Electron acceleration and ionization fronts induced by high frequency plasma turbulence

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Bengt Eliasson

ABP Group, Physics Department, SUPA
Strathclyde University, UK

Collaborators:
G. Milikh, K. Papadopoulos, X. Shao, U. Maryland
E. V. Mishin, Air Force Res. Lab., Albuquerque, New Mexico
K. Ronald, Strathclyde University, UK

Outline

A. Artificial aurora and descending ionospheric fronts in recent experiments

B. High-frequency turbulence induced by large amplitude electromagnetic waves

C. Electron acceleration by strong turbulence, ionization of neutral gas

D. Numerical full-scale modelling of turbulence, ionization and recombination

E. Scaling to laboratory experiments

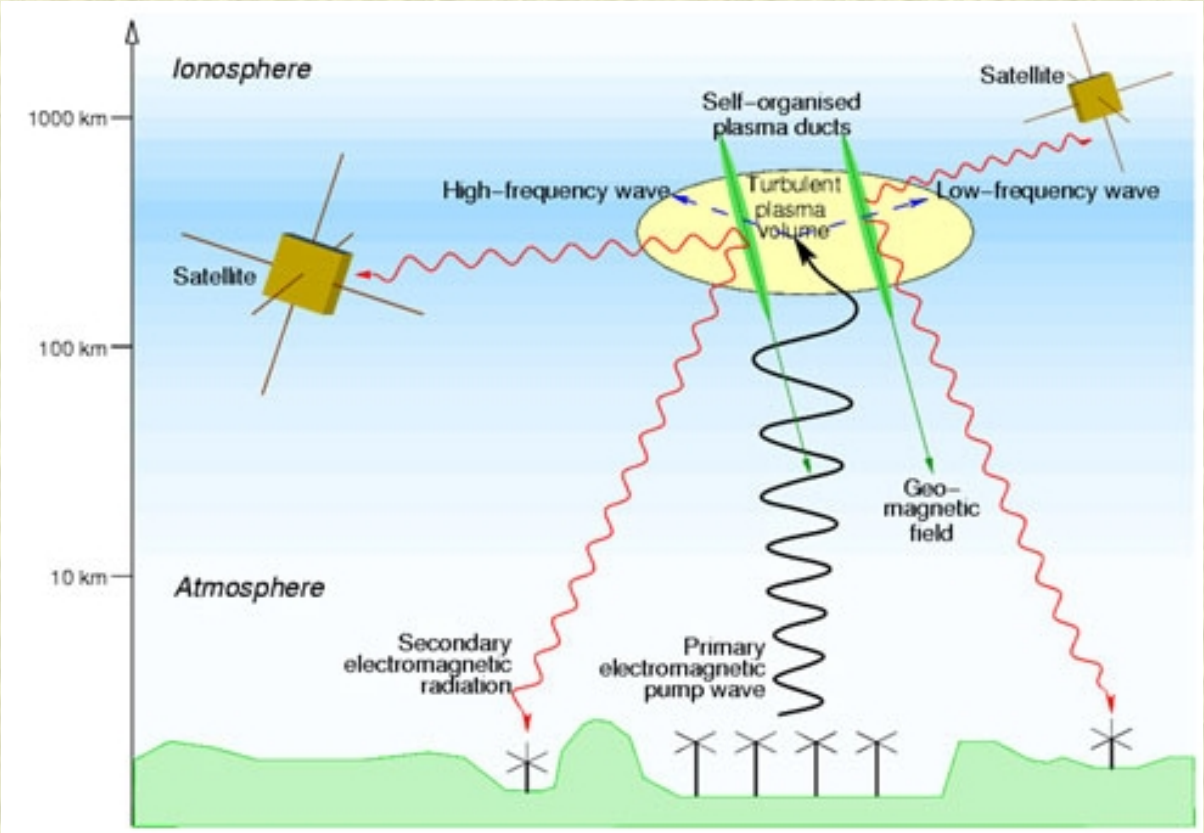
F. Summary

Natural Aurora Borealis

Photograph by Jan Curtis, near Fairbanks, Alaska

Sketch of experimental setup

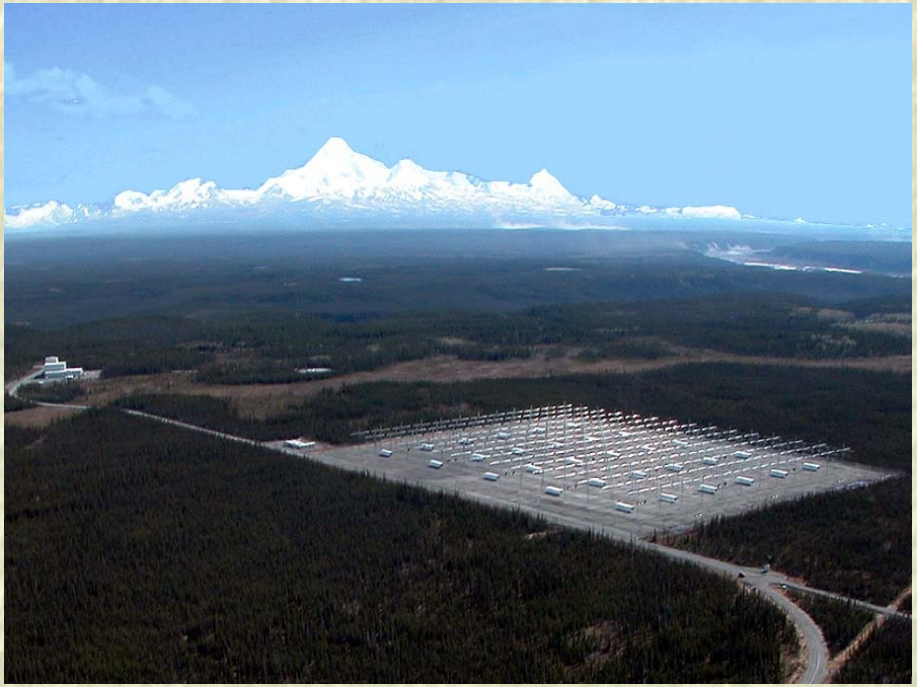
The Earth's ionosphere used as a natural laboratory to study turbulence in an unlimited magnetised plasma.



Diagnostics: Escaping radiation, radars, optical emissions, etc.

Courtesy of Bo Thidé (www.physics.irfu.se)

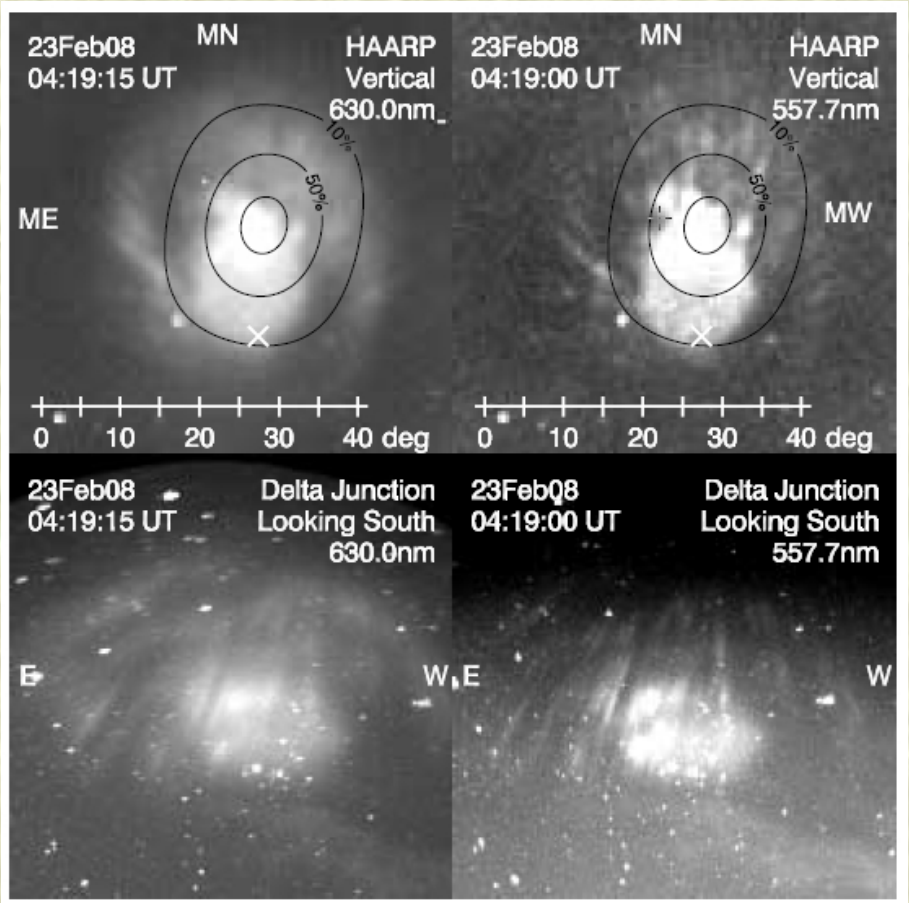
High Frequency Active Auroral Research Program (HAARP)

