Langmuir Solitons and their Role in Artificial Ionization in Ionospheric Heating Experiments

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B. Watkins, T. Pedersen, E.Mishin

LEONID RUDAKOV – ALWAYS AHEAD OF THE TIME

WEAK TURBULENCE

$$W / nT < (k\lambda_D)$$

OSCILLATIONS AND INSTABILITY OF A WEAKLY TURBULENT PLASMA*

A. A. VEDENOV, A. V. GORDEEV and L. I. RUDAKOV
I. V. Kurchatov Institute of Atomic Energy, Moscow, U.S.S.R.

(*Received* 19 *November* 1965)

THE PURPOSE of this paper is to study the possibility of describing effects associated with the interaction of collective oscillations of a plasma by means of a self-consistent system of equations: a kinetic equation for the distribution function of high frequency waves (in six-dimensional co-ordinate and wave vector space) and equations describing the slow motion of a plasma under the action of a high frequency pressure. By means of such a system of equations it is possible to investigate processes in which the characteristic periods and wavelengths considerably exceed the period and wavelength of high frequency oscillations; only averaged characteristics of the high frequency waves enter into the equations, and under such conditions these may be considered as quasi-particles.

STRONG TURBULENCE

$$W / nT > (k\lambda_D)$$

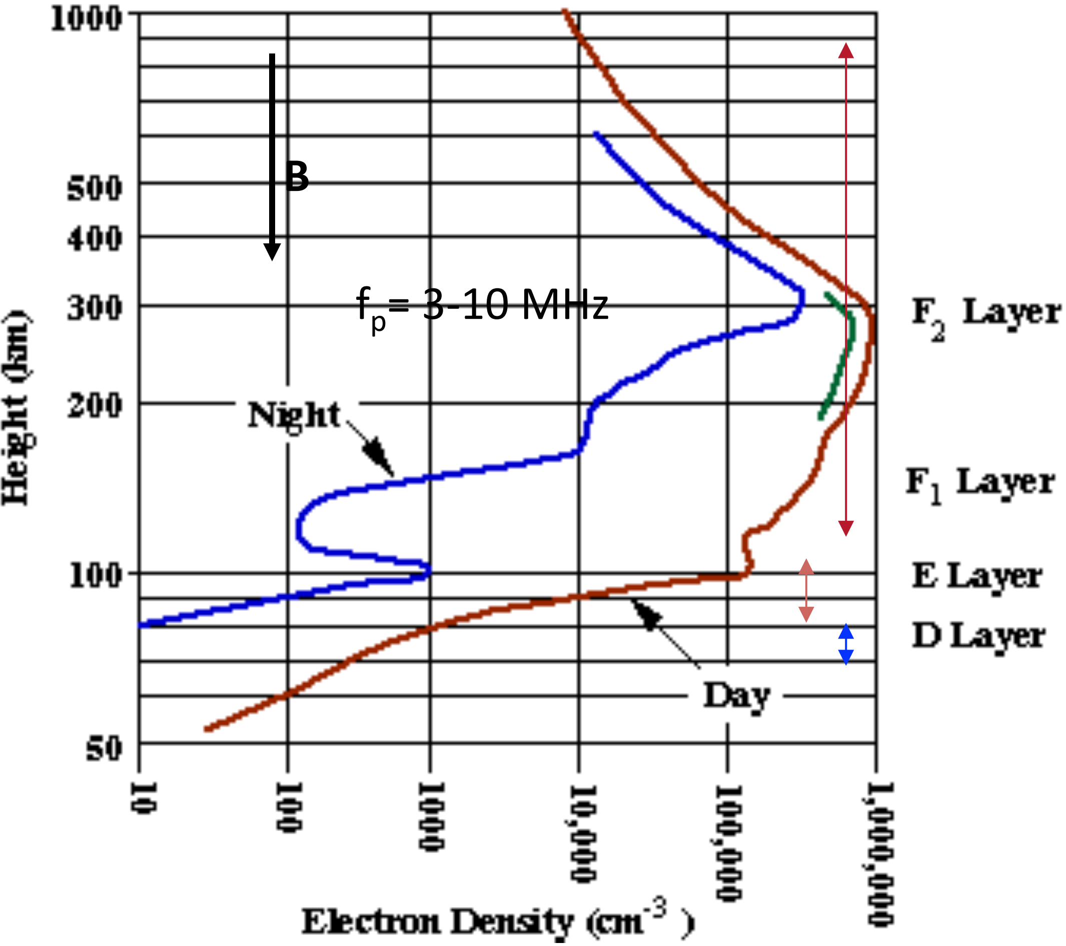
Spectra of Strong Langmuir Turbulence*

A. S. Kingsep,* L. I. Rudakov,* and R. N. Sudan†
International Centre for Theoretical Physics, Trieste, Italy

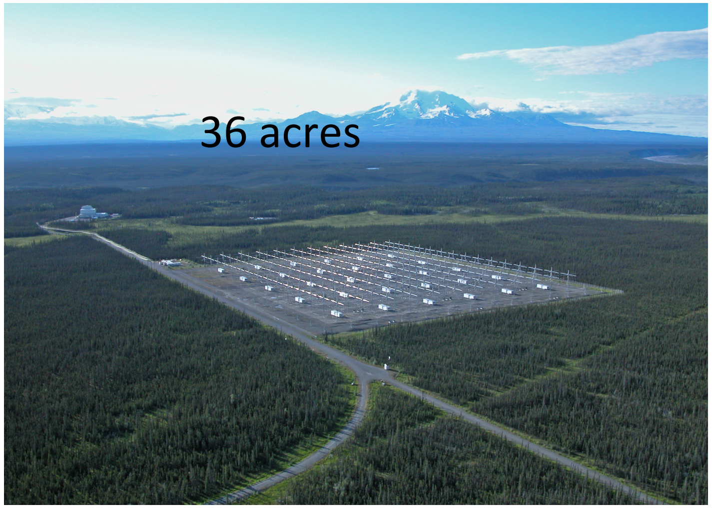
(Received 4 October 1973)

Strong Langmuir turbulence is described in terms of a random set of blobs of self-trapped plasma waves. The interaction of these blobs leads to the generation of power spectra $\langle |E_k|^2 \rangle \propto k^{-2}$ that agree with the results of one-dimensional computer simulation.

IONOSPHERIC HEATING AND HEATERS



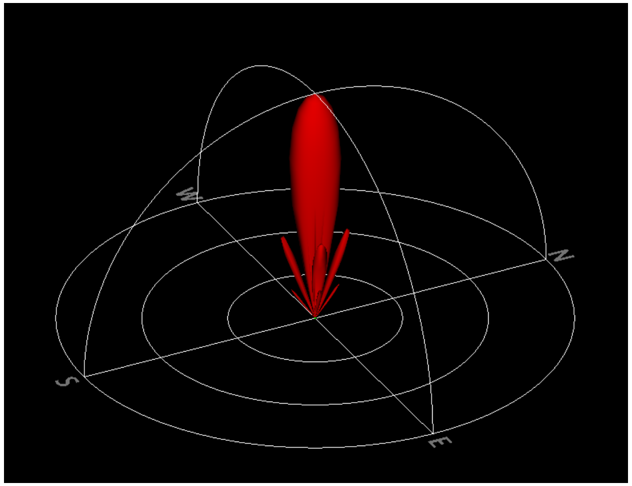
HAARP heater – Phase Array -360 el
2.8-10 MHz, ERP .6-5 GW



