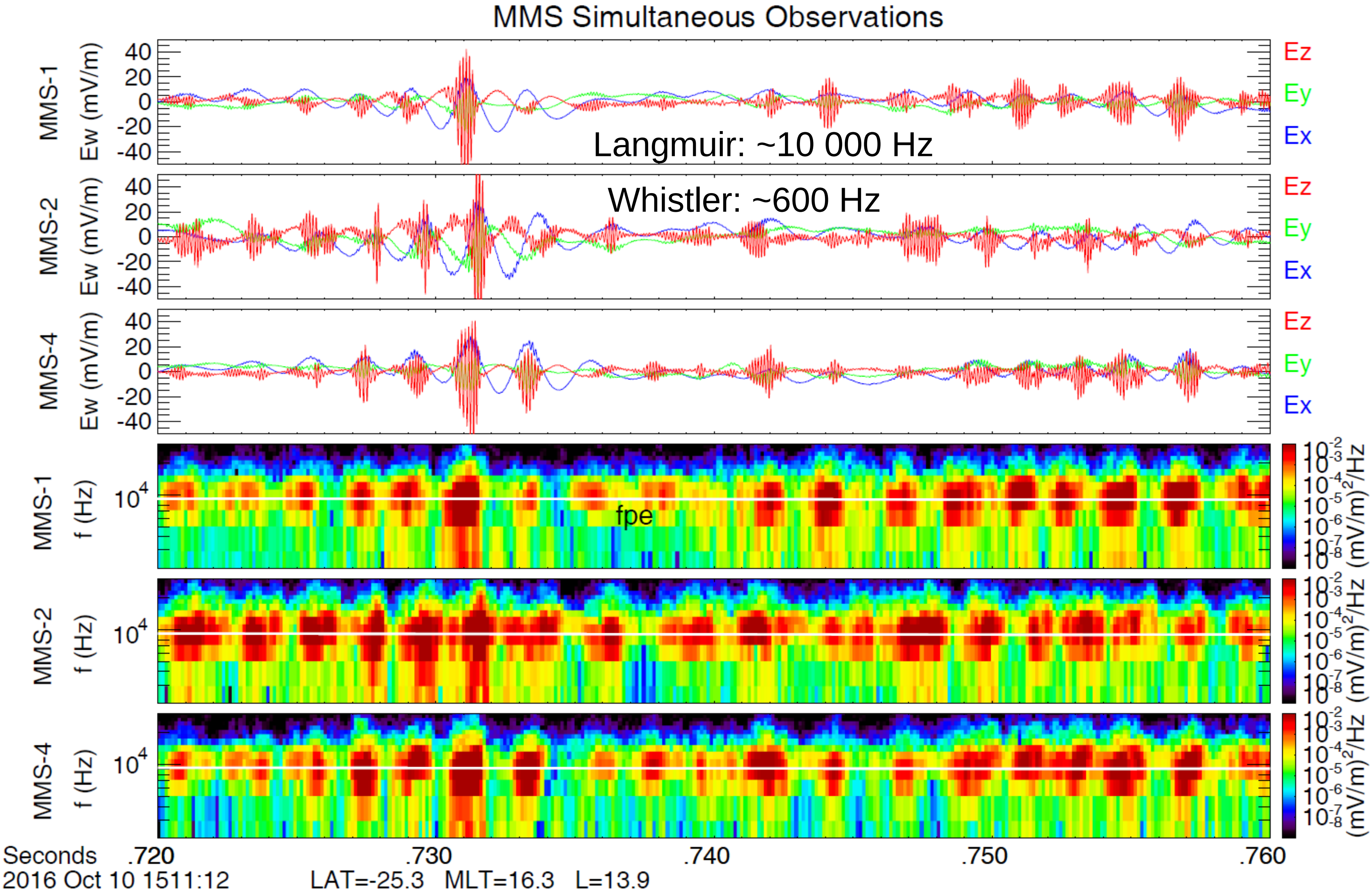
Current projects and results