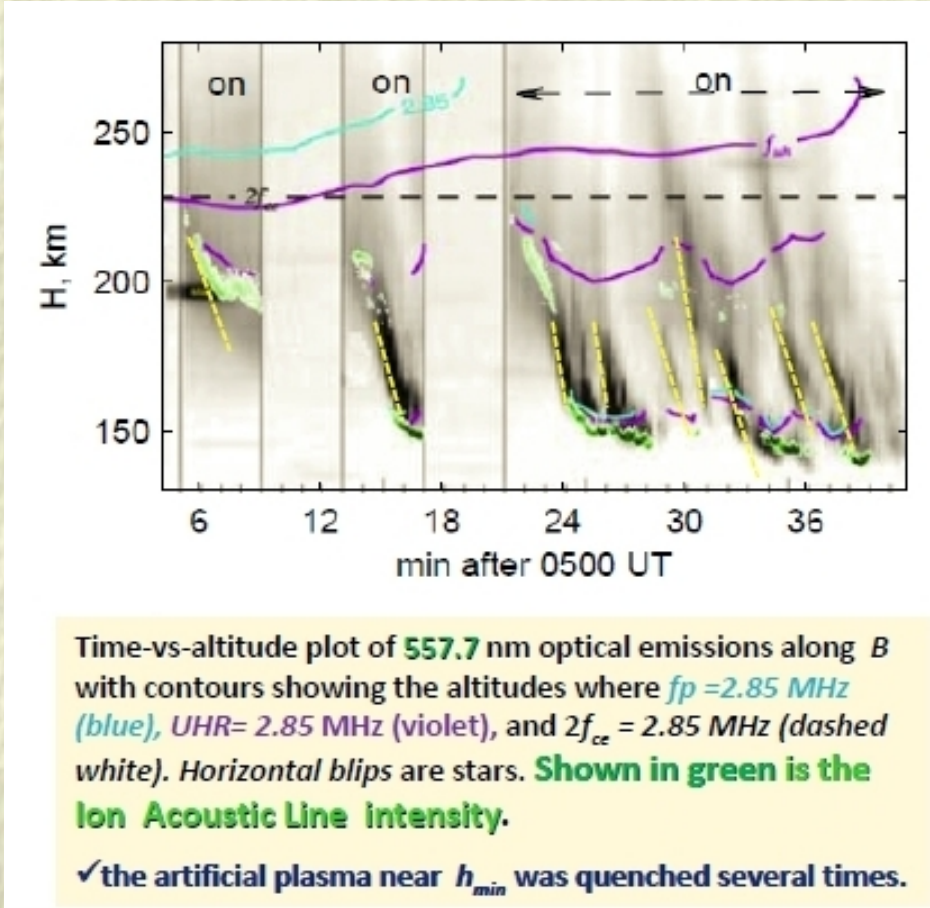


HAARP research station, near Gakona, Alaska

Established 1993, last major upgrade 2007. Designed and built by BAE Advanced Technologies.

Observations of descending aurora above HAARP

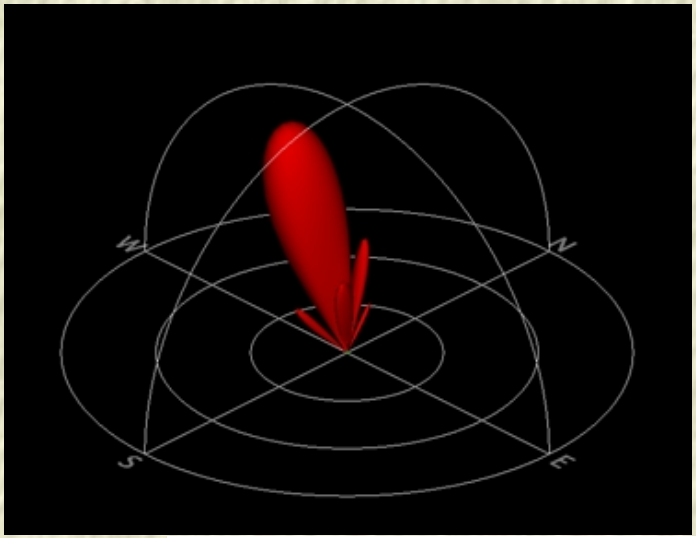


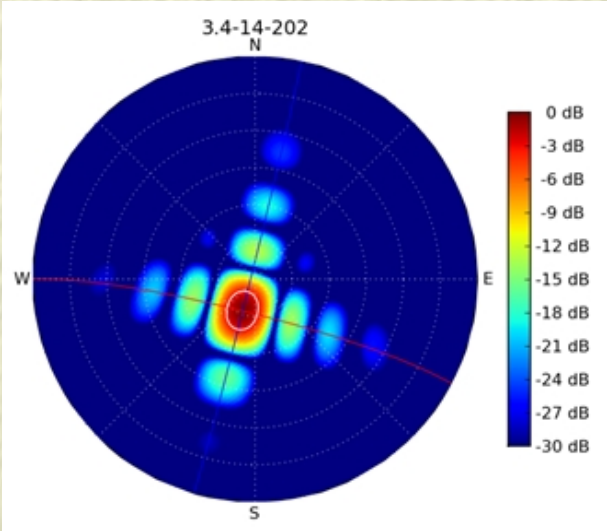


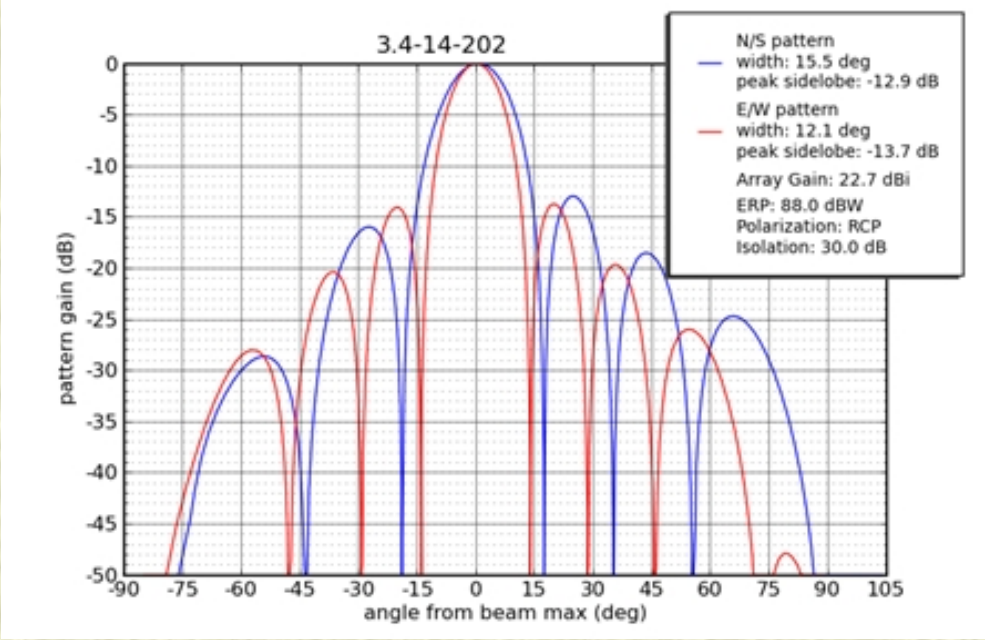
Pedersen, Gustavsson, Mishin *et al.*, Geophys. Res. Lett., 36, L18107 (2009).
Pedersen, Mishin *et al.*, Geophys. Res. Lett., 37, L02106 (2010).
Mishin & Pedersen, Geophys. Res. Lett., 38, L01105 (2011).

Radiation pattern HAARP

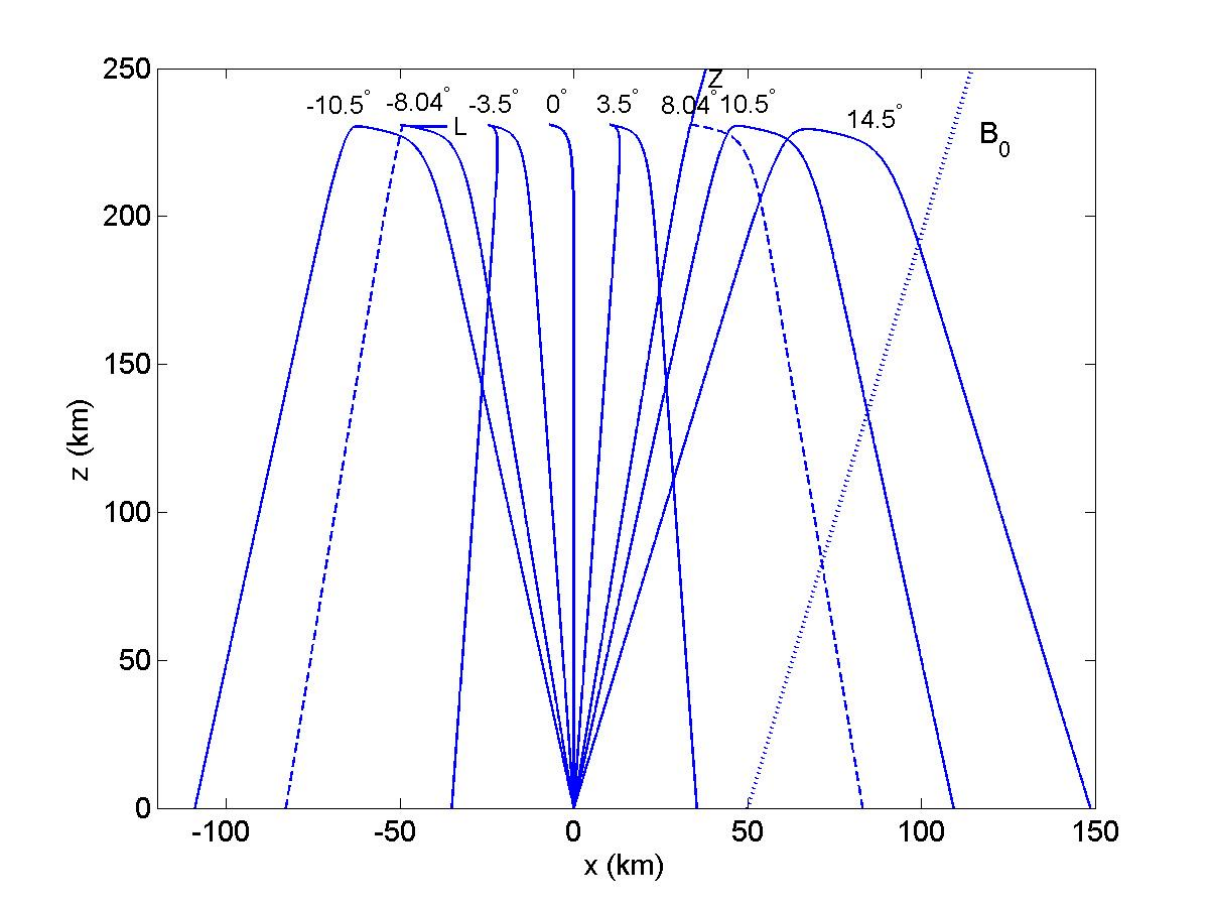
HAARP beam 3.4MHz directed along Magnetic Zenith. Beam width about $15°$.