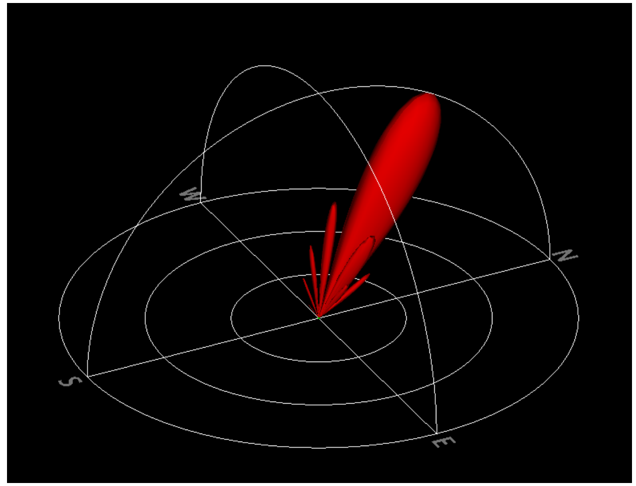
E≈1-1.5 V/m at 150 km, 5 MHz

$\tilde{V} / V_e \approx .1$ at 230 km

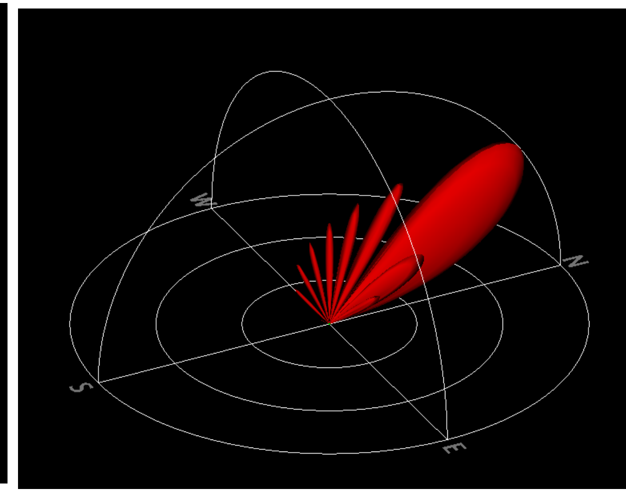
4.5 MHz, Azimuth=0



Zenith =0

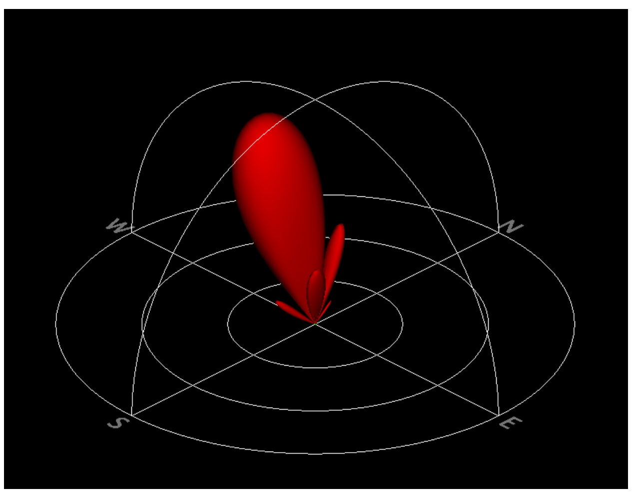


Zenith=45

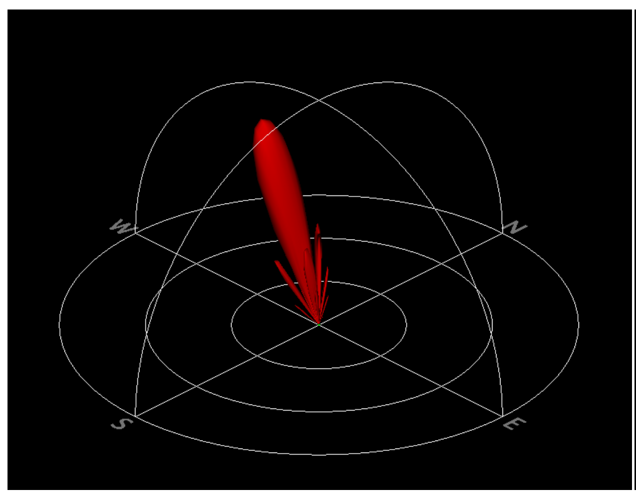


Zenith=60

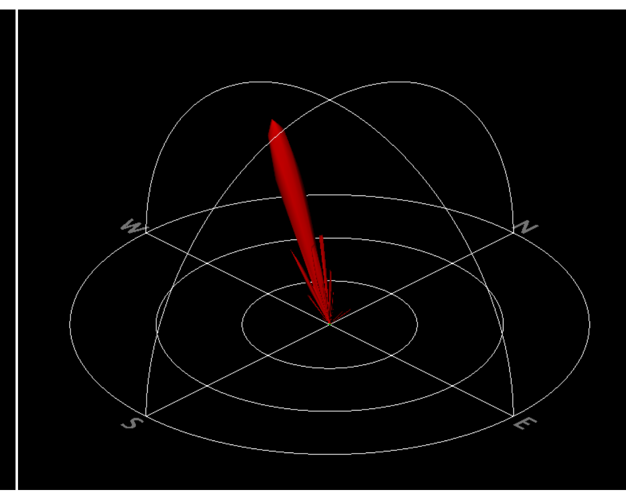
Magnetic Zenith



2.70 MHz



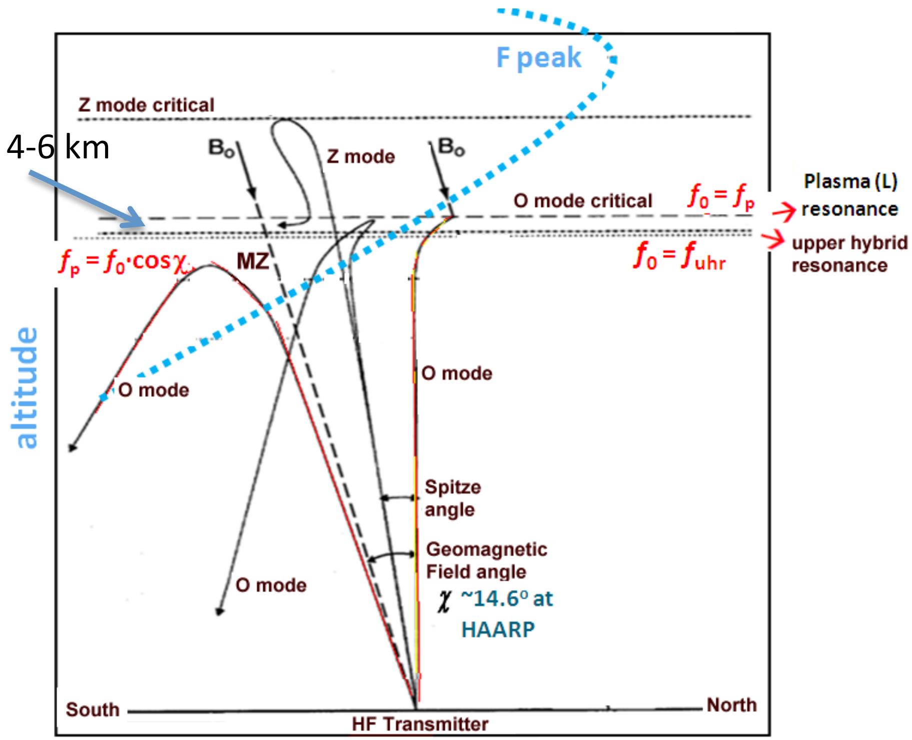
5.95 MHz

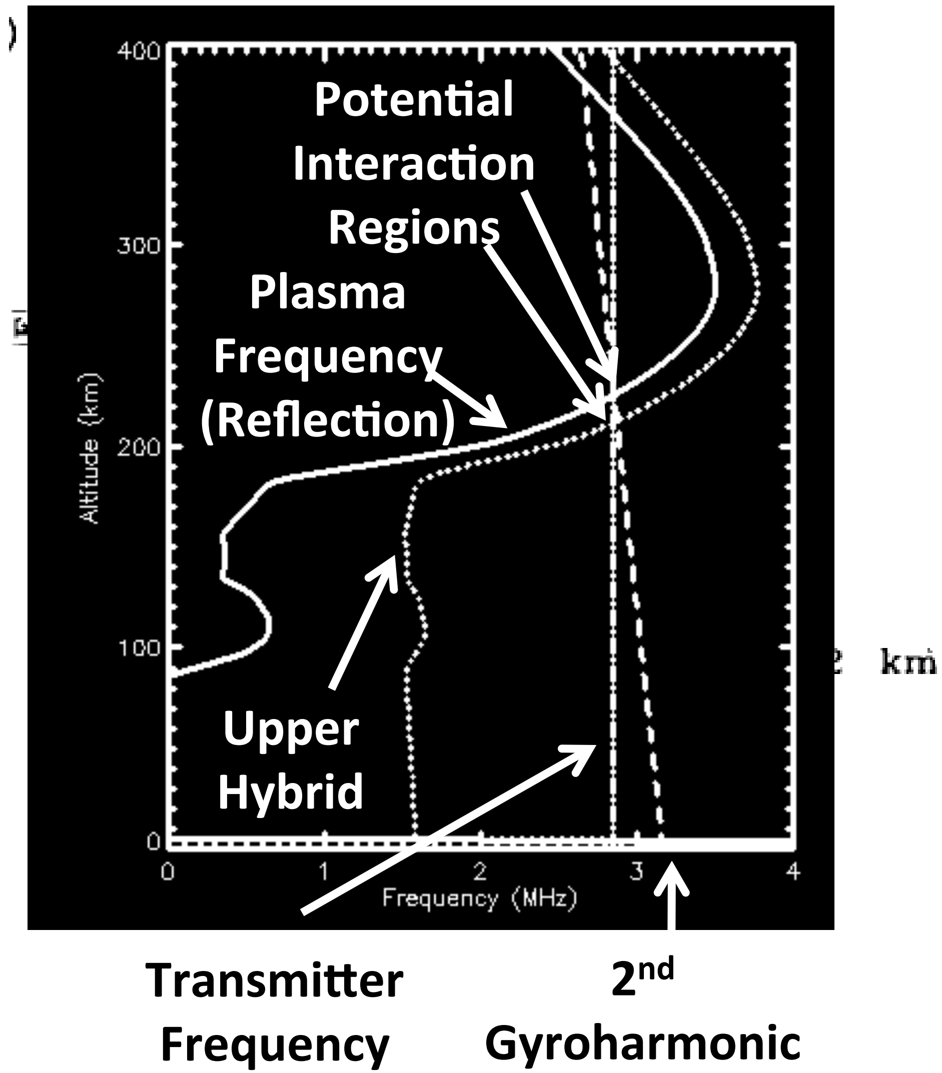


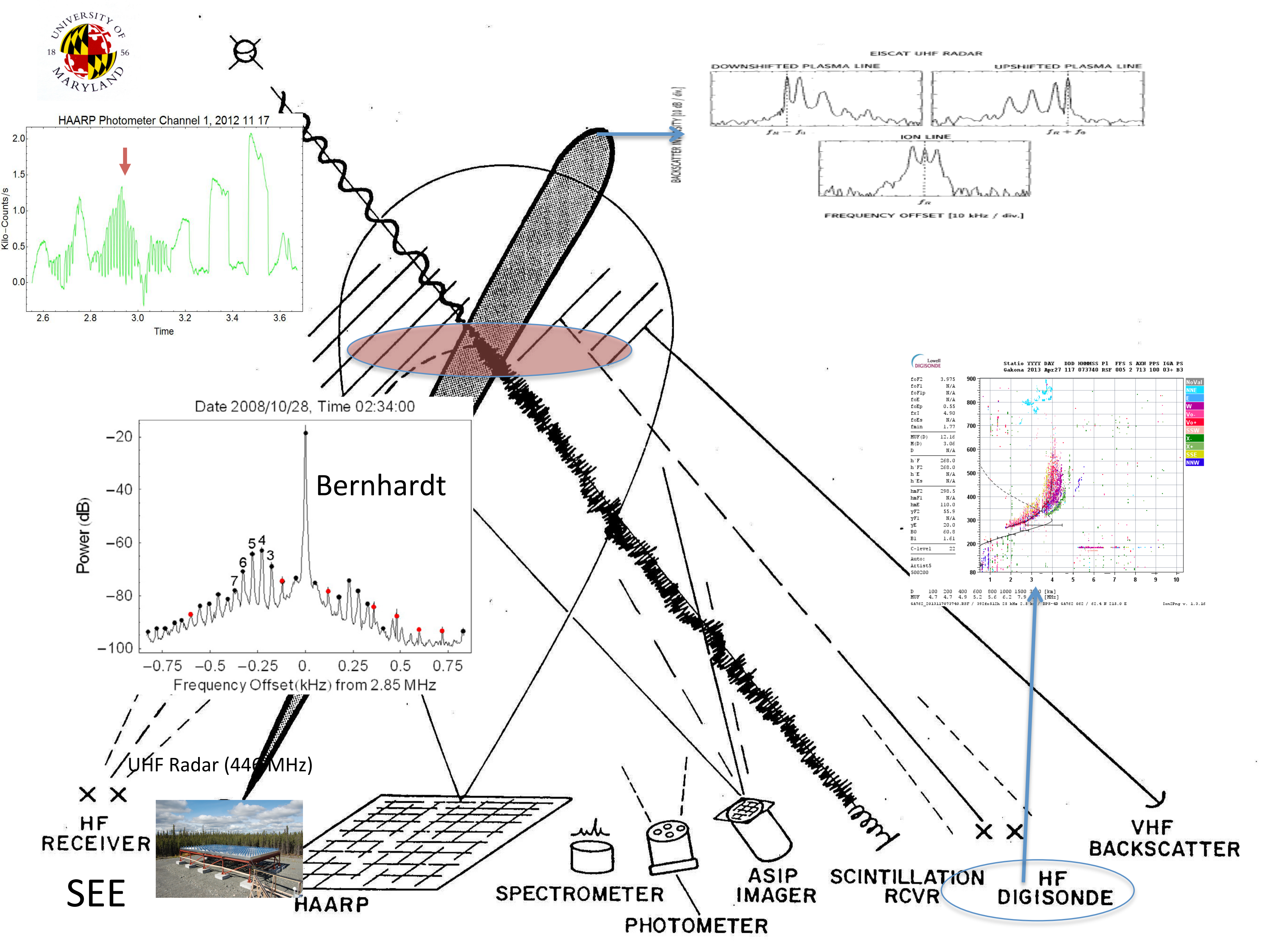
9.2 MHz

HF PATHS – RESONANCE FREQUENCIES

HF frequency equals; Plasma frequency, Upper hybrid, **double resonance** if upper hybrid coincides with cyclotron frequency

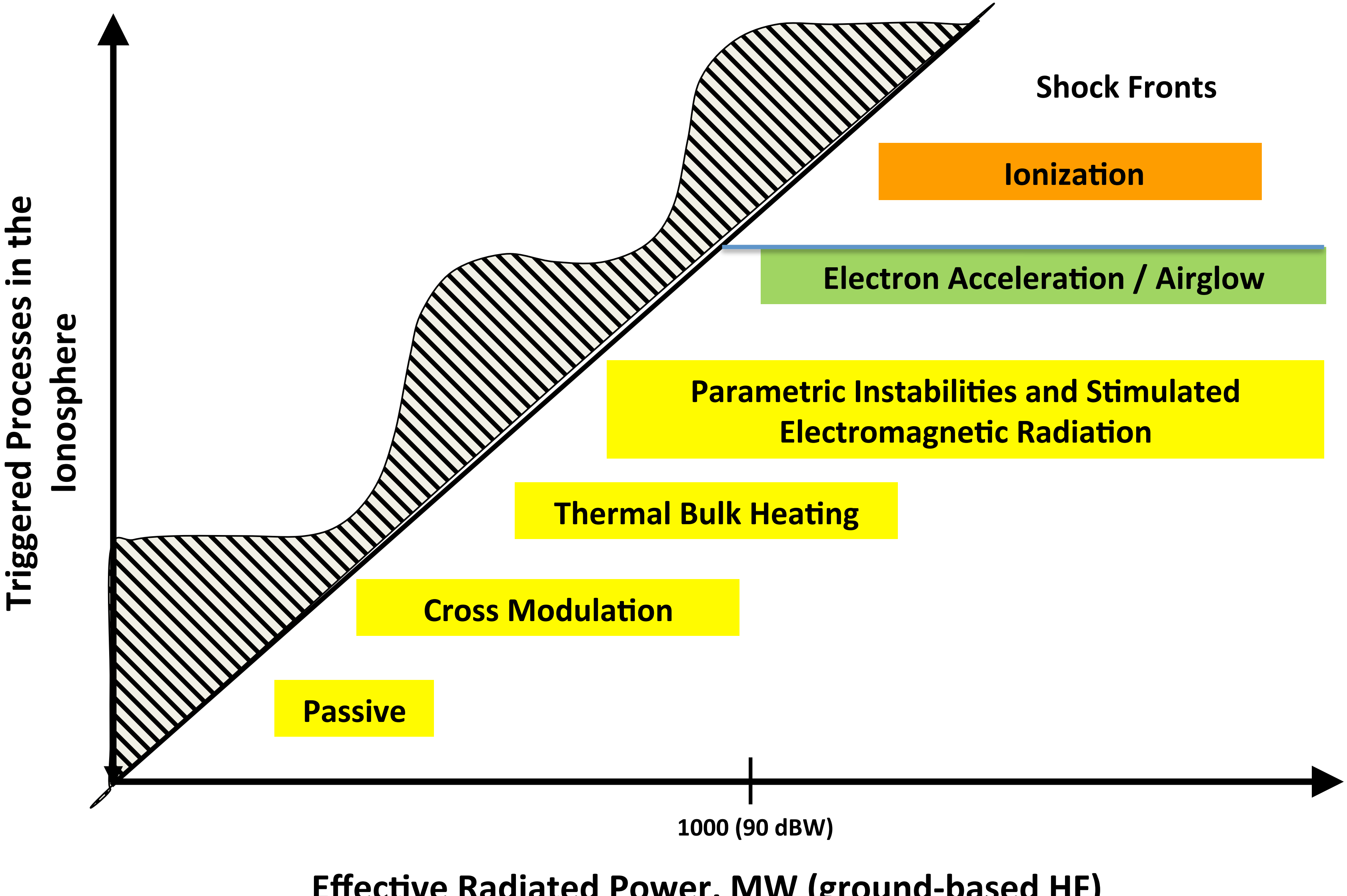




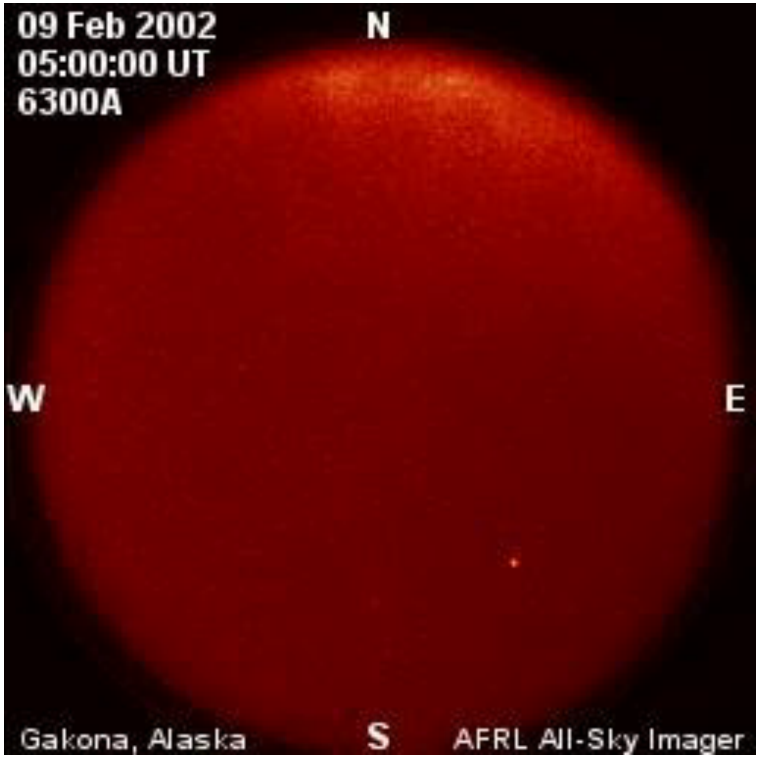


UNIVERSITY OF MARYLAND
HAARP Photometer Channel 1, 2012 11 17
Kilo-Counts/s
Time
EISCAT UHF RADAR
DOWNSHIFTED PLASMA LINE
UPSHIFTED PLASMA LINE
ION LINE
FREQUENCY OFFSET [10 kHz / div.]
Date 2008/10/28, Time 02:34:00
Bernhardt
Power (dB)
Frequency Offset(kHz) from 2.85 MHz
UHF Radar (446 MHz)
HF RECEIVER
SEE
HAARP
SPECTROMETER
PHOTOMETER
ASIP IMAGER
SCINTILLATION RCVR
HF DIGISONDE
VHF BACKSCATTER

Power Thresholds to Trigger Processes in the Ionosphere



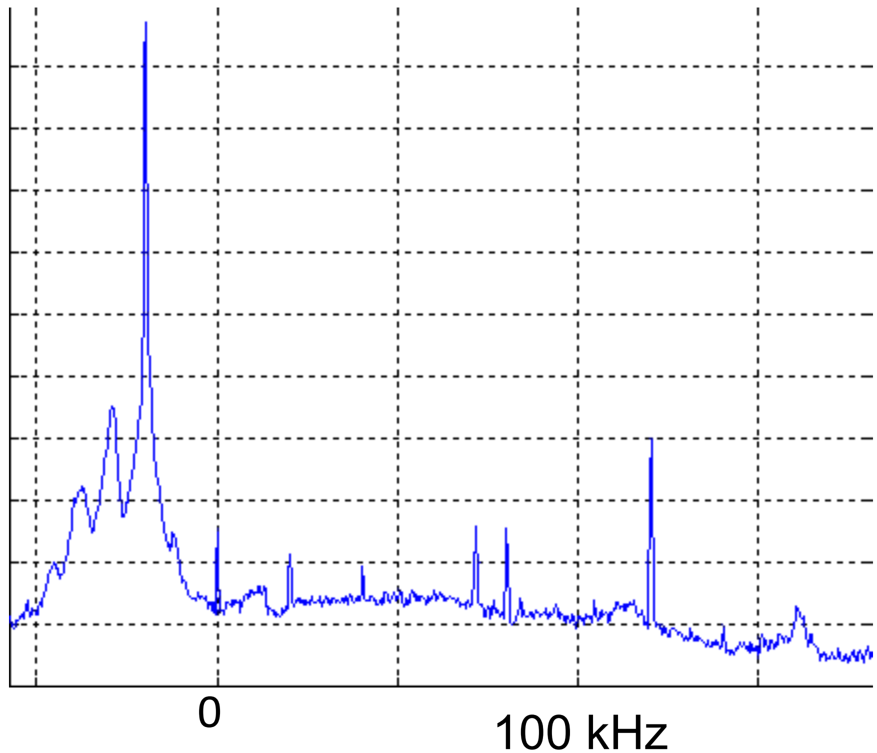
Artificial Aurora – The Zenith Effect
Electron Acceleration (HAARP at 1 MW, EISCAT)