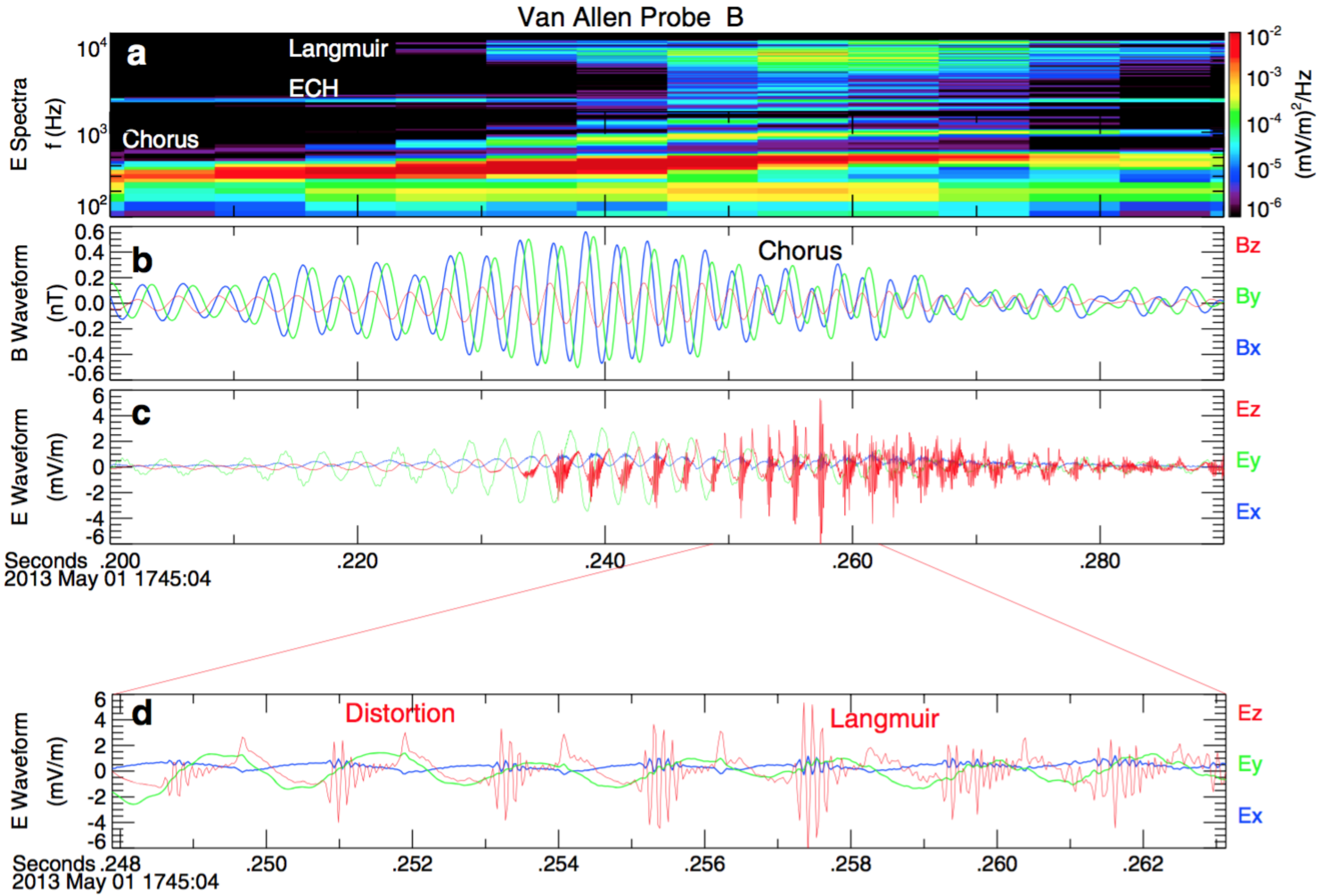
2017

SCIENCE MISSION DIRECTORATE

TECHNOLOGY HIGHLIGHTS