Rays of ordinary mode waves



Ray-tracing

$$\frac{d\mathbf{k}}{dt} = -\nabla_{\mathbf{r}}\omega$$

$$\frac{d\mathbf{r}}{dt} = \nabla_{\mathbf{k}}\omega$$

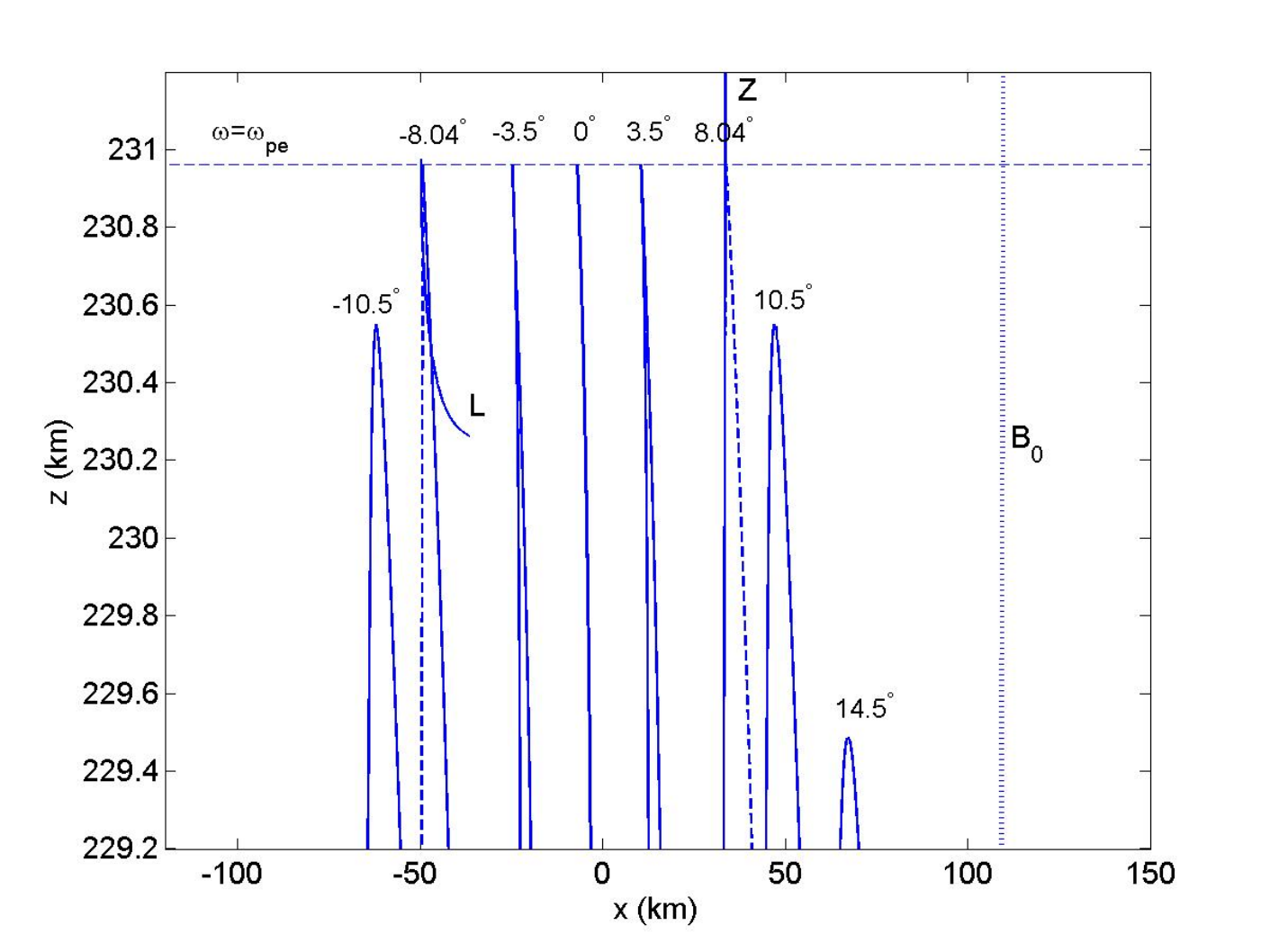
Appleton-Hartree dispersion relation gives $\omega(\mathbf{k}, \mathbf{r})$

Magnetic field $\mathbf{B}_0 = 5 \times 10^{-5}\,\mathrm{T}$, tilted $14.5°$ to vertical. Electron cyclotron frequency $f_{ce} = 1.4\,\mathrm{MHz}$.

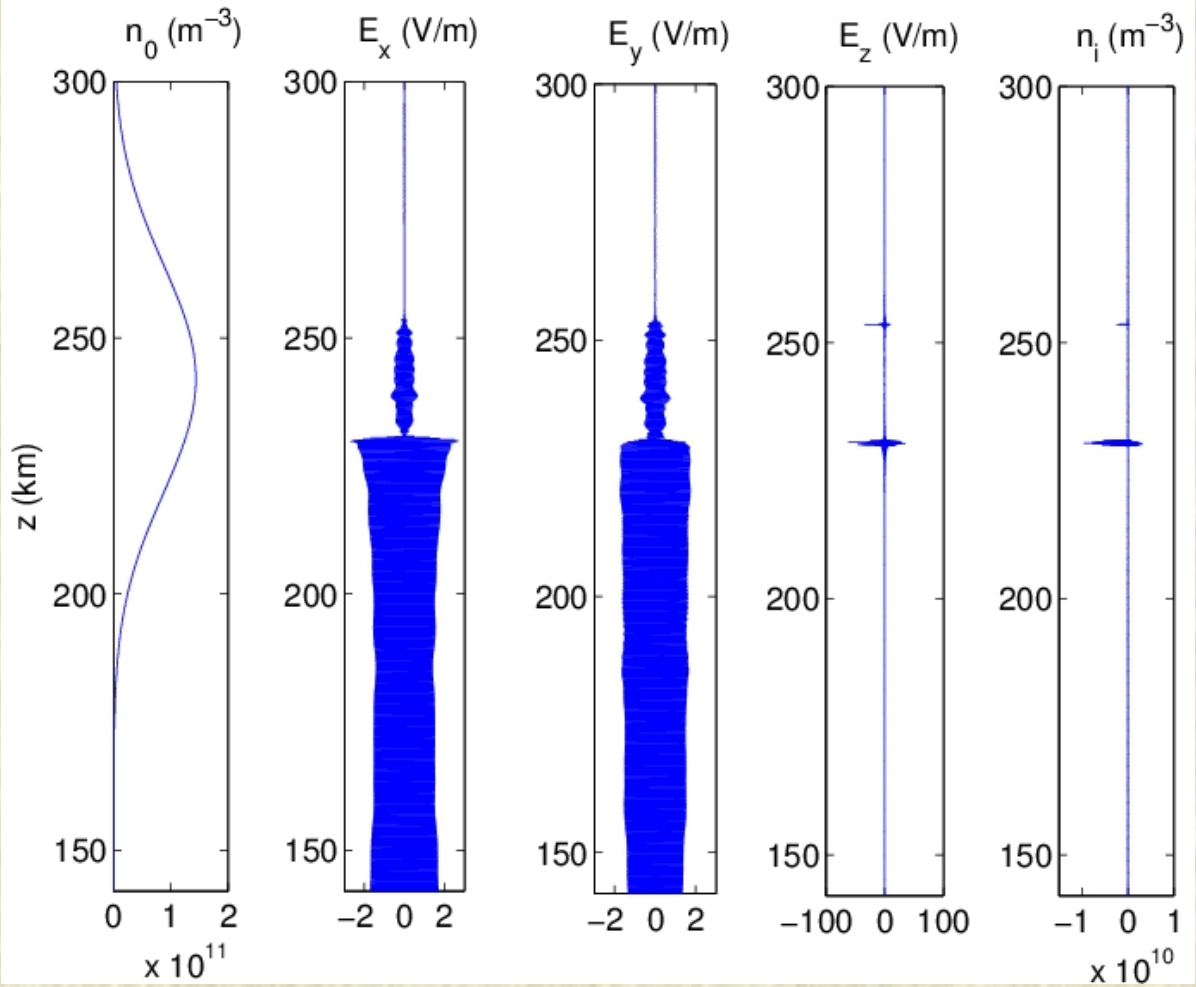
$f_0 = 3.2$ MHz transmitted frequency, ~ 100 m vacuum wavelength.