SEE Gyro-Harmonics

Sub-threshold Power

Double resonance near 4th cyclotron harmonic- HF frequency at zero shift 5.4 MHz

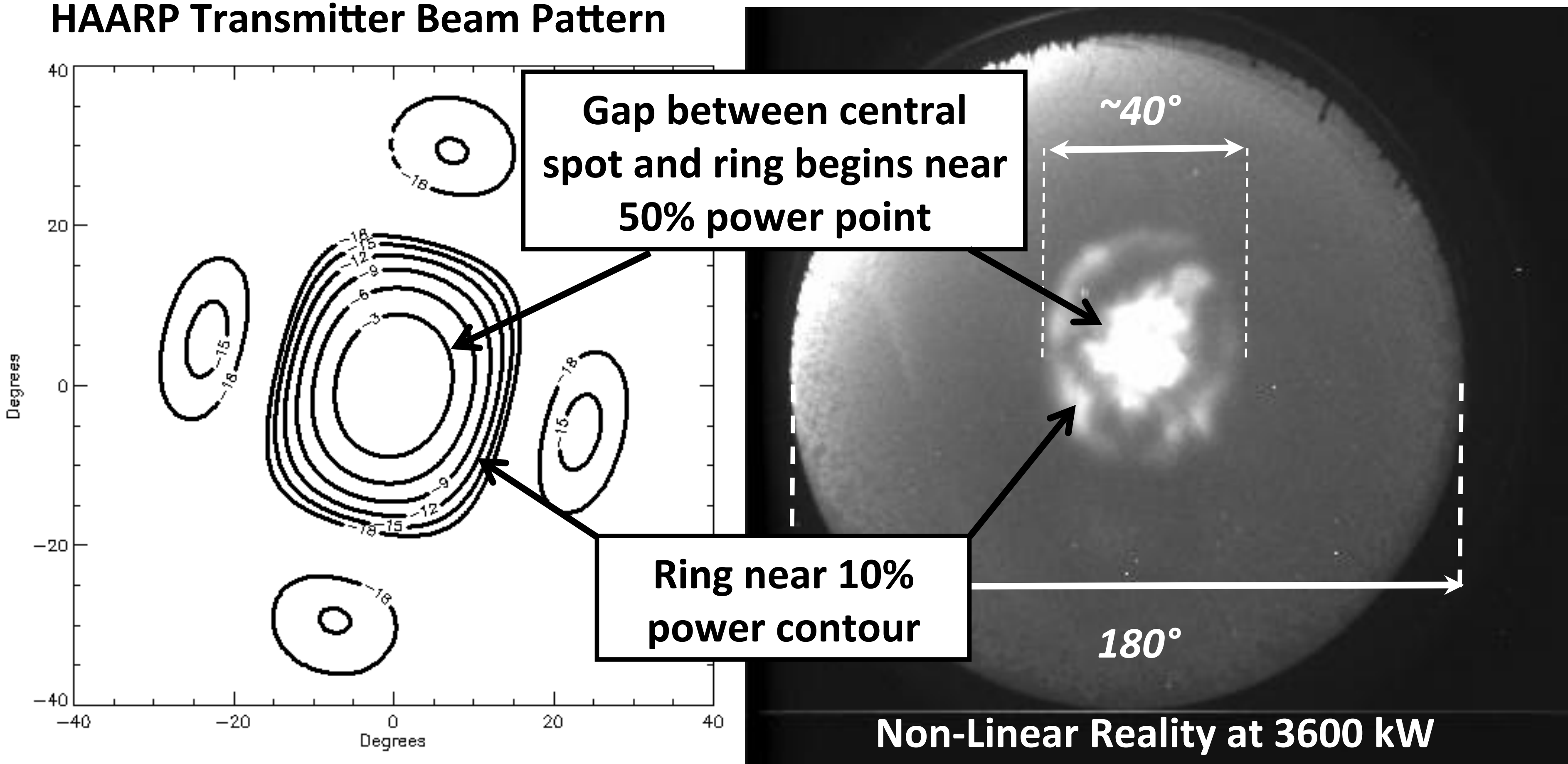


SURA Facility SEE Carozzi et al.JGR 2002

HAARP AT 3.6 MW – NEW THRESHOLD - APL

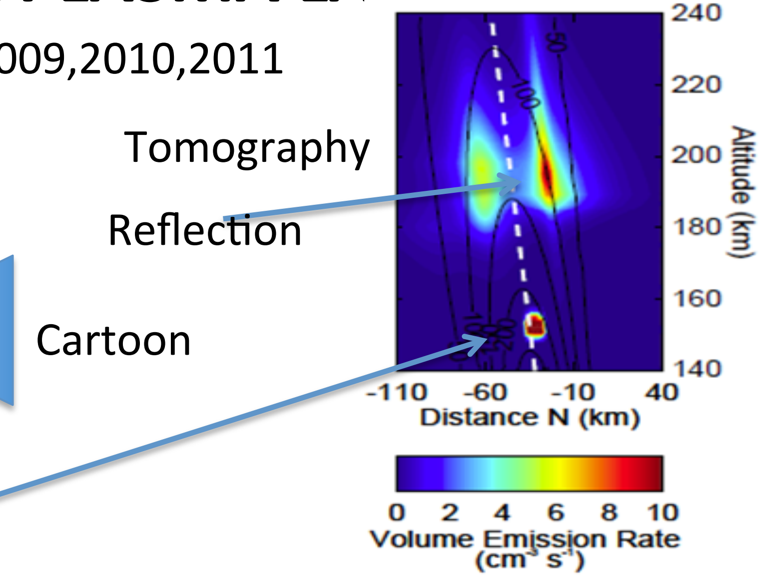
- First science experiments at full power showed unexplained spot-within-ring, bull's-eye patterns in optical emissions extending beyond beam edges filling ~¼ of sky. Pedersen et al. GRL, 2009

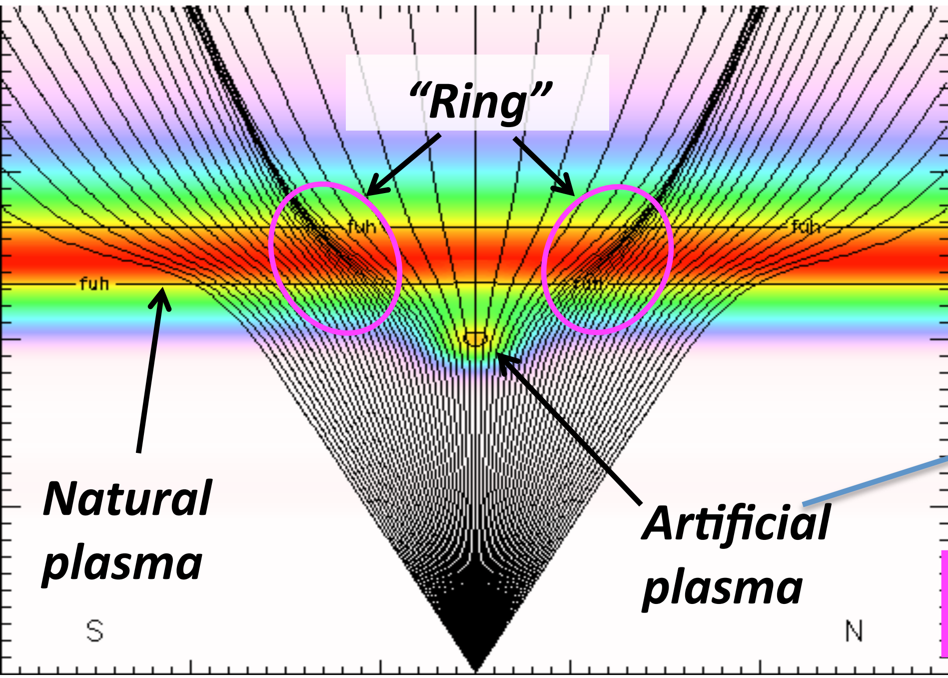
HAARP Transmitter Beam Pattern

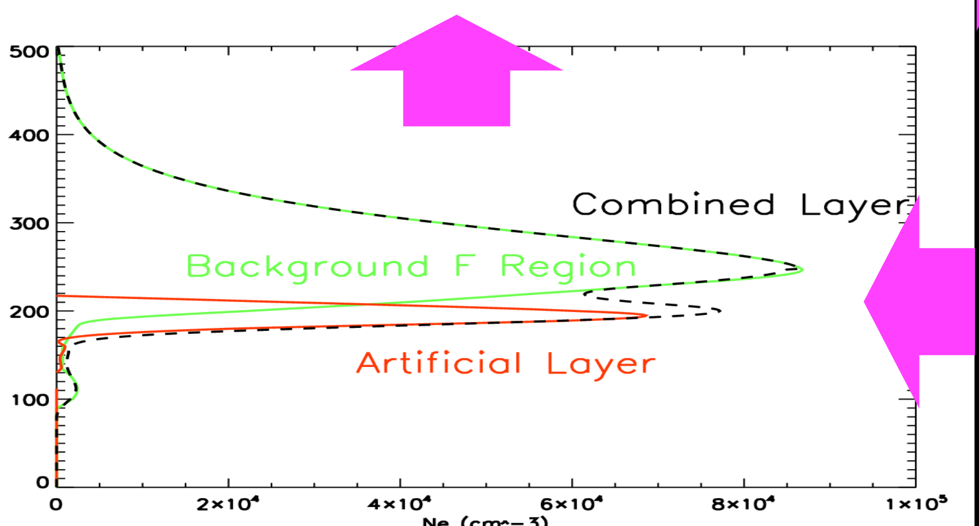


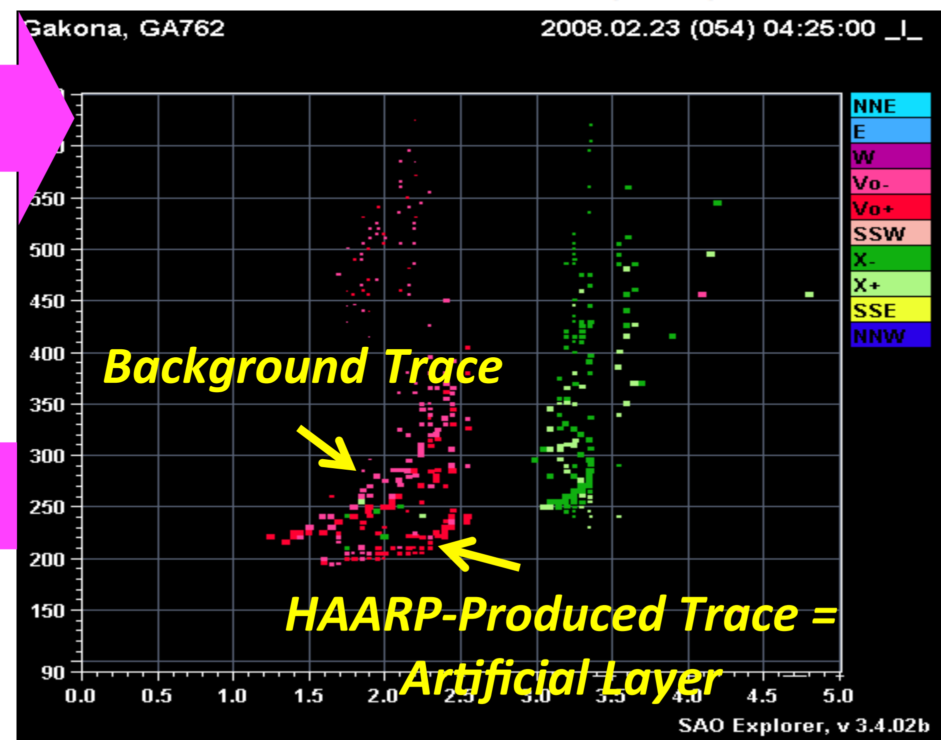
HYPOTHESIS – ARTIFICAL PLASMA LAYER

PEDERSEN ET AL, GRL 2009,2010,2011



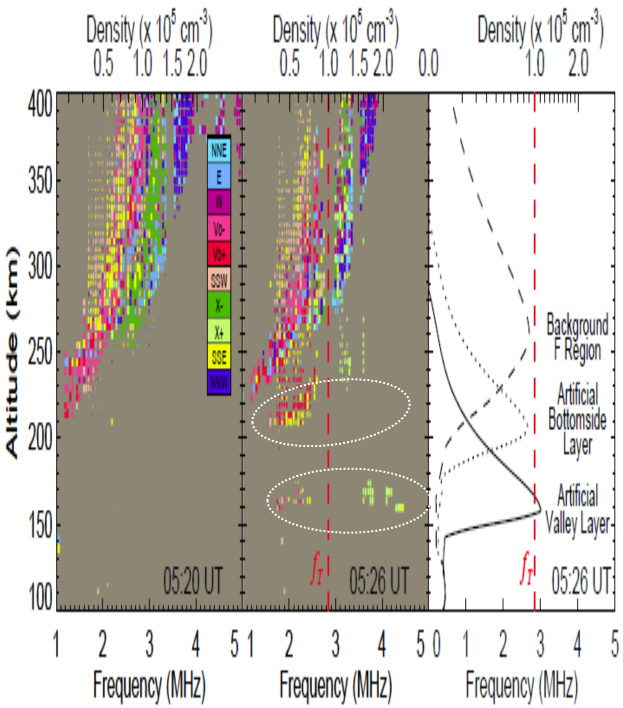




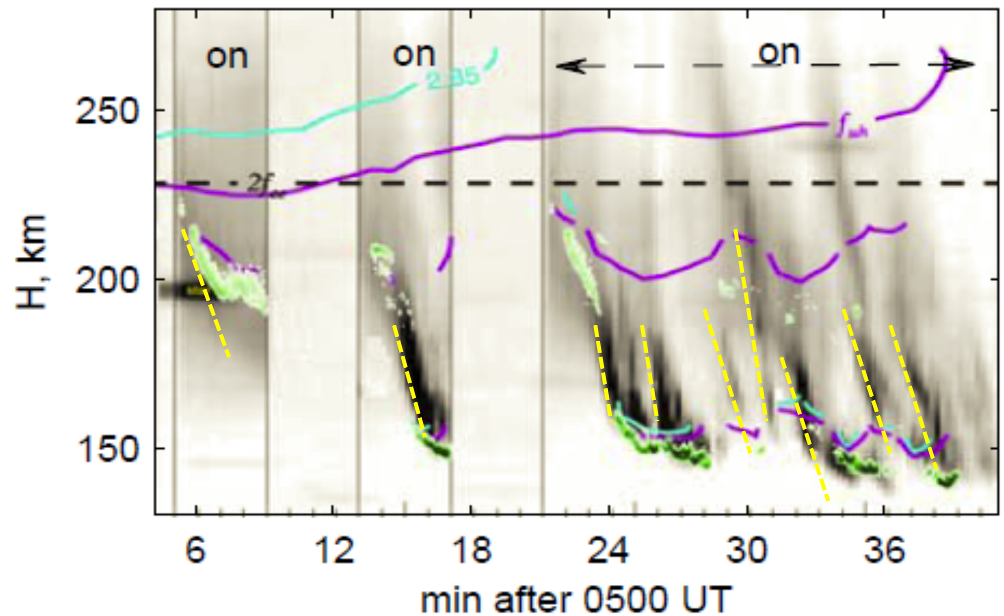


Descending APL

2GH, 440 MW, MZ



- (left) Background echoes (the heater off).
- **(center) Heater on**: Two lower layers of echoes near 160 and 200 km virtual height for 210 s.
- (right) True height profiles.



Time-vs-altitude plot of 557.7 nm optical emissions along *B* with contours showing the altitudes where *fp =2.85 MHz (blue)*, *UHR= 2.85* MHz (violet), and $2f_{ce}$ *= 2.85 MHz (dashed white)*. *Horizontal blips* are stars. Green is the Ion Acoustic Line intensity.