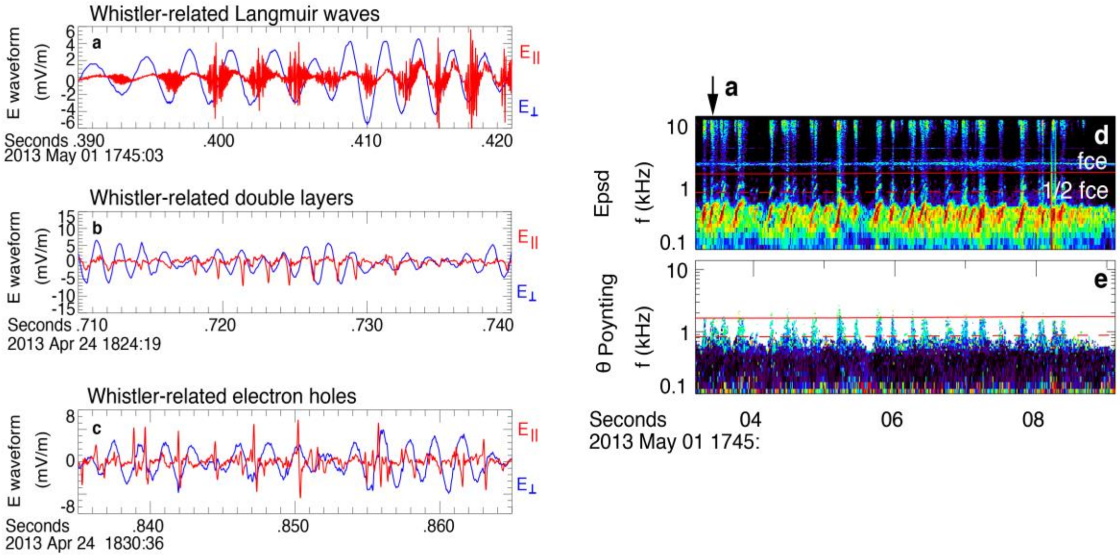
Whistler mode waves modulate Langmuir waves