Ordinary mode waves are reflected near the critical layer where $\omega = \omega_{pe}$.

Rays closeup near reflection point



Full-wave simulation model

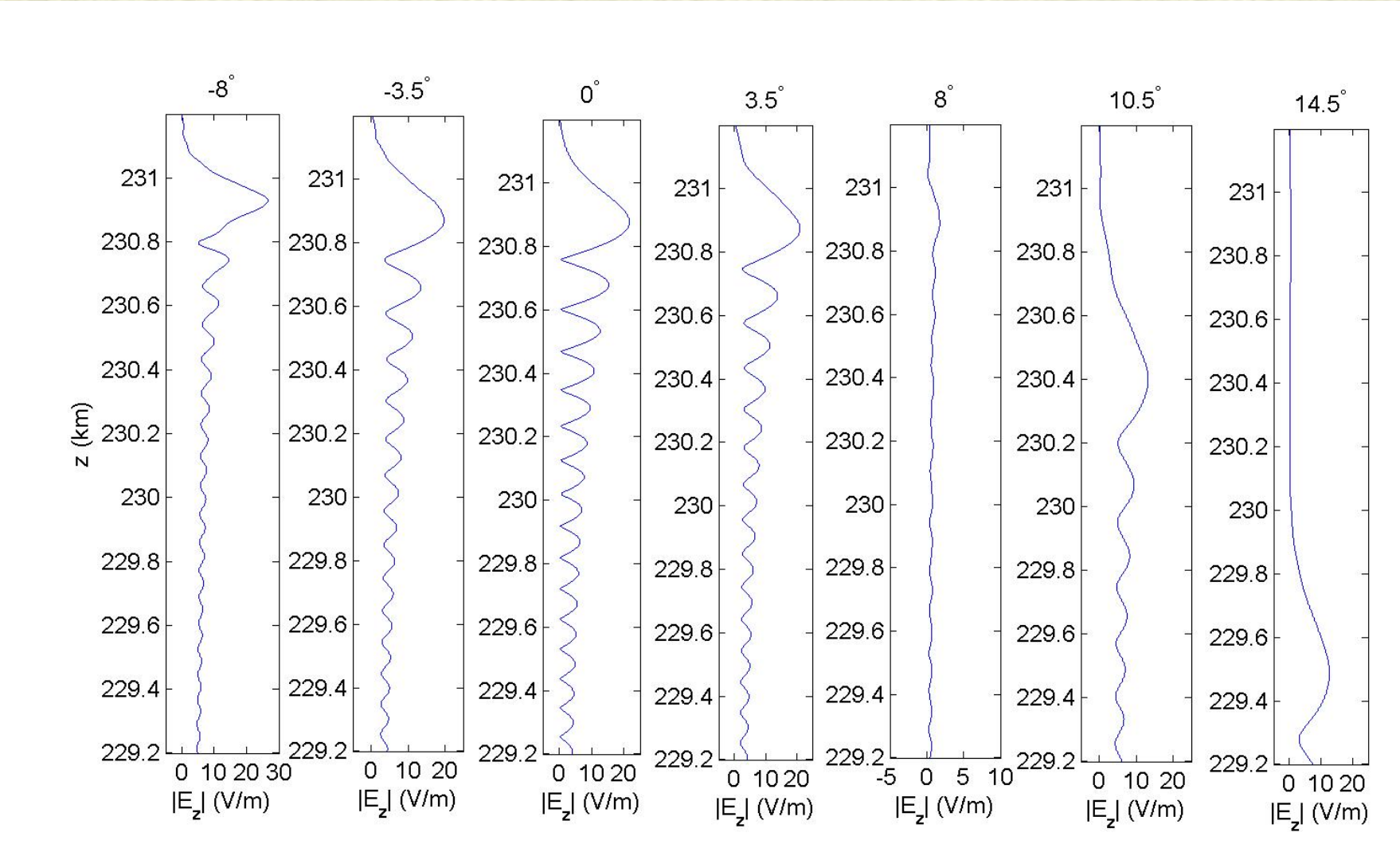


- Electromagnetic wave propagation. Inhomogeneous, magnetized plasma.
- Nonlinear coupling to electron and ion dynamics.

Standing wave pattern vertical electric field

Full wave simulations at different angles of incidence. 1 V/m injected O mode.

One millisecond after switch-on of transmitter

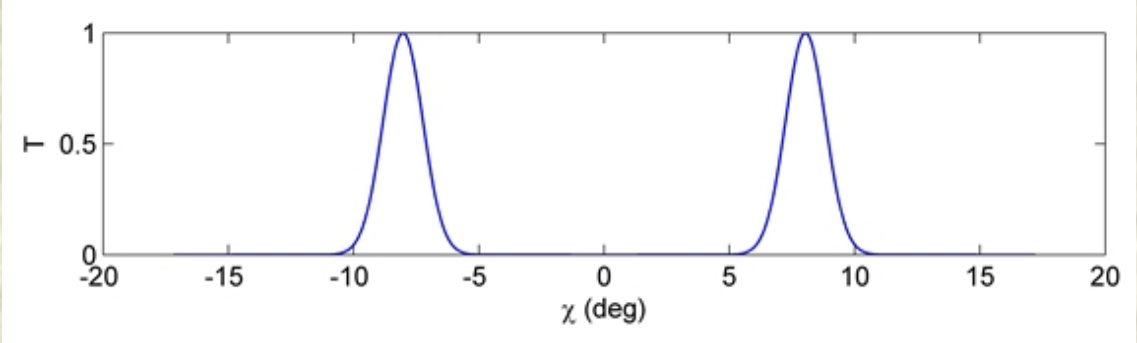


Resonant absorption — Spitze angle

Linear absorption takes place at certain angles of incidence between magnetic field angle and vertical.

$Y = f_{ce}/f_0 = 0.4$ and $\theta = 14.5°$

Spitze angles $\chi_S = \pm \arcsin[\sqrt{Y/(1+Y)}\sin(\theta)] \approx \pm 8.04°$

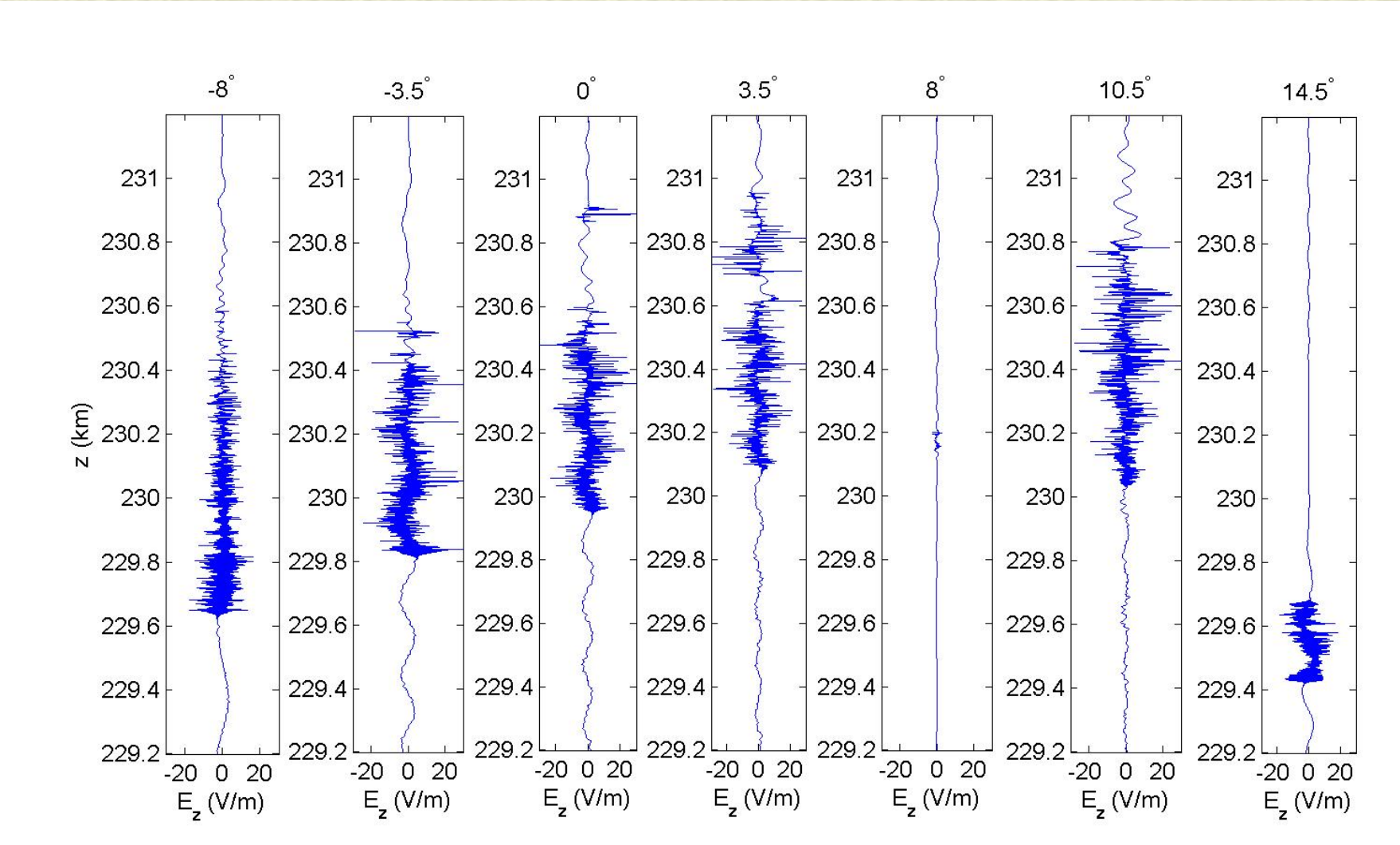


$T =$ absorbed intensity / injected intensity.