✓the artificial plasma near h_{min} was quenched several times.

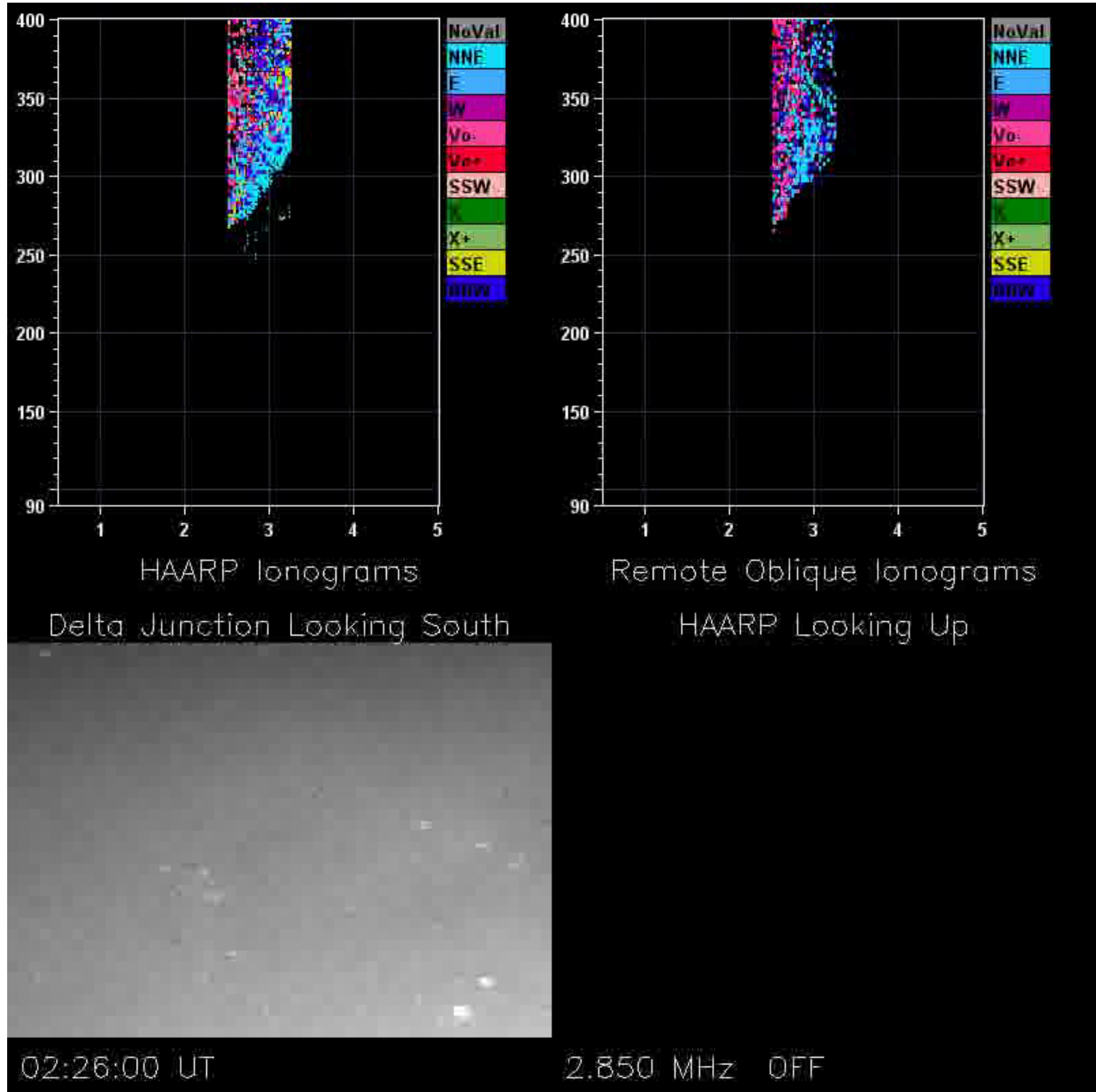
Courtesy of E. Mishin

Pedersen et al., GRL 2010

Mishin & Pedersen , GRL 2011

Multi-Site Optical and Ionosonde Measurements During Frequency Ramp

- Simultaneous local and remote optical and ionosonde measurements
- Complicated 3-D structure clearly apparent
- Two descending layers observed
- Apparently correspond to spot and ring
- Gradually die out at low altitude



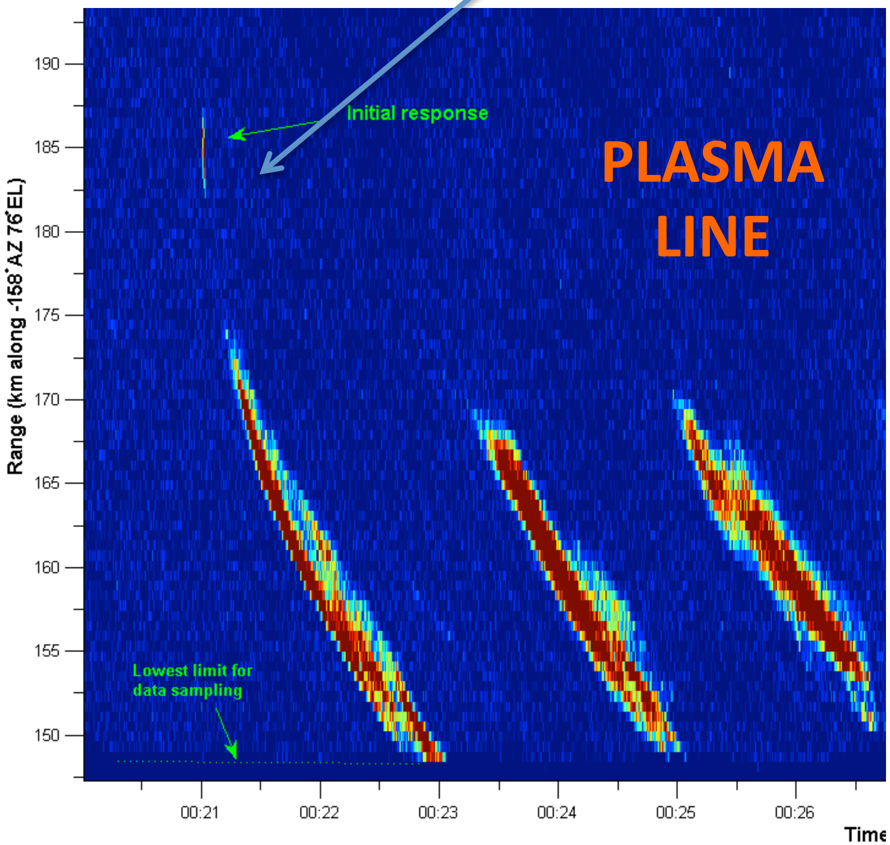
Courtesy of T. Pedersen

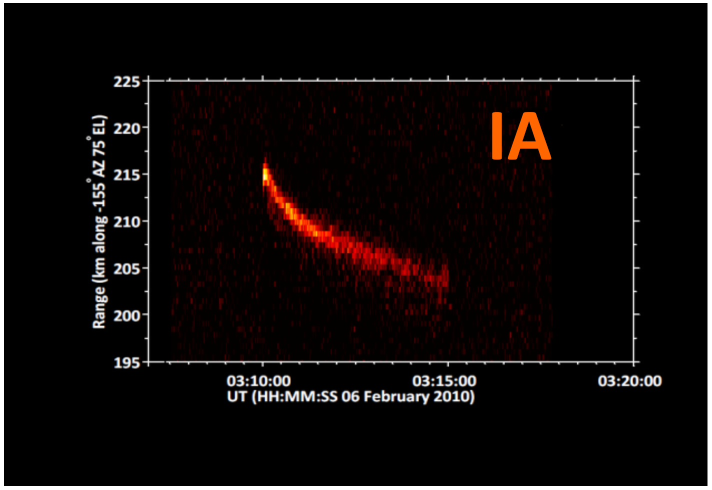
Note similarity with optical emissions descent except for initial response

MUIR DATA - WATKINS

frequency shift from 446 MHz

Example: UHF radar data showing downward progression of signals during 5 minutes of HF power



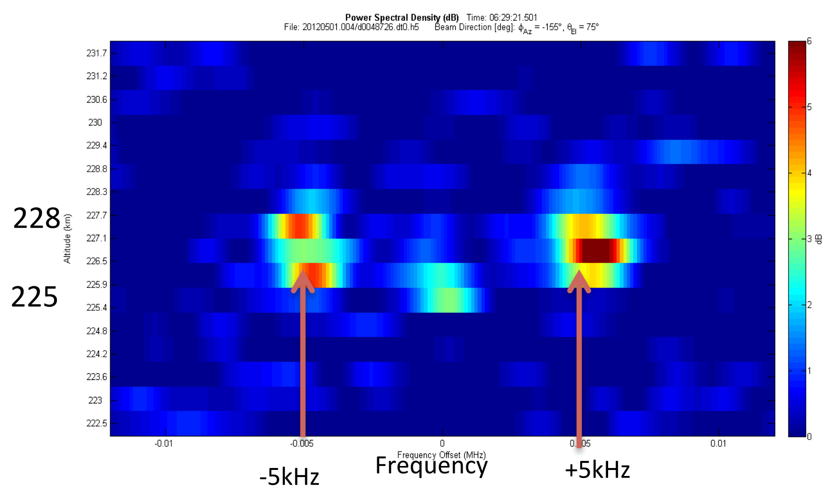


Descending ion-line and plasma line structures observed with UHF radar during heating.

$$\Delta\omega \approx kC_s = 2k_o C_s$$

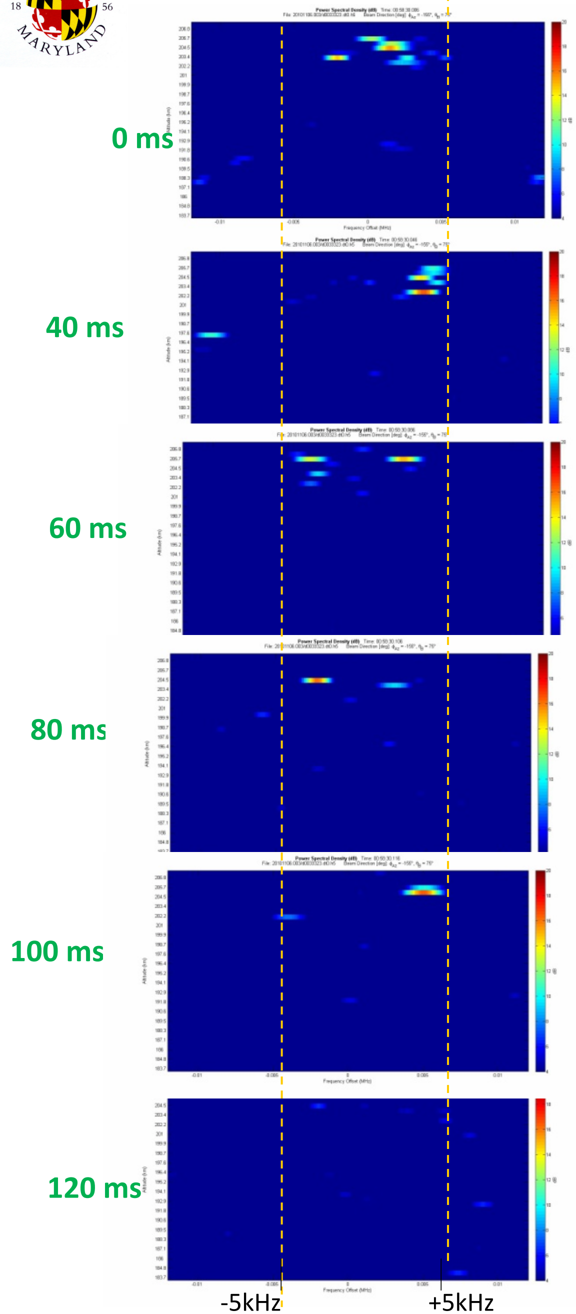
$$C_s = \sqrt{\frac{\gamma T_e}{M}}$$

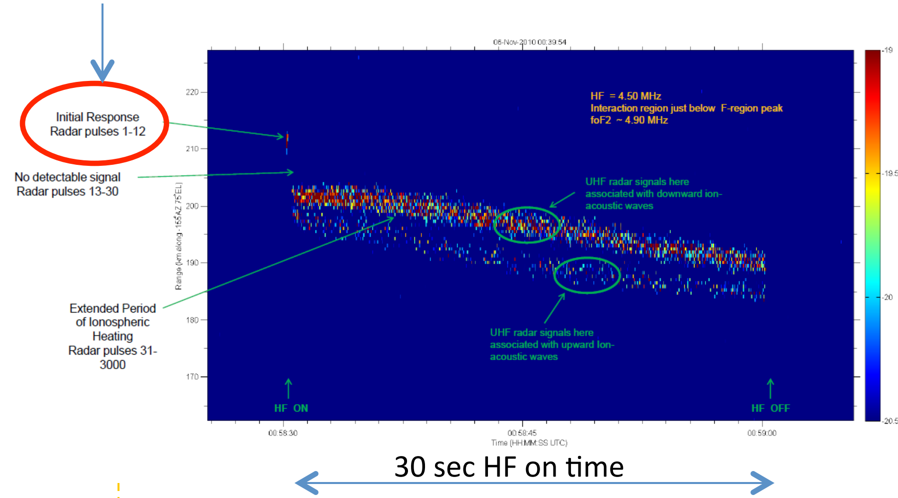
$$T_e \approx .65(M_{eff}/20\gamma)(\Delta f/5kHz)eV$$

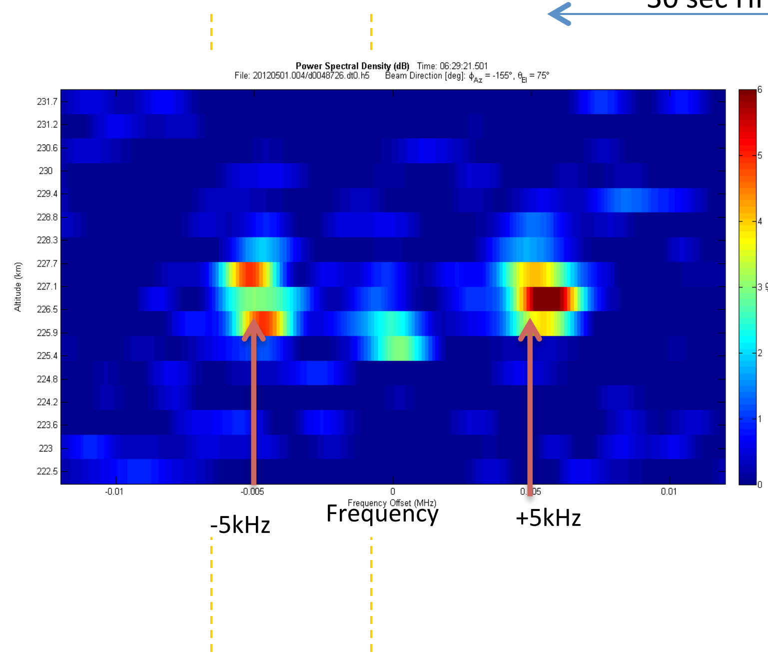


UHF Power Spectra During Initial Response Time

(First 12 pulses after HF turn on - 120 milli-sec)