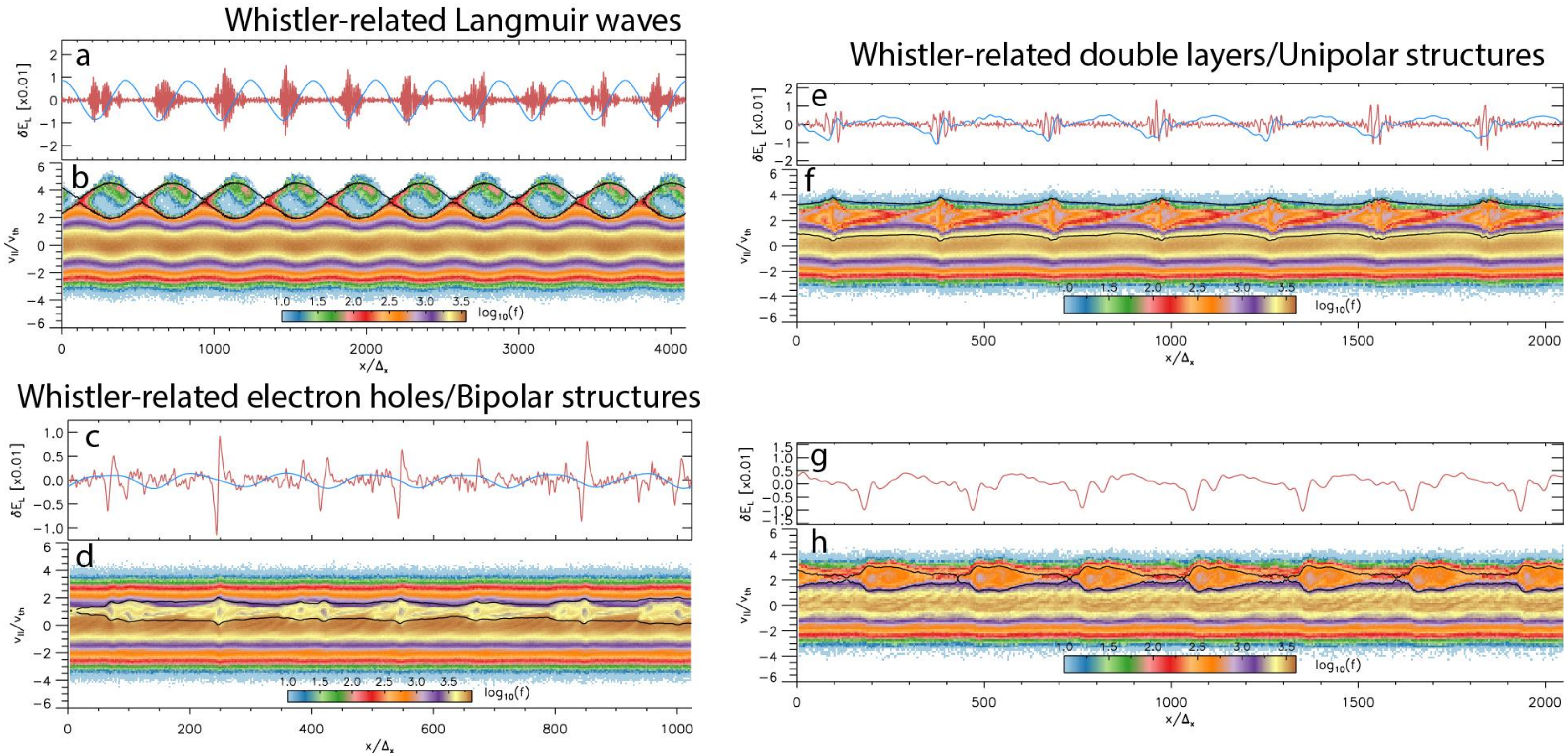




Li, J., Bortnik, J., An, X., Li, W., Thorne, R. M., Zhou, M., ... Spence, H. E. (2017). Chorus wave modulation of Langmuir waves in the radiation belts. GRL, 44, 11,713

An, X., J. Li, J. Bortnik, V. Decyk, C. Kletzing, G. Hospodarsky, A unified view of nonlinear wave structures associated with whistler-mode chorus, *Physical Review Letters* [accepted]





2. Where we are now

Current projects and results: status

- Experiments at UCLA/LAPD ongoing
  - Design/construction of 3D velocity sensor
  - 3D PIC simulations ongoing: electrostatic structures have turned into boundary problems, interesting relationship to foreshock bubbles!
- Funding is a REAL issue
  - Limited funding opportunities for space/lab work
  - NASA/LNAPP renewal declined
  - NSF/DOE program not available to us.
  - Funding ends June 2019 (maybe NCTE). No more coming!
  - Continuity of projects impacted, progress impeded.
- sds

3. Where (I think) we're going

US standing in international research (Q4)

- Recent meeting of VERSIM [J. Bortnik chair] (Apatity, Russia, March 2018): 3 other lab experiments report, none come near the technical sophistication of LAPD equipment
- Russian/international space experiments (student-led cubesat/smallsat projects) becoming comparable to US cubesats. Large projects not comparable.
- Intersection of lab-space is quite low
- Usually lab work not discussed in space physics meetings (e.g., AGU/SPA, NSF/GEM)

3. Where (I think) we're going

Role of/future opportunities of universities within large national programs (Q8)

- Grant funding structure forces universities to behave more like research labs, i.e., performance is results/outcomes based
- This results in reduced risk-taking, proposing only "safe" projects resulting in incremental results
- Hiring of postdocs preferred to grad students (~2-3 year lag before they produce results).
- Natural de-emphasis on education/training. Reduced breadth of expertise.