Efficient absorption within angles $\sim \pm 1°$ from Spitze $\rightarrow$ relatively small region compared to typical beam width.

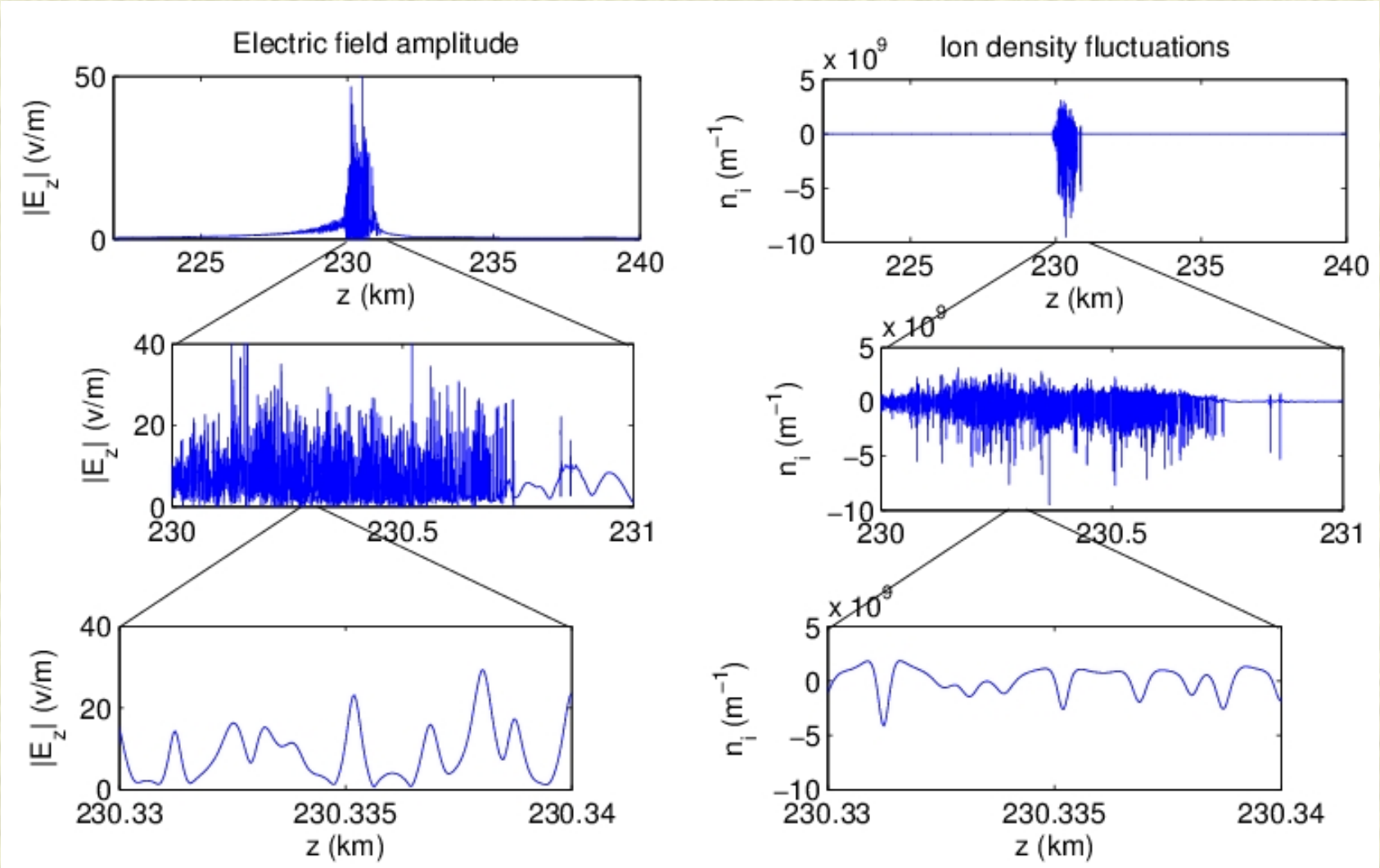
E. Mjølhus, Radio Science **25**, 1321 (1990)

10 milliseconds after switch-on: Turbulence



Coupling between high-frequency electron plasma waves and low-frequency ion waves.

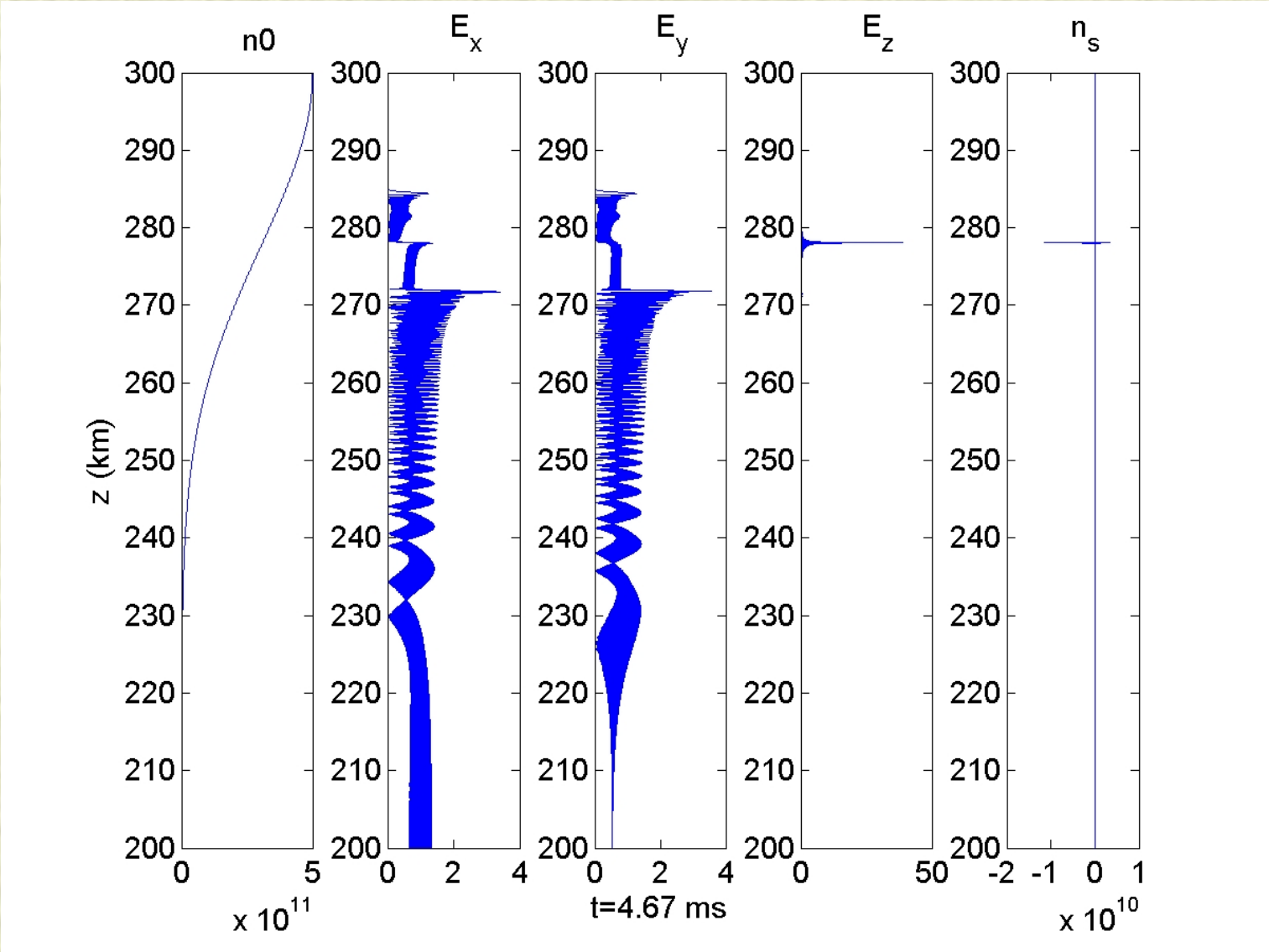
Physics at different length-scales



Small-scale strong Langmuir turbulence: few tens of centimetre structures.