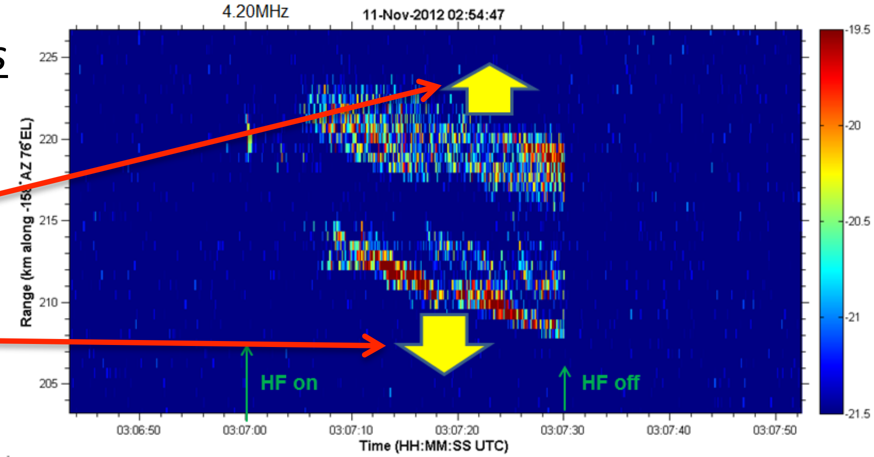
UHF Radar Doppler Power Spectra Observations

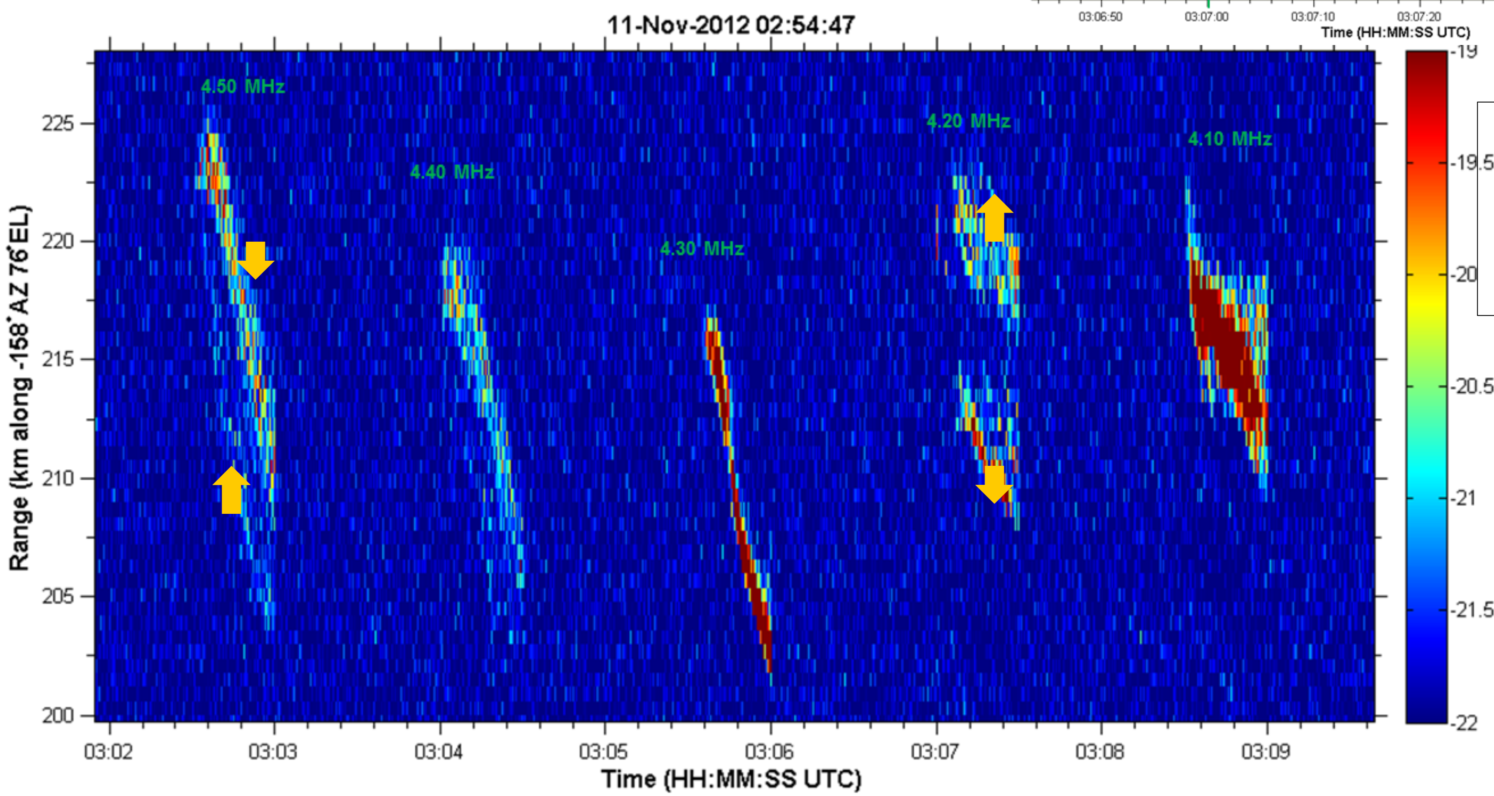
Courtesy of B. Watkins

IA asymmetry ?

Upward

Downward





Results for 4 HF frequencies near the 3rd Gyro Harmonic HF power cycled: 30secs on 60 secs off

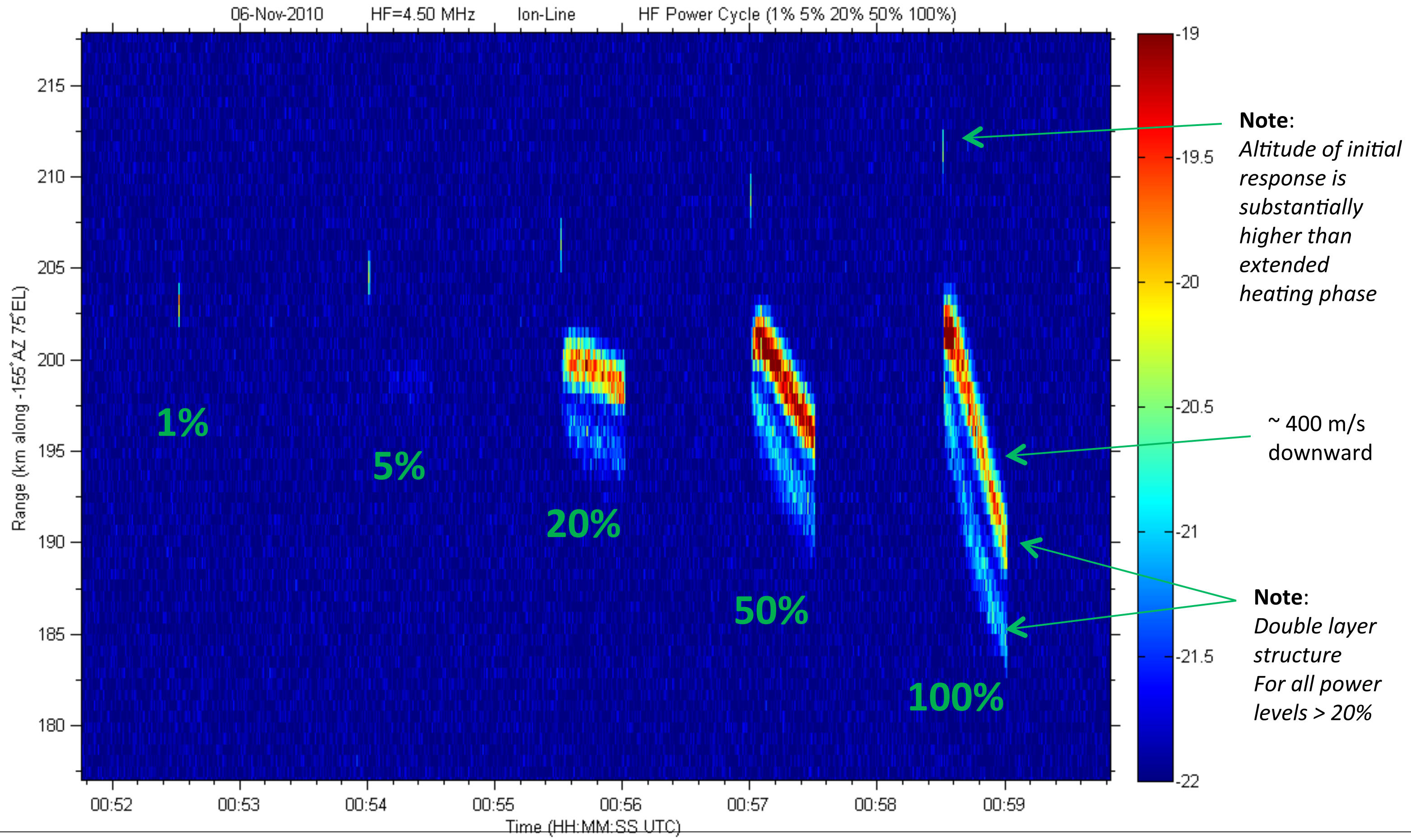
1. The 4.20 MHz frequency results show two distinct layers. (3rd gyro harmonic between 4.20 and 4.30 MHz)
2. Rate of descent approx same for 4.3, 4.4, 4.5 MHz. Lower descent rates for 4.1 and 4.2 MHz
3. Note direction of ion-acoustic waves for double layers that occur for 4.50 and 4.20 MHz. (yellow arrows)

POWER THRESHOLD

Figure below: UHF radar scattering from HF-enhanced ion-line for HAARP power levels 1%, 5%, 20%, 50% 100% (3.6MW)

Downward progression of signals is indicative of large-scale heating.

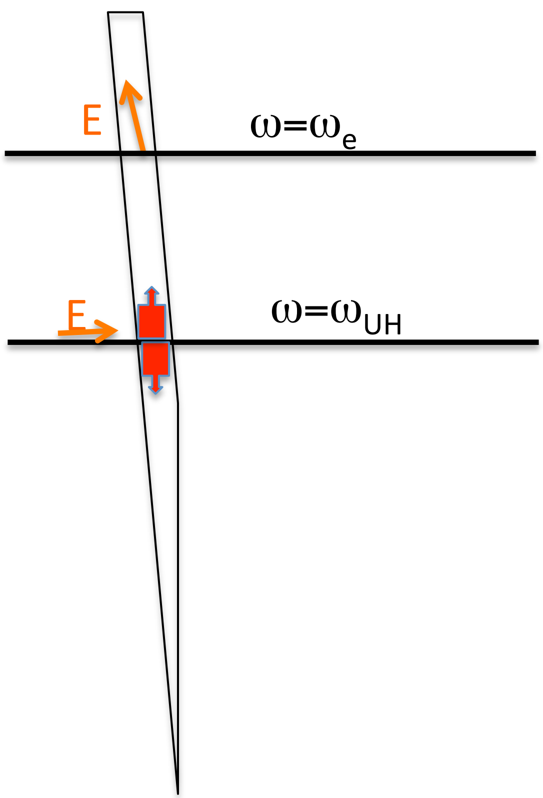
Range-Time-Power plot , 30 secs on – one minute off, 4.50 MHz HF power cycle

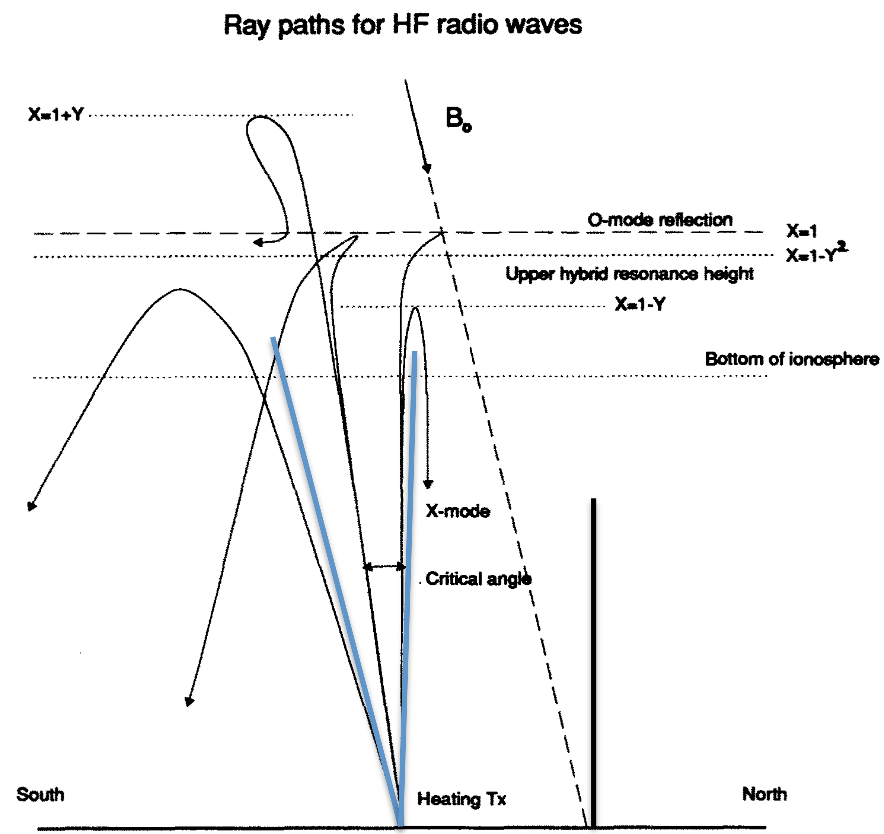


1. *At least 20% of HAARP full power is required to attain substantial large-scale modification of ionospheric structure.*
2. *Double layer effect is not power-dependent. Exists for power greater than 20% level when signals are present.*

Theory/Modeling - Key Physics Ideas

- Electron acceleration controlled by Langmuir turbulence at the reflection height
- Electron heating controlled by upper hybrid heating including dual resonance
- Field aligned heat transport of heated plasma and energetic electrons

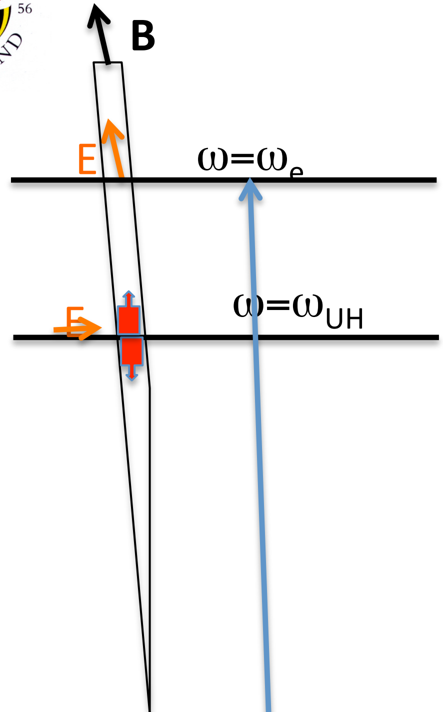




Multi-time and length scale modular code (DAIL code suite- Eliasson et al. JGR 2012):

Input: (i) HF E at 100 or 150 km (ii) Ambient density (iii) T_e

Output: (i)Temporal evolution of density (ii) optical emissions (iii) Supra-thermal EDF (iv) Plasma line



Code Components: (i) Multi-grid HF wave propagation with Zakharov eqs module (ii) Electron acceleration module using velocity diffusion tested against particle tracing (iii) Energetic electron transport model including elastic and inelastic collisions (iv) Ionization-recombination module (v) chemistry package (vi) optical emission package (vi) plasma wave package