3. Where (I think) we're going

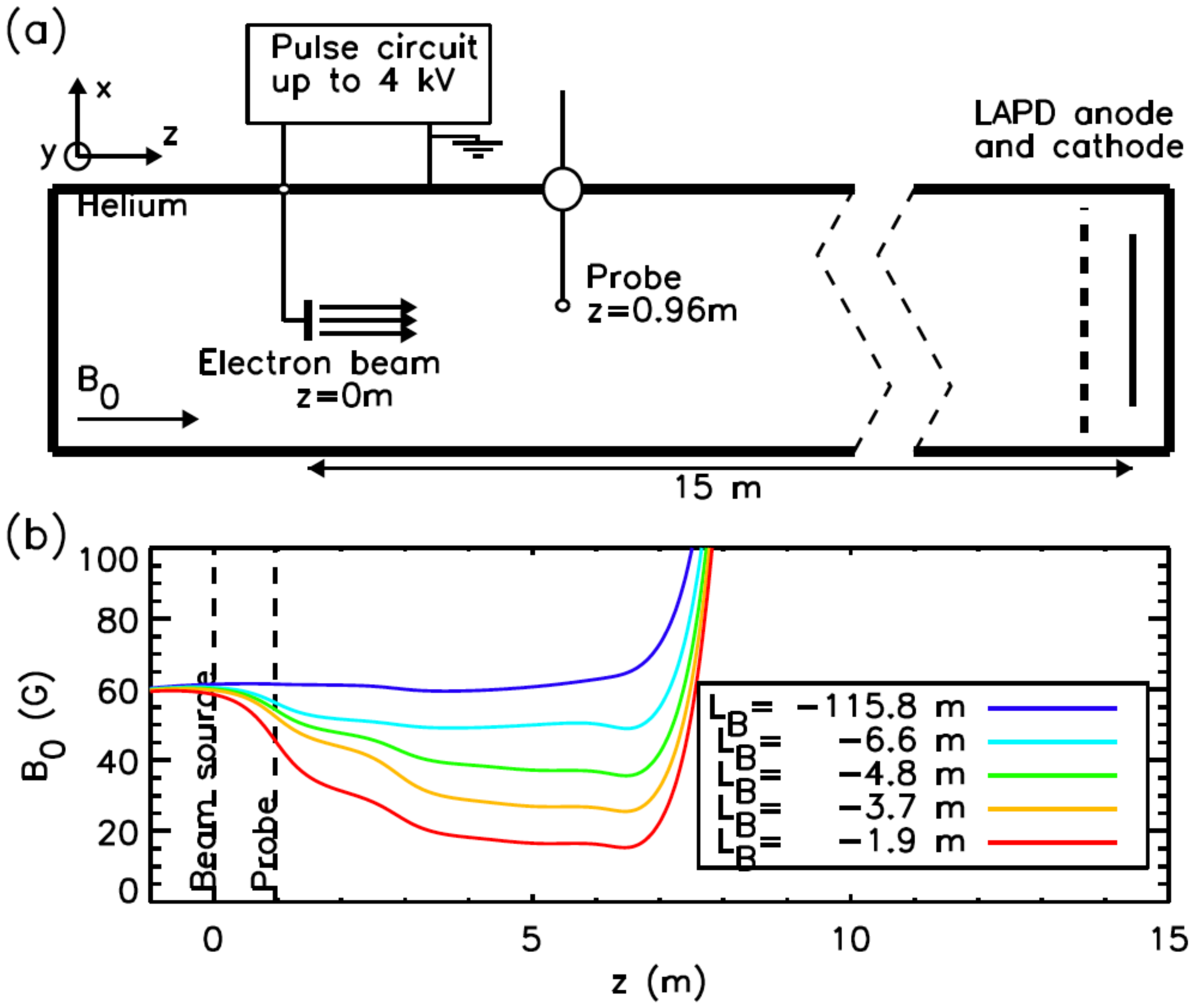
How plasma science contributes to US national needs beyond plasma science (Q6)

- Plasma science is COMPLEX (that's a good thing!)
- Students trained in fundamental disciplines, many of which are translatable skills: electromagnetism (e.g., telecoms, optics, electric power generation), numerical/computing skills (critical for the 21st century), math proficiency, fundamental physics & thermodynamics, problem solving.
- Plasma science itself critical in various applications such as astrophysics, space physics/weather, integrated circuits (nanoelectronics), energy production (e.g., fusion), propulsion, etc.