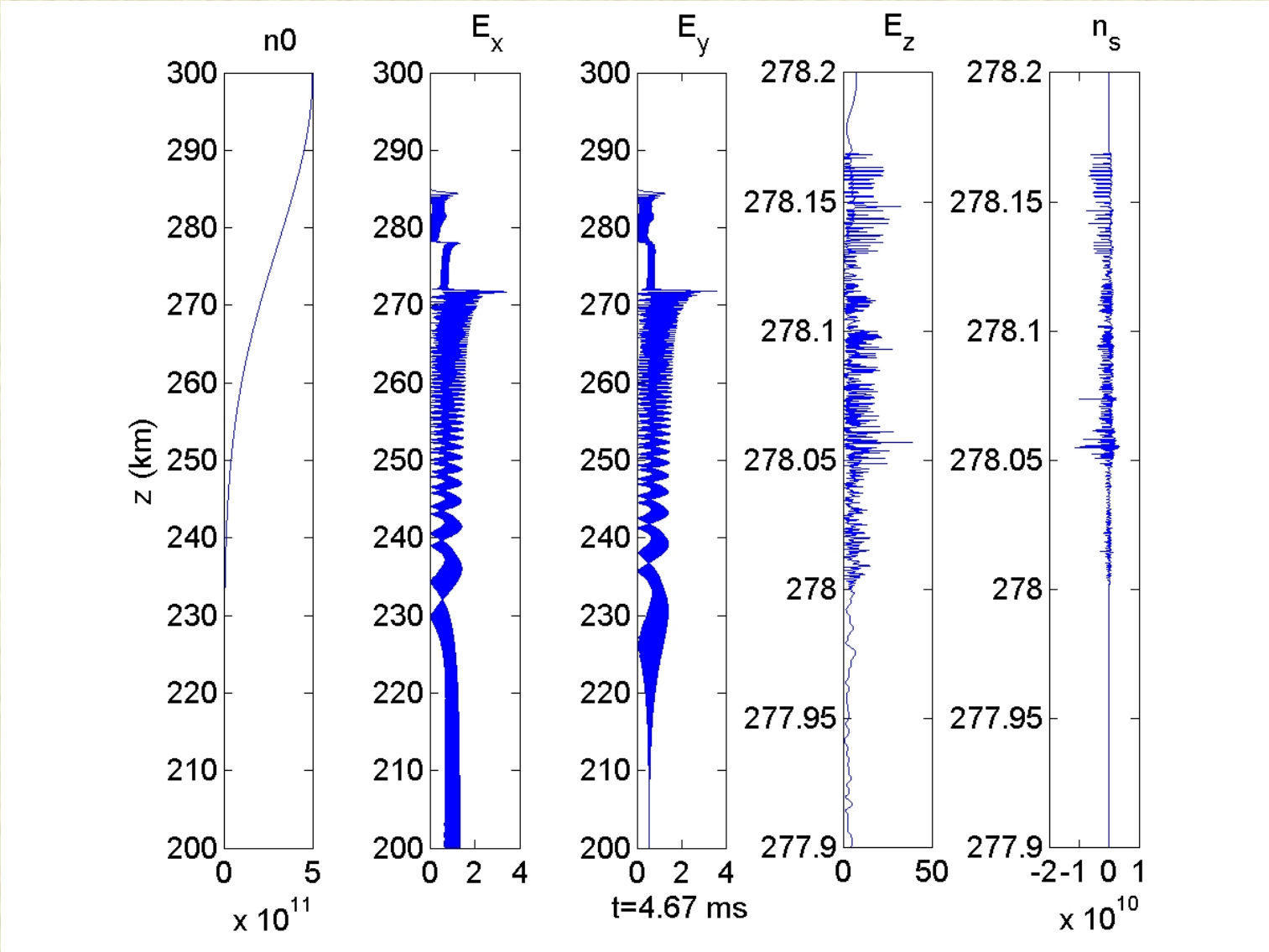
Large amplitude electric field envelopes trapped in density cavities.

Full-scale simulation, vertical incidence



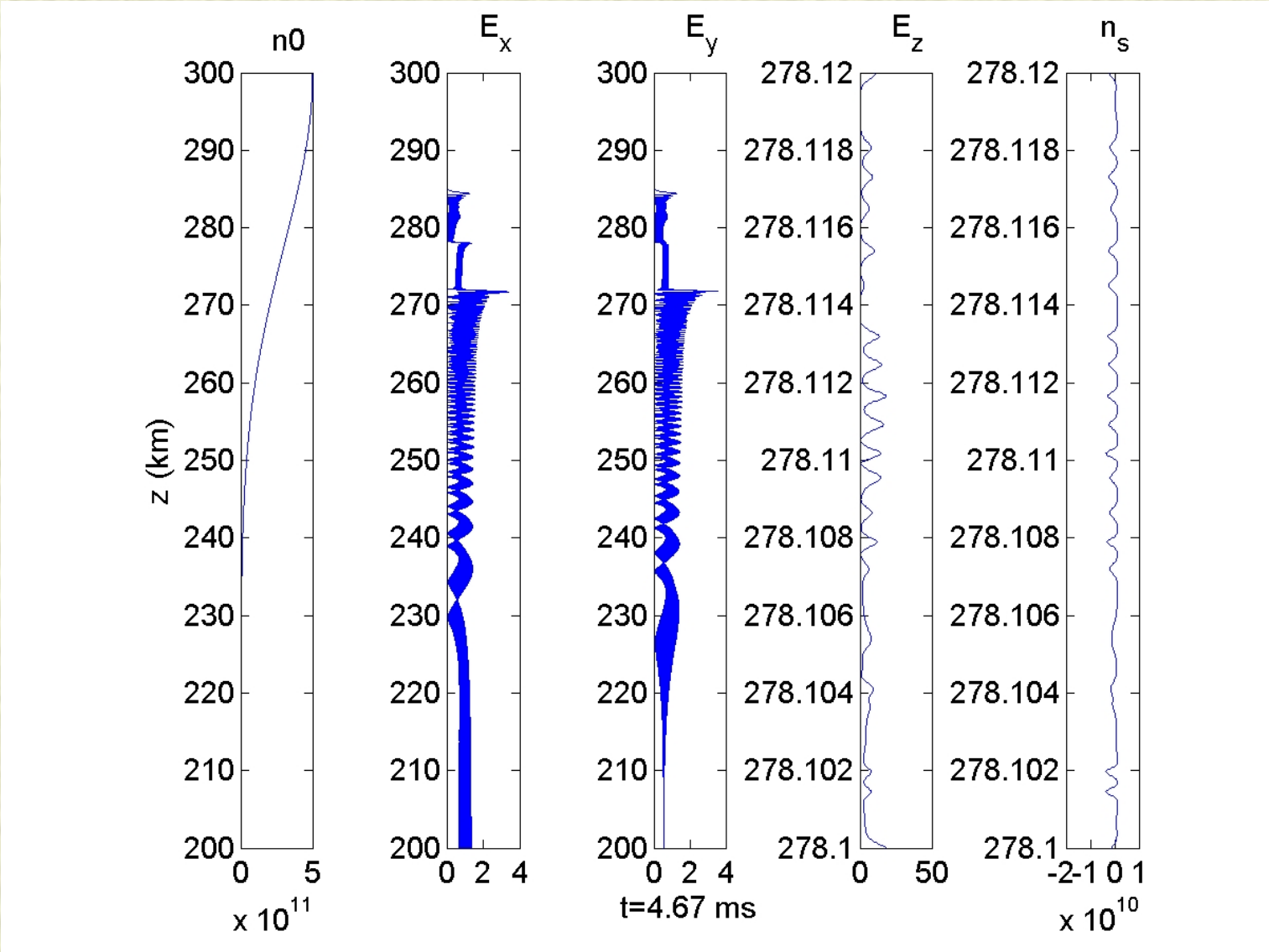
B. Eliasson and L. Stenflo, *J. Plasma Phys.* **76**, 369 (2010).

Closeup 300 meter window



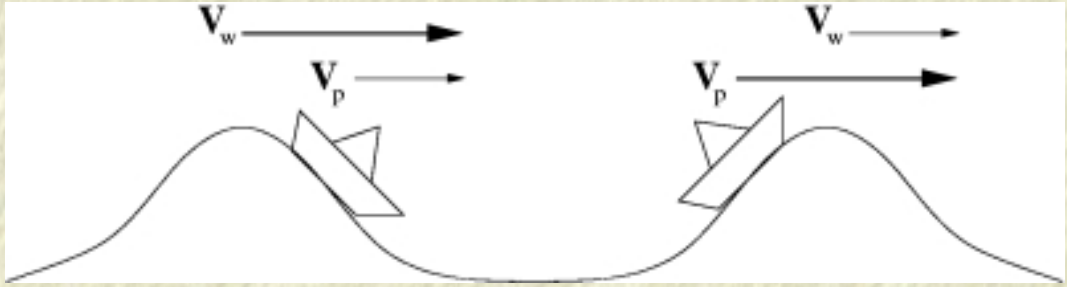
B. Eliasson and L. Stenflo, *J. Plasma Phys.* **76**, 369 (2010).