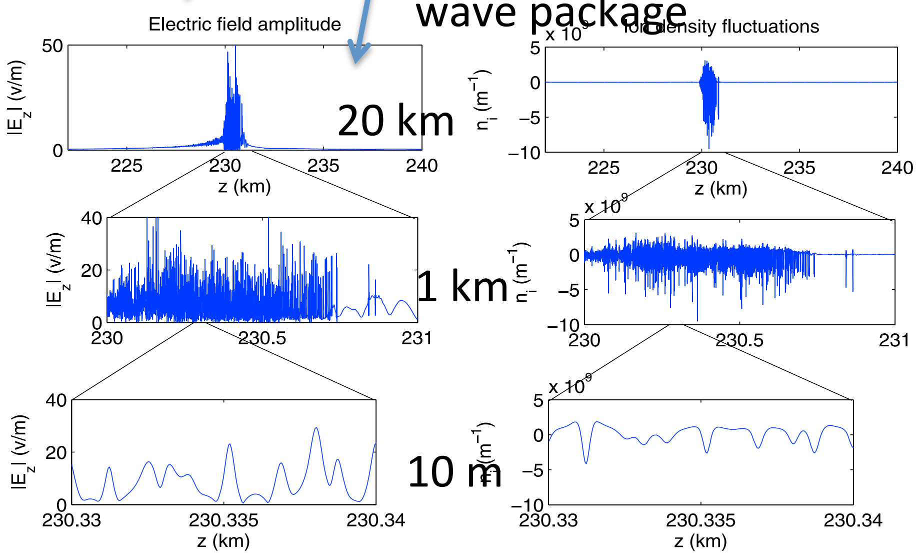
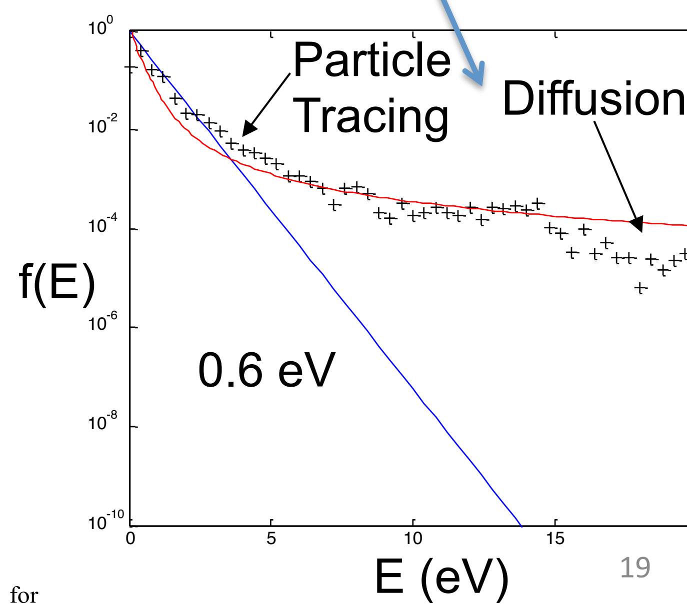
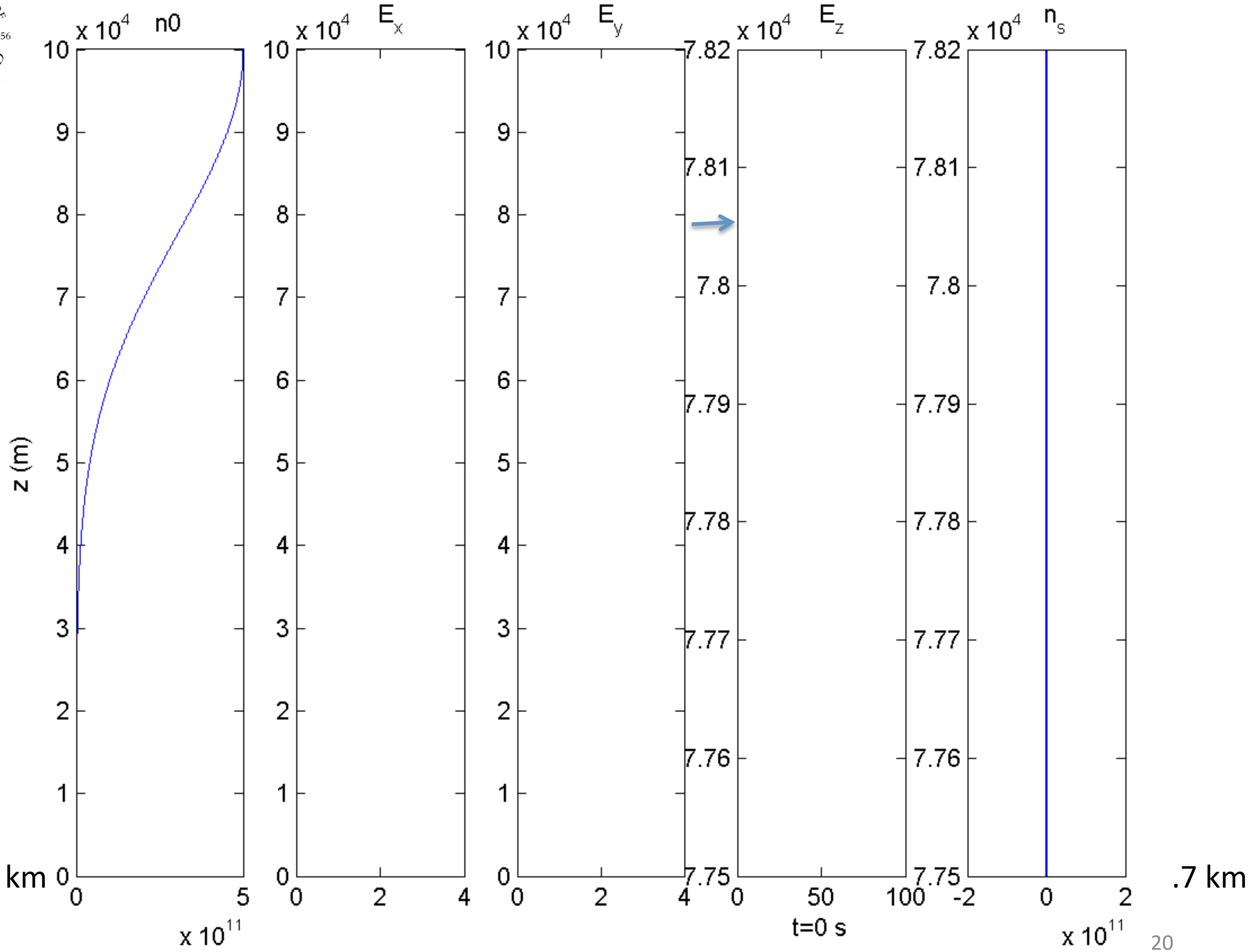


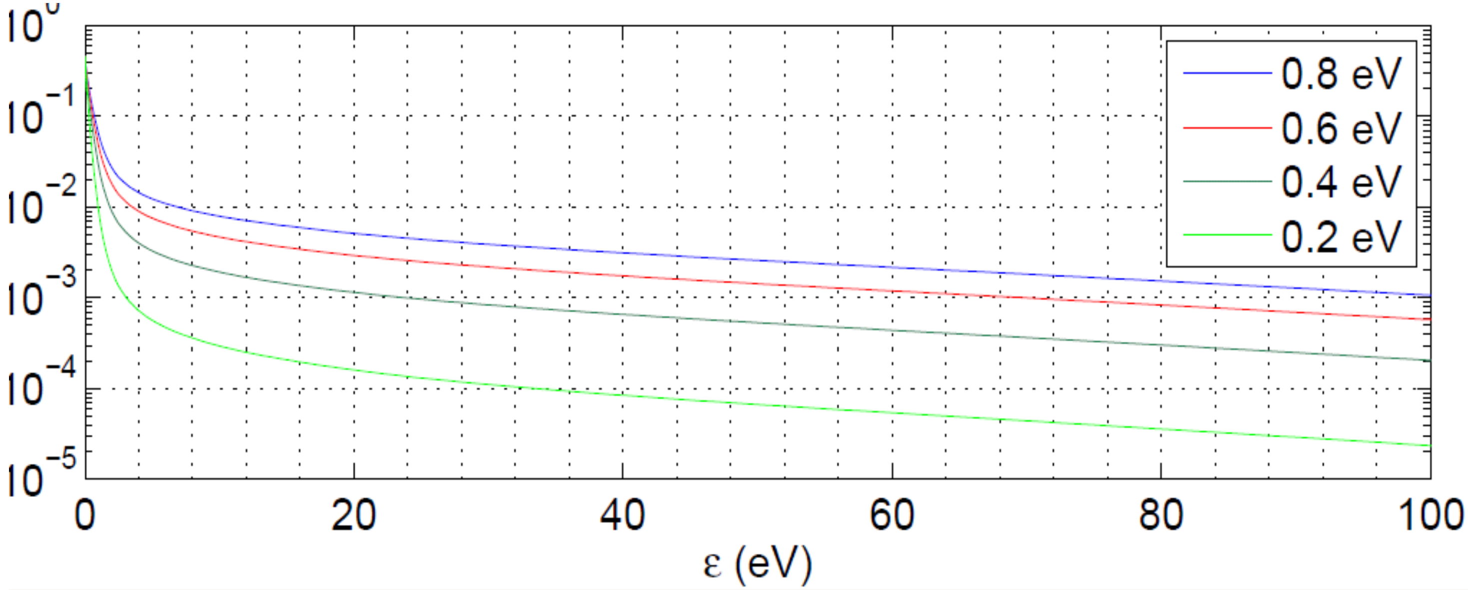
Figure 2. The amplitude of E_z and slowly varying ion density fluctuations n_i at various altitudes, for $E_O = 1.5$V/m.

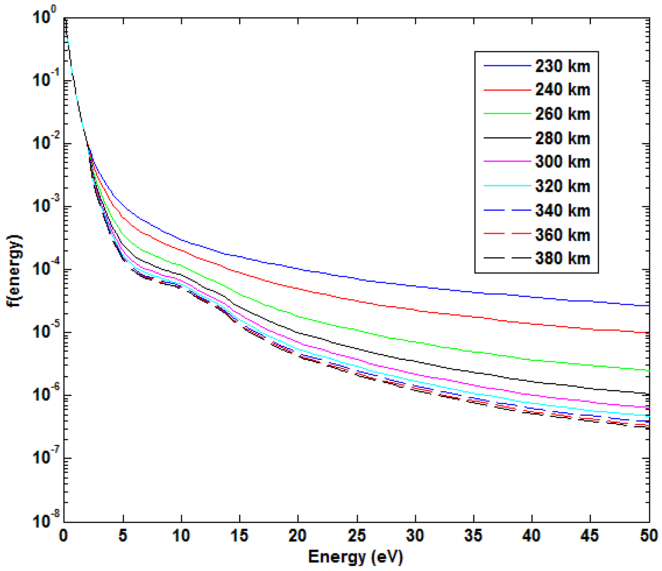




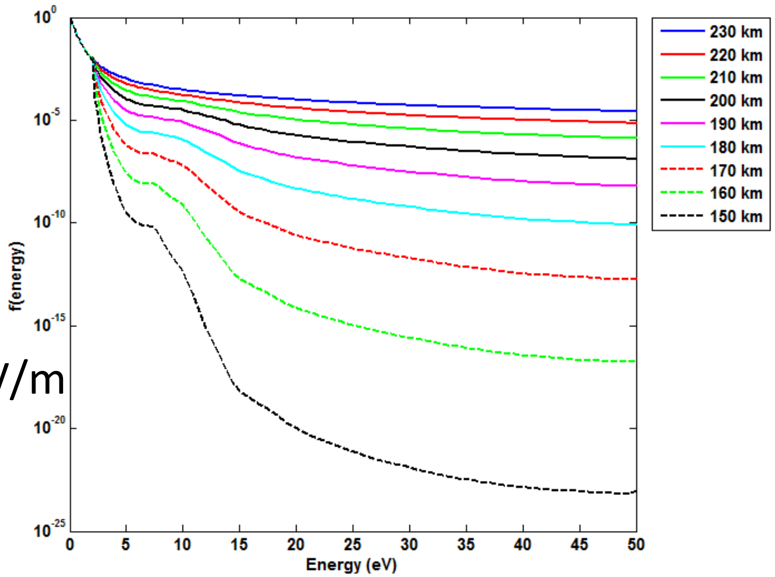
n0
E_x
E_y
E_z
n_s
x 10^4
z (m)
x 10^{11}
t=0 s
100 km
.7 km

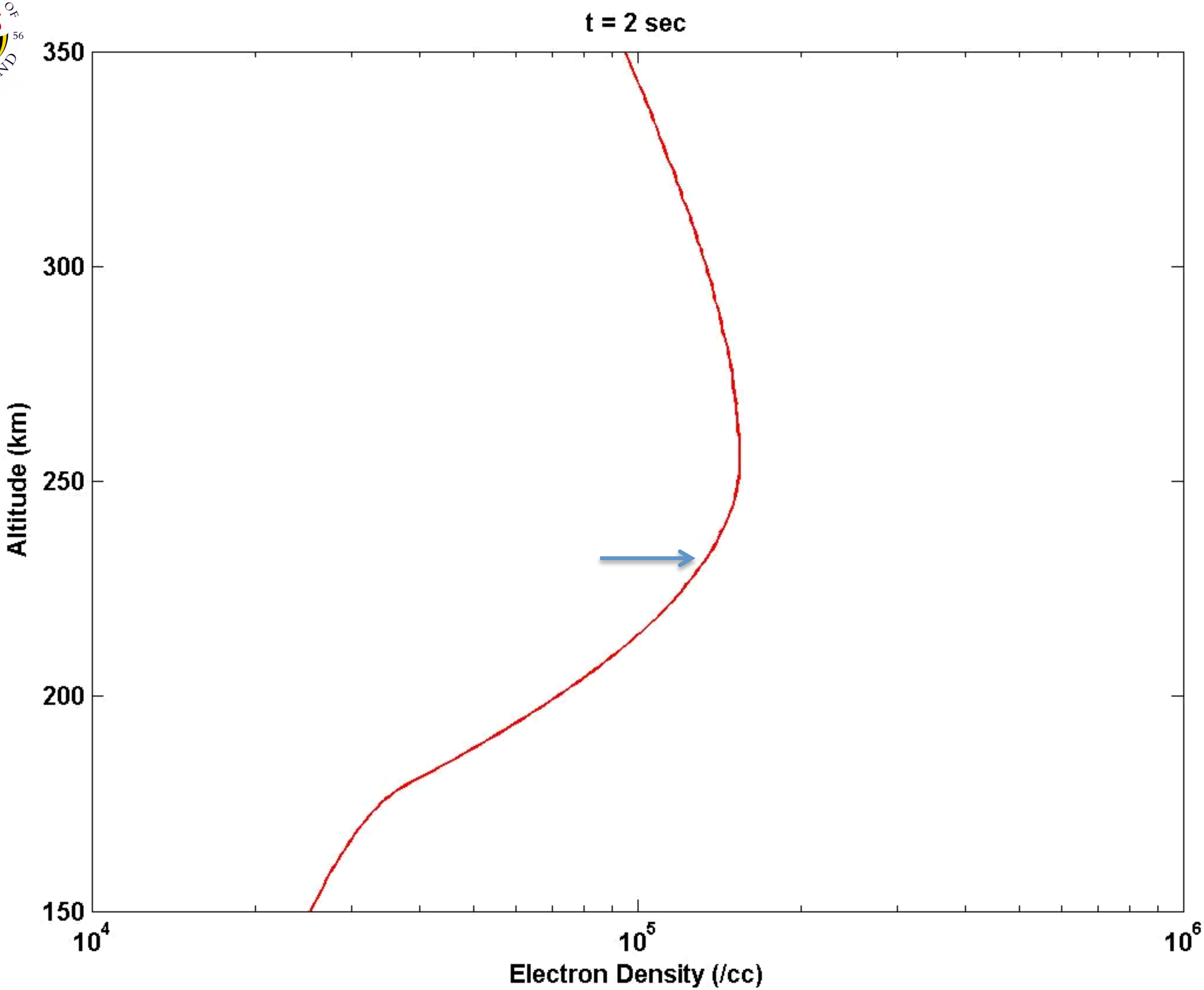
Normalized EDF of supra-thermal electrons for E 1.5 V/m at 100 km