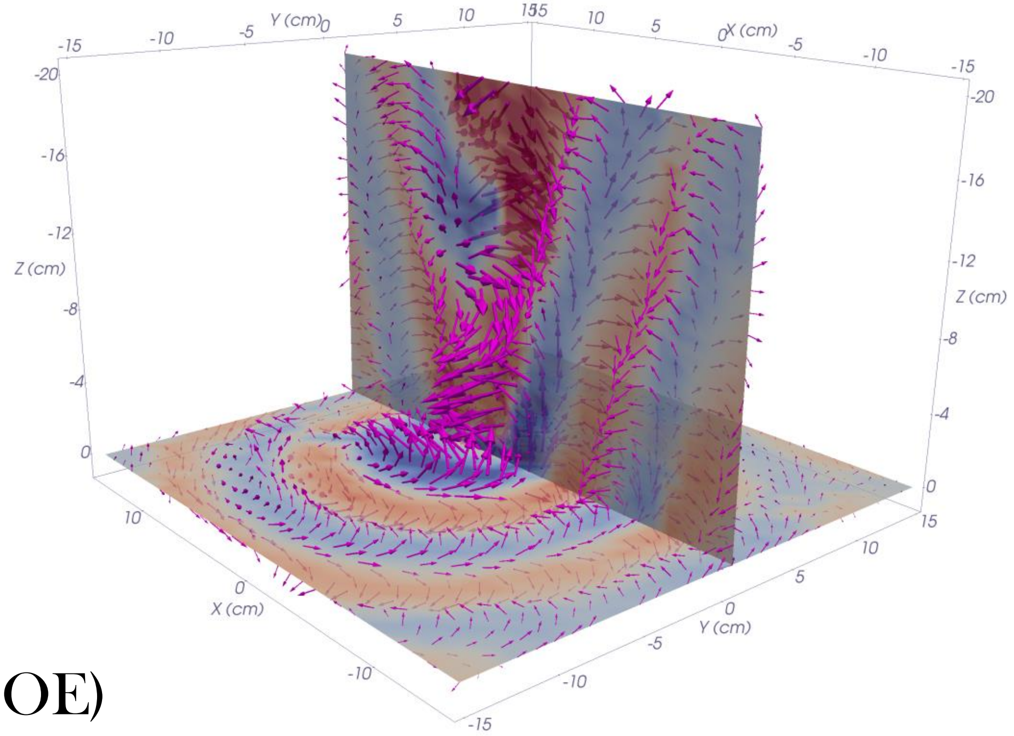
Summary

- Laboratory plasmas form a complementary way to probe whistler wave excitation and properties in space
  - Detected resonant energetic electron scattering due to whistlers
  - Created & studied first chirping whistler waves in lab
  - Discovered the unifying mechanism linking whistler-modulated electrostatic structures
- Laboratory experiments going very well, new detectors being designed/built, new areas being explored. Funding is a REAL issue for continuity and progress.
- Future: we are currently in excellent position internationally; plasma science is applicable in itself, and as a training tool for essential skills. The economics don't optimize for education and should be re-thought.

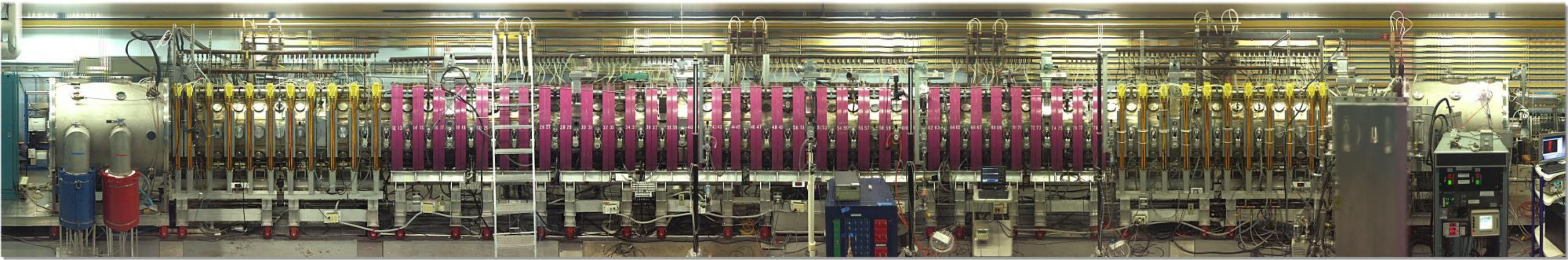
Experimental setup



Fundamental wave-particle interactions



- Large plasma device (LAPD at UCLA, operated under Basic Plasma Science Facility (NSF/DOE)
- 18m long, 60 cm diameter, extremely accessible for measurements, 450 radial ports, computer controlled scanning probes
- First observation of resonant electron scattering by whistler waves [Van Compernolle et al., 2014 *PRL*]
- First laboratory excitation of whistler-mode ‘chorus’ elements.



Conceptual model

When propagation direction of whistler waves changes orientation, the Langmuir waves get excited on the opposite phase.

Conceptually, this could be due to parallel electron beams accelerated by whistler $E_{||}$ which then relaxes and forms Langmuir waves.