Closeup 20 meter window

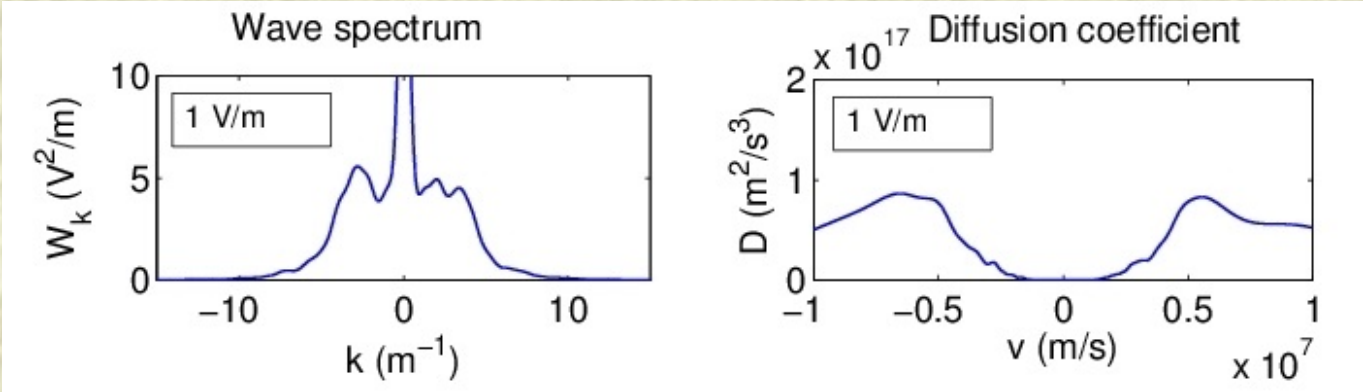


B. Eliasson and L. Stenflo, *J. Plasma Phys.* **76**, 369 (2010).

Electron acceleration by plasma waves



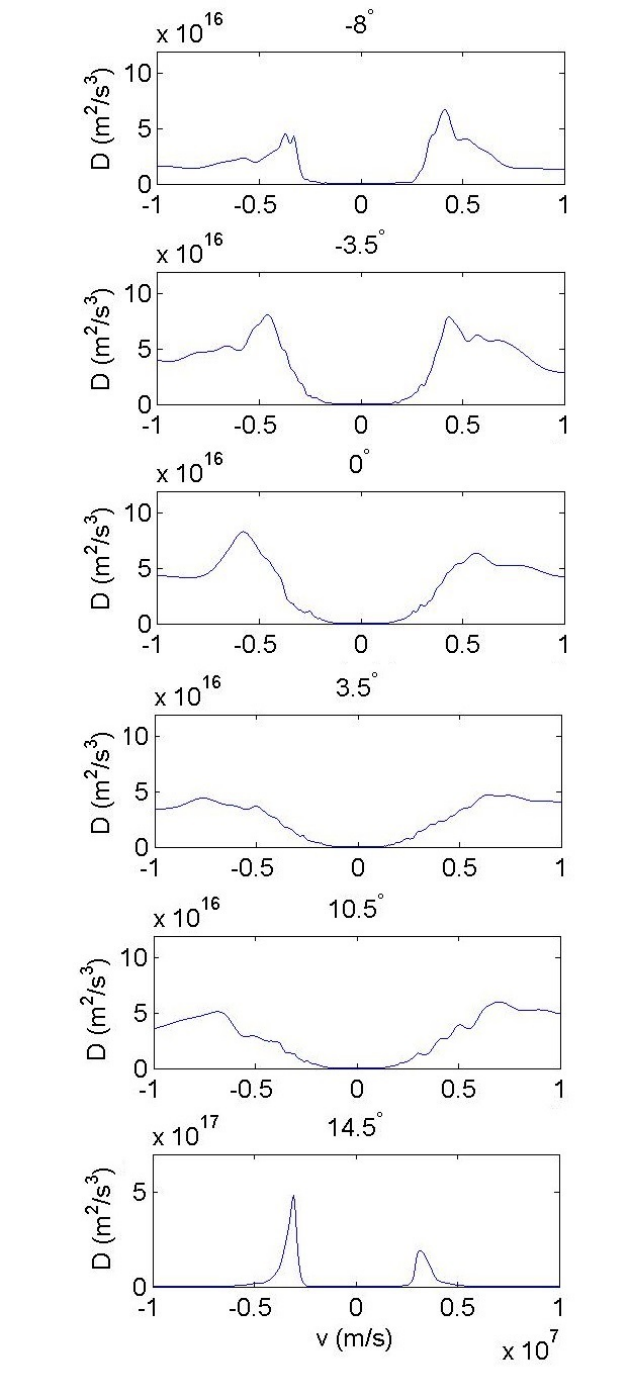
Electrons can surf on the wave if the wave's and electron's velocities almost the same. Many waves give random walk and diffusion of electron velocity.

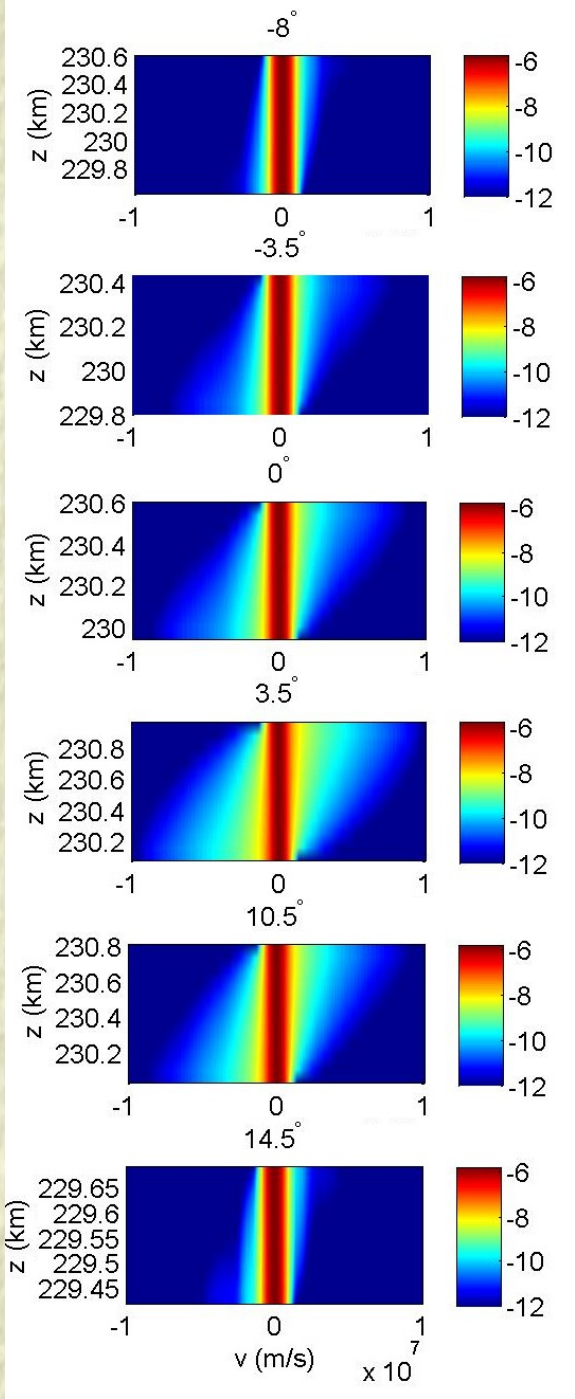


Fokker-Planck equation and diffusion coefficient.

$$\frac{\partial f}{\partial t} + v\frac{\partial f}{\partial z} = \frac{\partial}{\partial v} D(v) \frac{\partial f}{\partial v}, \qquad D(v) = \frac{\pi e^2}{m_e^2} \frac{W_k(\omega, k)}{|v|}, \quad k = \frac{\omega}{v}.$$

Sagdeev & Galeev (1969); Stix, *Waves in Plasmas* (1992).