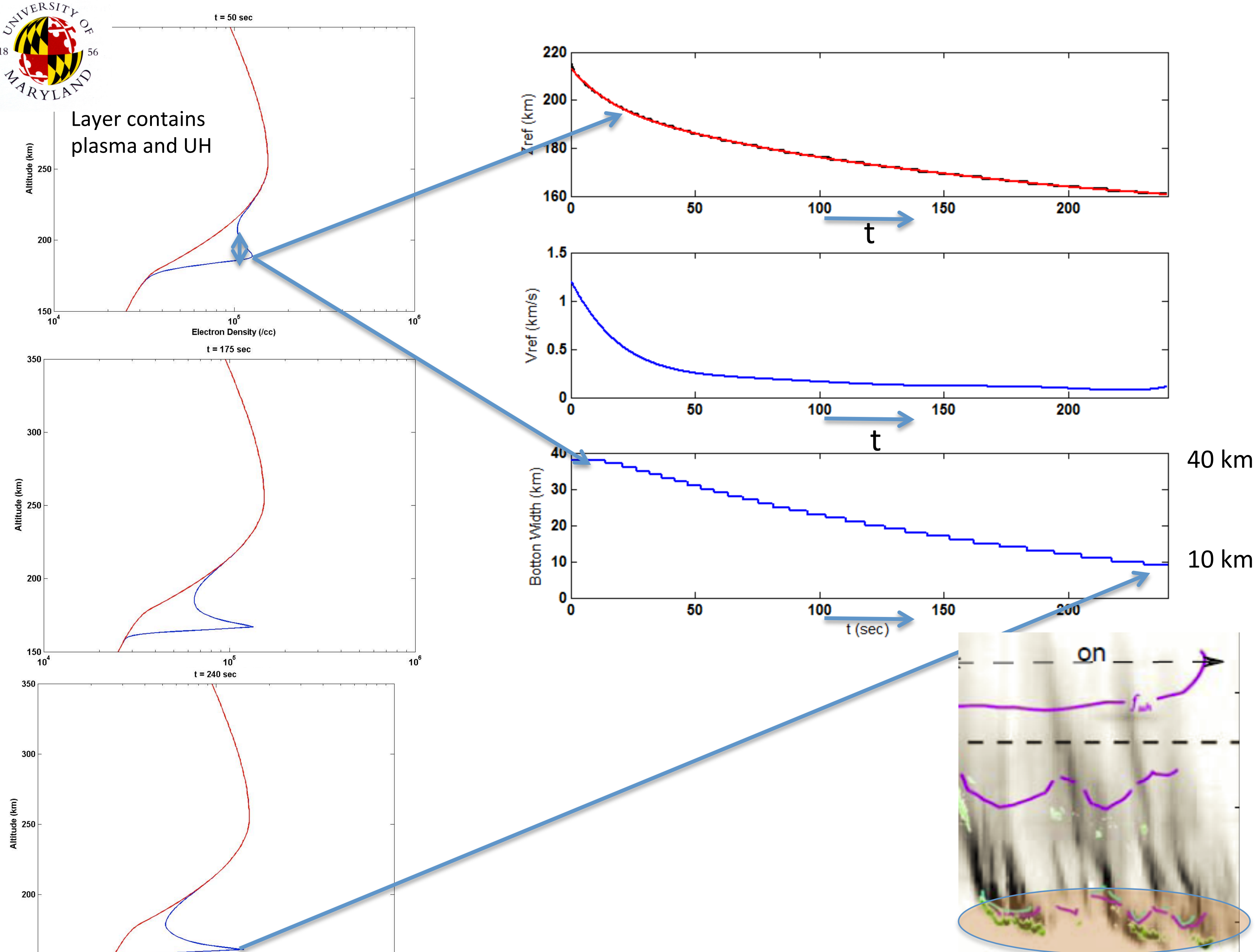


.6 eV, 1.5 V/m





t = 2 sec
350
300
250
200
150
Altitude (km)
10^4
10^5
10^6
Electron Density (/cc)


t = 50 sec
Layer contains plasma and UH
Altitude (km)
Electron Density (/cc)
t = 175 sec
t = 240 sec
Zref (km)
Vref (km/s)
Botton Width (km)
t
t (sec)
40 km
10 km
on
24
30
36

Algorithm

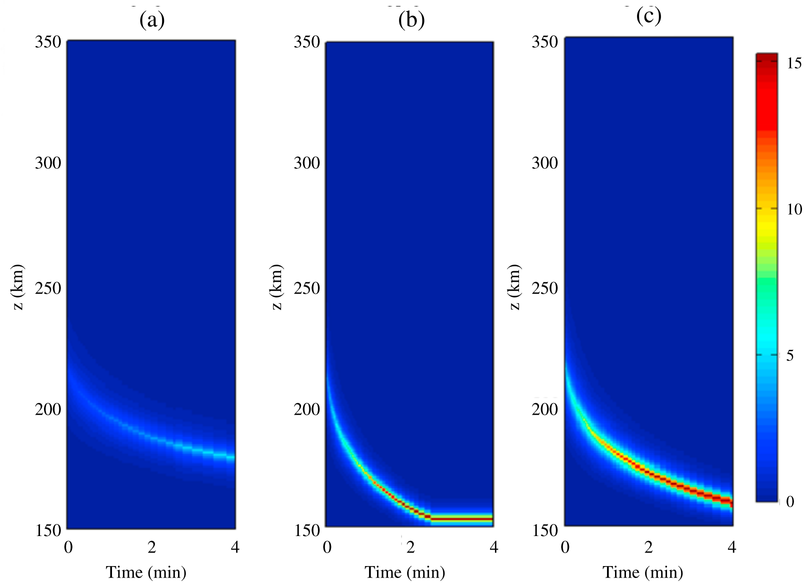
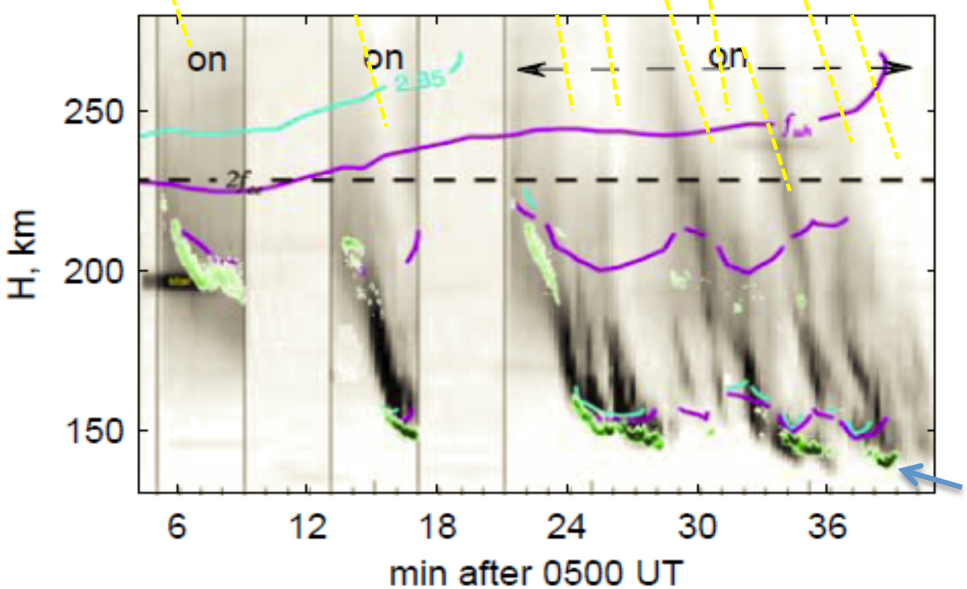


Figure 13. Green line emission as derived from simulation for different input wave amplitude and initial electron thermal energy: (a) $E_0 = 1$ V/m, $T_e = 0.4$ eV, (b) $E_0 = 1.5$ V/m, $T_e = 0.4$ eV, and (c) $E_0 = 1$ V/m, $T_e = 0.6$ eV

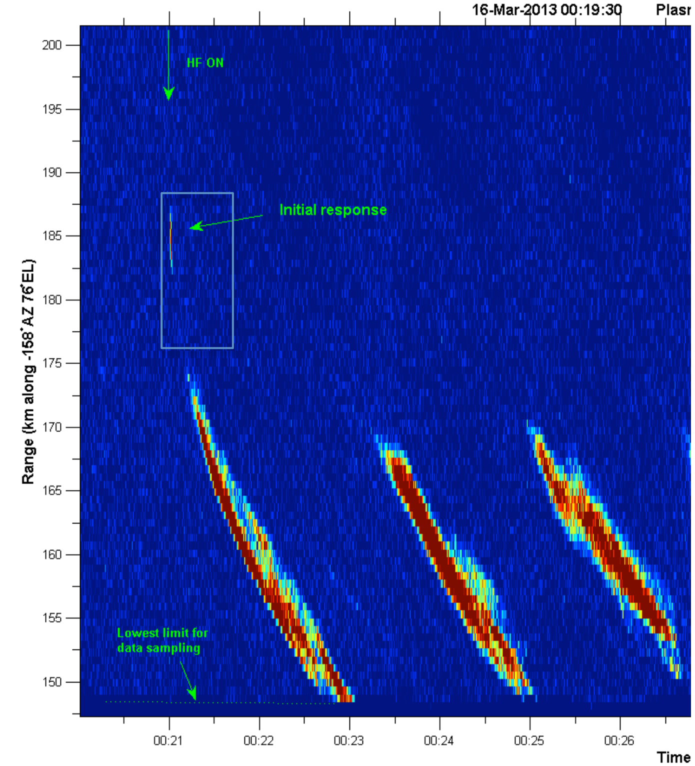


IA

f_p =2.85 MHz (blue), f_{UH} = 2.85 (violet)

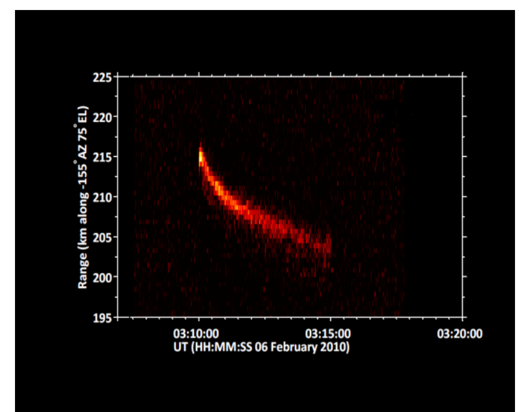
Pedersen et al. 2010

Plasma Line



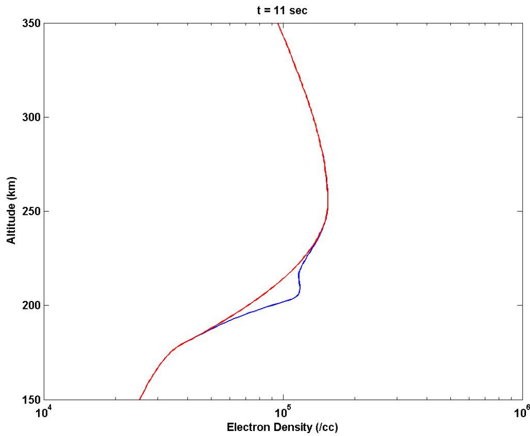
Descending ion-line and plasma line structures observed with UHF radar during heating.

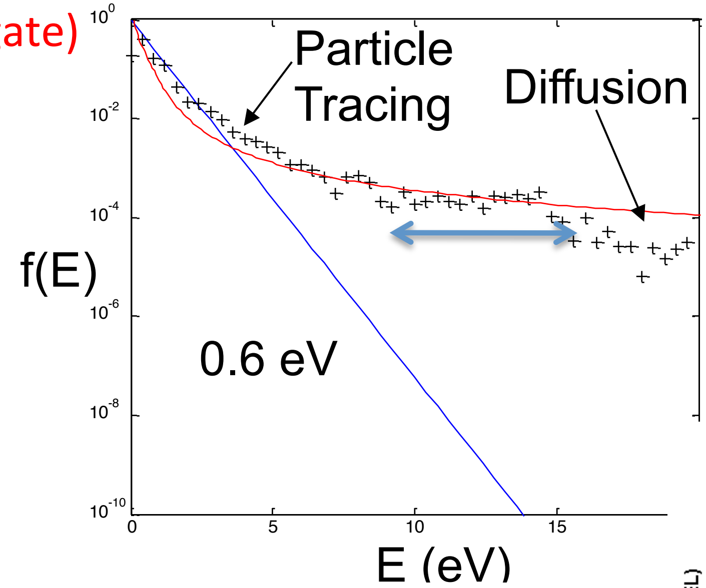
Watkins



Ion Line

HYPOTHESIS: Hot plasma .4-.6 eV with supra - thermal tails creates enhanced IA and electron plasma waves locally –(IA and plasma waves are damped within few meters and do not propagate)



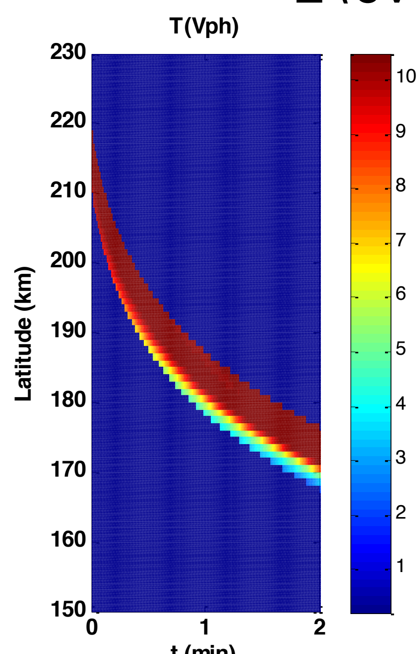


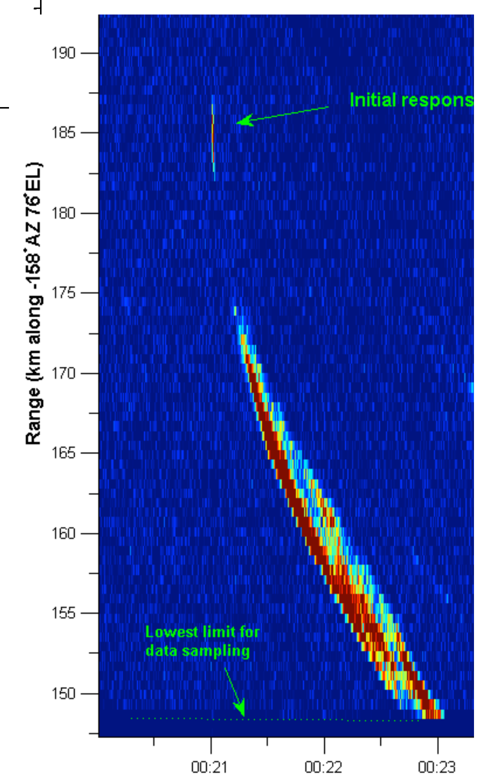
Classic signature of hot plasma with supra-thermal tails

$$\frac{<E^2>}{8\pi} \approx \frac{8ne^2}{\omega_e}\int_{k_1}^{k_2} dkk\, \frac{F_T(\omega_e/k)}{\left|F_T^{'}(\omega_e/k)\right|}$$

$$R \prec \frac{V_T^2/V_e^2}{/n(V_E/\alpha V_e)} \to (\lambda_R/\lambda_D)^2$$

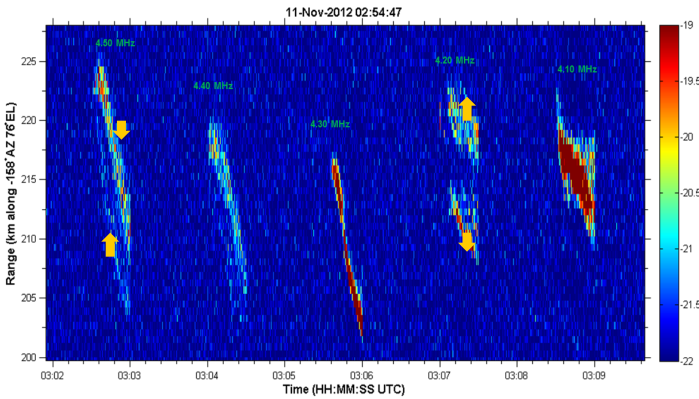
$$\text{if } \nu < \omega_e u_{ph}^2 F'(u_{ph})$$