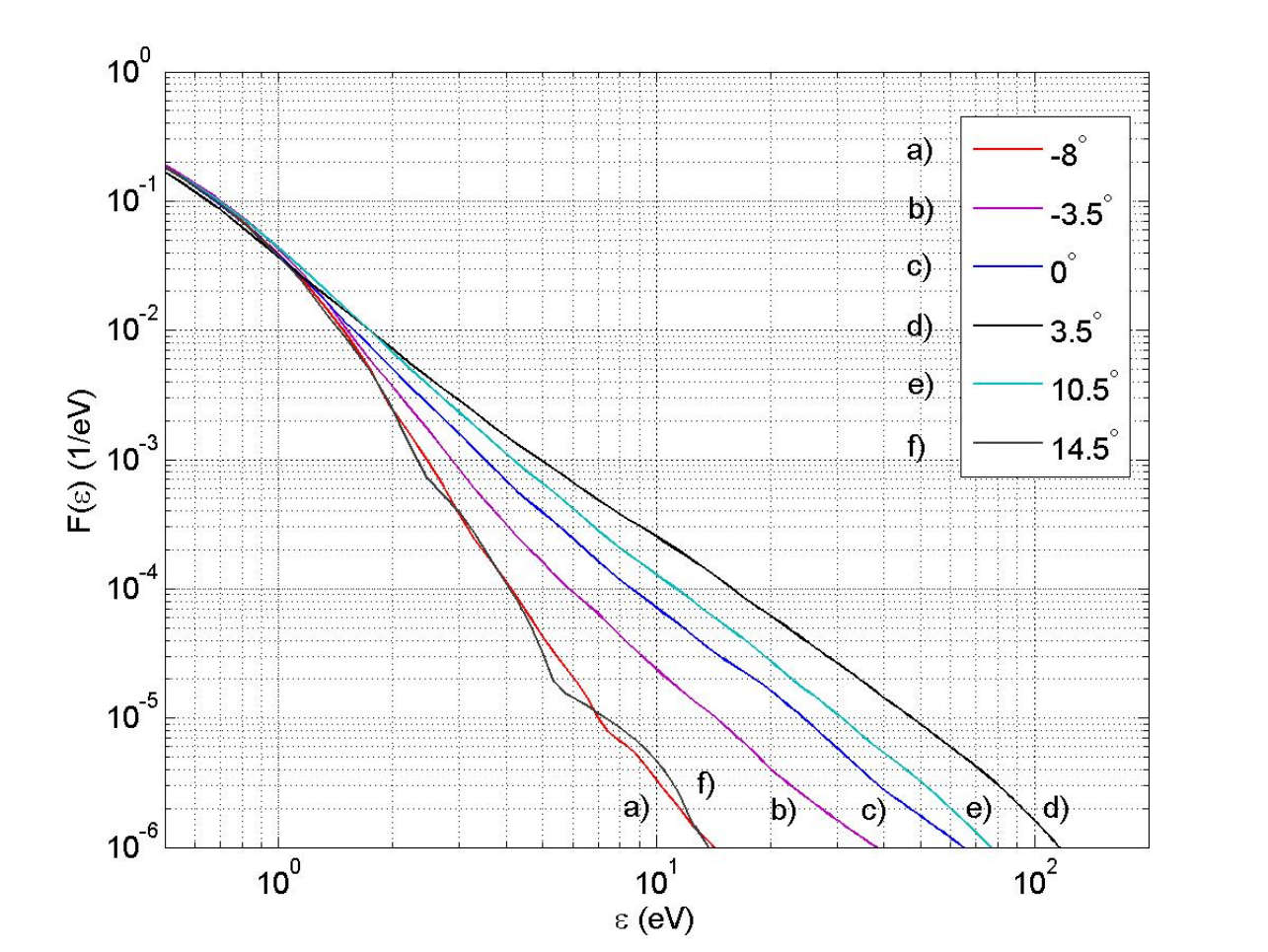




Diffusion coefficients and Fokker-Planck solutions (velocity distribution) for different angles of incidence

Most significant acceleration at $3.5°$ **and** $10.5°$

Energy distribution with high-energy tails



Electrons above 2 eV give rise to optical emissions.

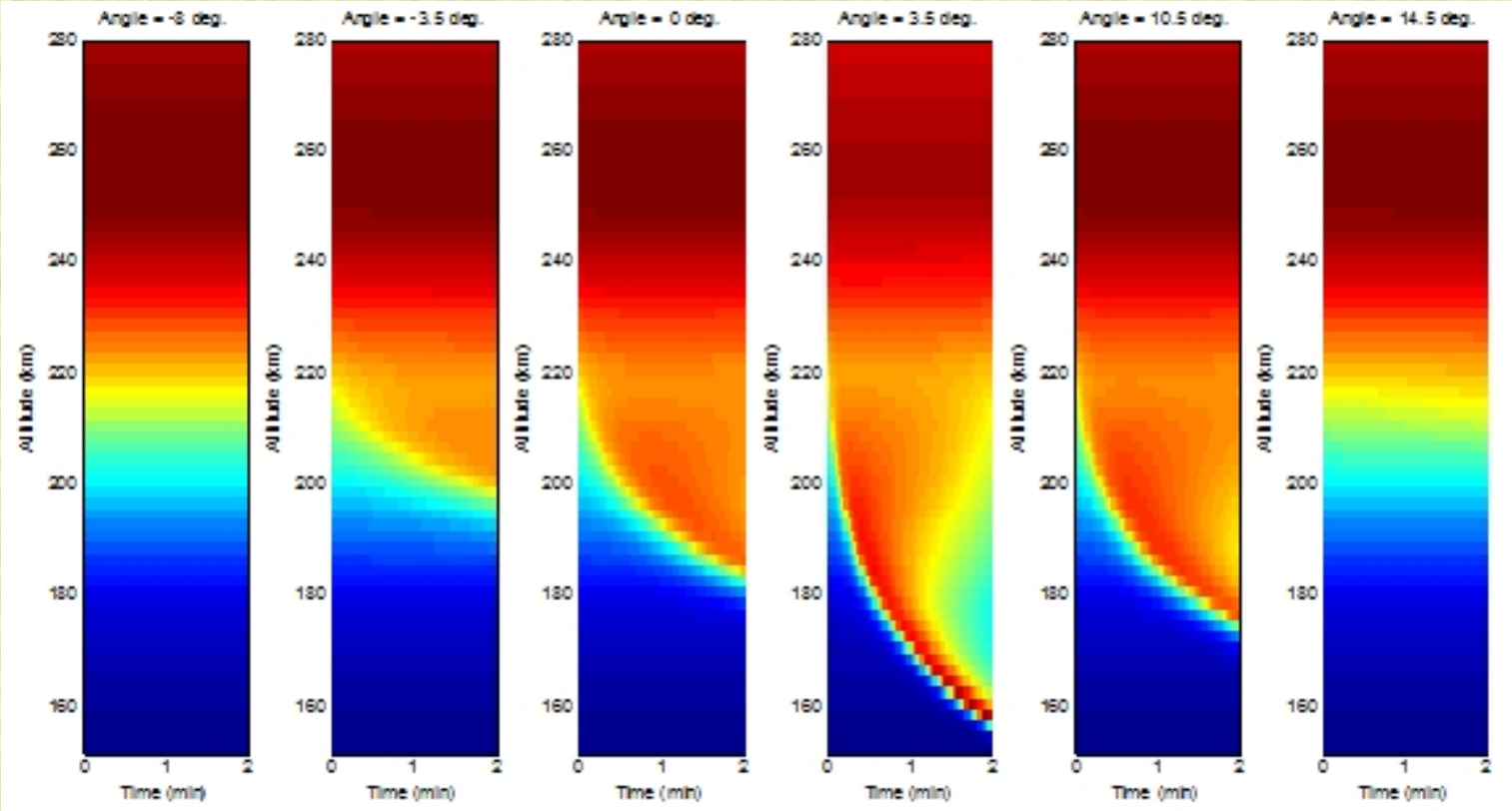
Electrons above 12 eV ionize neutrals to ions (creates a plasma).

Dynamical model for ionization and recombination

- Transport model for energetic electrons through the ionosphere.

- Ionization due to collisions between high energy electrons and neutral atoms.
  - Ionization of atomic and molecular oxygen and nitrogen by high-energy electrons
    ($O + e^- \rightarrow O^+ + 2e^-$ and $O_2 + e^- \rightarrow O_2^+ + 2e^-$, etc.)
  - Production of molecular oxygen ions and nitrogen monoxide ions via charge exchange collisions
    ($O^+ + O_2 \rightarrow O_2^+ + O$ and $O^+ + N_2 \rightarrow NO^+ + N$)
  - Dissociative recombination between electrons and molecular ions
    $O_2^+ + e^- \rightarrow 2O$ and $NO^+ + e^- \rightarrow N + O$).

Simulated descending artificial ionospheric layer



- Ionization fronts descending from about 200 km to 150 km in a few minutes, consistent with the experiments.
- Physics on microsecond → millisecond → several minutes timescales!

Scaling to laboratory experiment

- Decrease length scale a factor $10\,000$ to fit into experiment on 1-m scale
- Radio waves 3MHz frequency and 100 m wavelength $\rightarrow$ microwaves 10GHz and 3 cm wavelength
- Radio wave intensity 1 mW/m^2 $\rightarrow$ microwave intensity 100 kW/m^2.
- Plasma density 10^{11}m^{-3} $\rightarrow$ 10^{18}m^{-3}–10^{19}m^{-3}.
- New linear plasma helicon device planned at Strathclyde University to produce plasmas with typical diameter 50 cm, densities above 10^{18} and magnetic field 0.05-0.1 T.

References on numerical modelling

- B. Eliasson, Full-scale simulations of ionospheric Langmuir turbulence. Modern Physics Letters B 27(8), 1330005 (2013).
- B. Eliasson, X. Shao, G. Milikh, E. V. Mishin, and K. Papadopoulos, Numerical modeling of artificial ionospheric layers driven by high-power HF-heating, J. Geophys. Res. 117, A10321 (2012).
- B. Eliasson and L. Stenflo, Full-scale simulation study of electromagnetic emissions: The first ten milliseconds, *J. Plasma Phys.* 76, 369-375 (2010).
- B. Eliasson, A nonuniform nested grid method for simulations of RF induced ionospheric turbulence, *Comput. Phys. Commun.* 178, 8-14 (2008).
- B. Eliasson and L. Stenflo, Full-scale simulation study of the initial stage of ionospheric turbulence, *J. Geophys. Res.* 113, A02305 (2008).
- B. Eliasson, Full-scale simulation study of the generation of topside ionospheric turbulence using a generalized Zakharov model, *Geophys. Res. Lett.* 35, L11104 (2008).

Summary

- Formation of descending aurora/ionization fronts in experiments. Ionosphere used as a plasma laboratory!
- Electron quasi-linear acceleration by strong Langmuir turbulence
- Optical emissions and ionization by energetic electrons
- Scaling to laboratory experiment
- Physics occurs on vastly different length- and time-scales, (microseconds to minutes, cm to tens of km)!
- Work in progress: Upper hybrid heating and coupling to electron Bernstein modes, stochastic heating, Vlasov simulations.