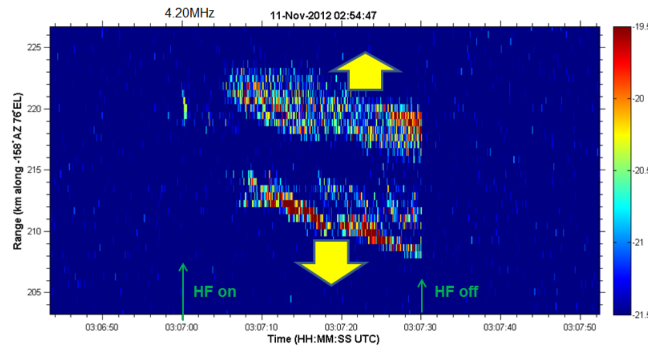


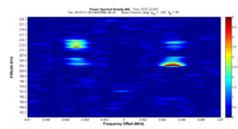


ION LINE PECULIARITIES

B. Watkins

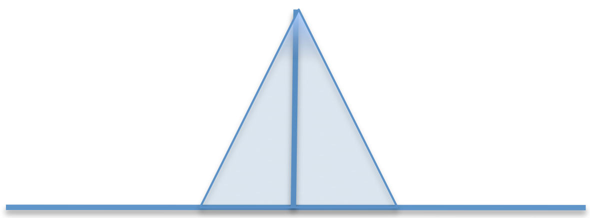




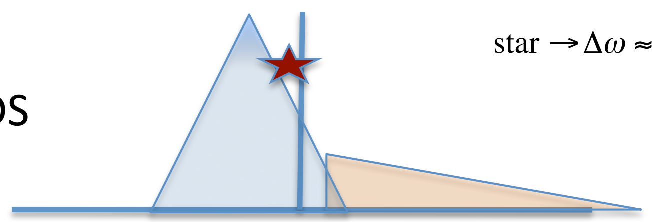


Power-height-time plot of HF-enhanced ion-line signals. Close to 3[rd] gyro-harmonic signals split into two layers. Doppler spectra (example to left) show strong asymmetries that indicate mainly upward propagating only ion-acoustic waves in the upper layer. The downward layer is associated with primarily downward propagating ion-acoustic waves.

The above spectral asymmetries are interpreted to be the result of electron flow upward and downward from the HF interaction region as indicated by the yellow-colored arrows.

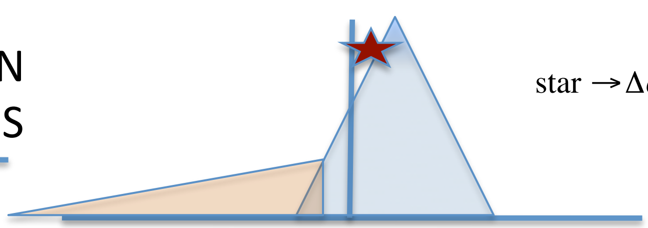


INJECTION DOWNWARDS →



star $\rightarrow \Delta\omega \approx 2k_R c_s$

INJECTION UPWARDS ←

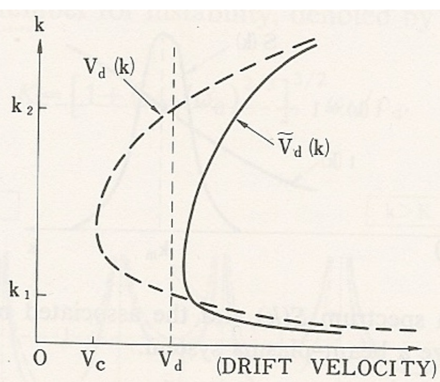


star $\rightarrow \Delta\omega \approx -2k_R c_s$

Plasma with drift
γ(k)=0 gives

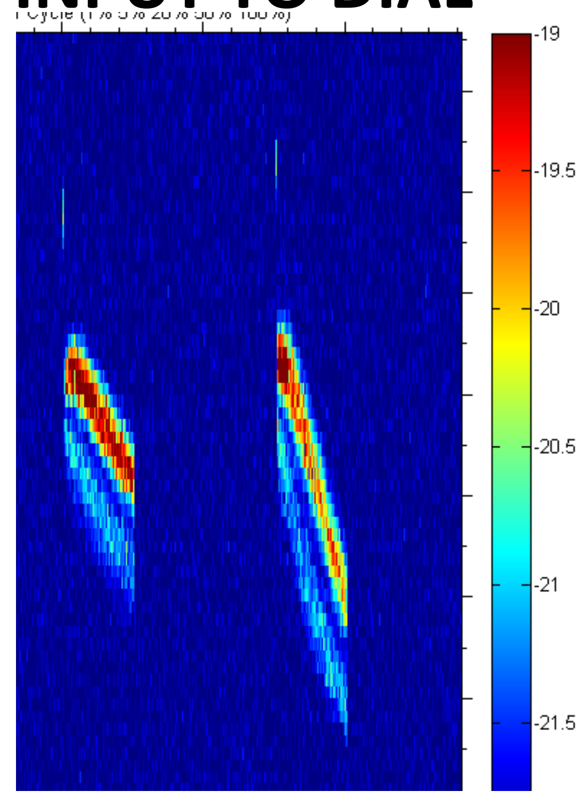
$$V_d(k) = (\omega_k / k) + (ion \text{ L damping})$$

$$S(k) = \frac{1}{2} \frac{\omega_k / k}{V_d(k) - Vd}$$

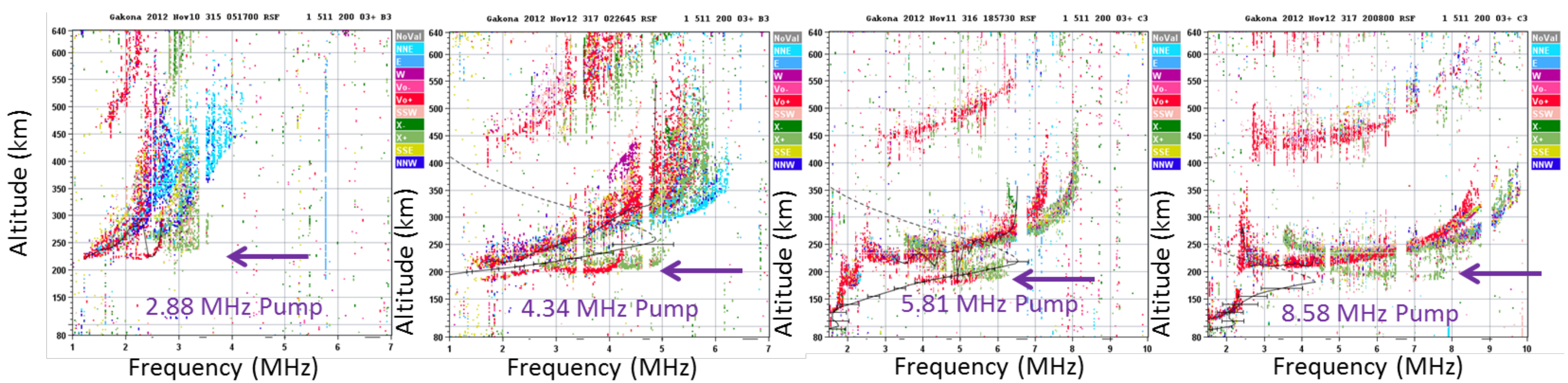


ONGOING PHYSICS STUDIES FOR INPUT TO DIAL MODEL

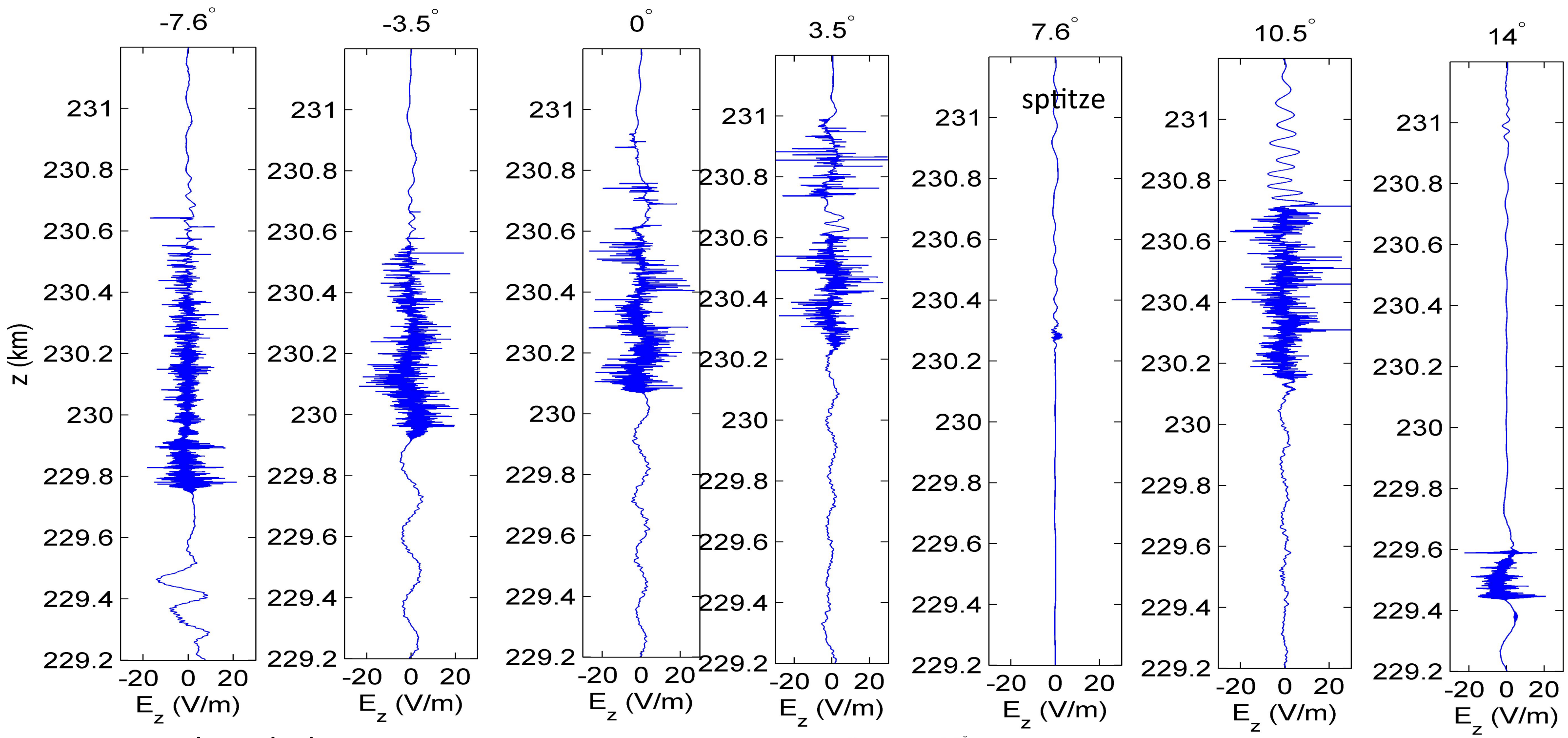
1. MULTI-DIMENSIONAL ISSUES
2. UPPER HYBRID
3. DOUBLE RESONANCE HEATING

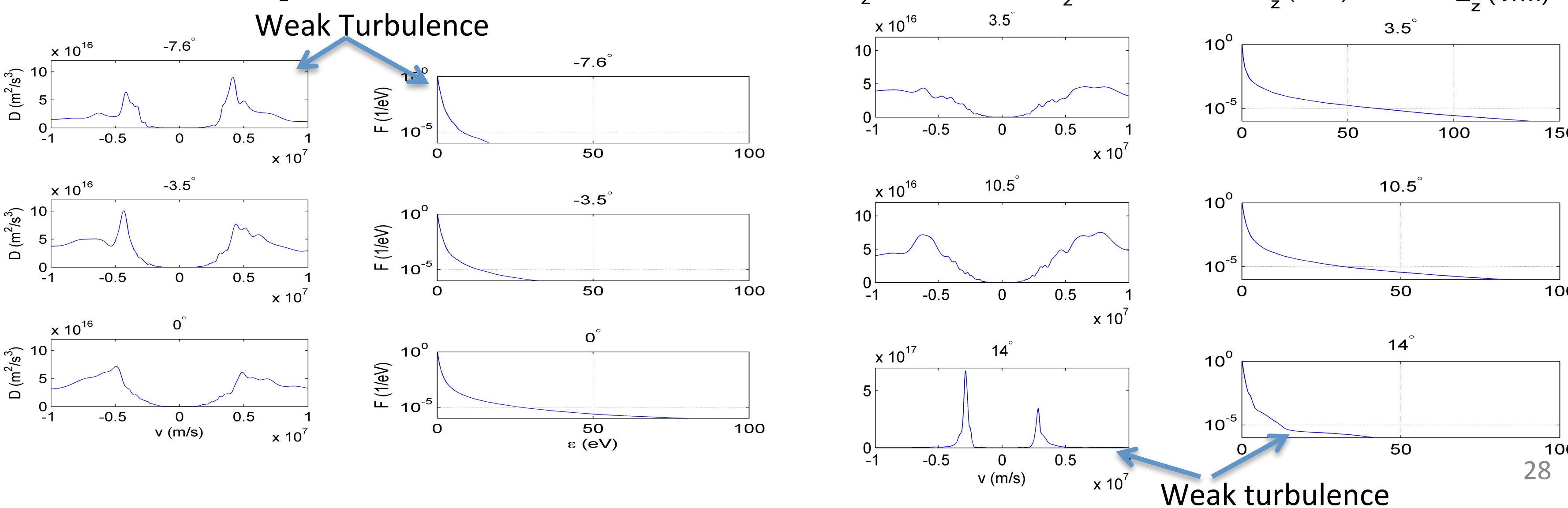


P. BERNHARDT



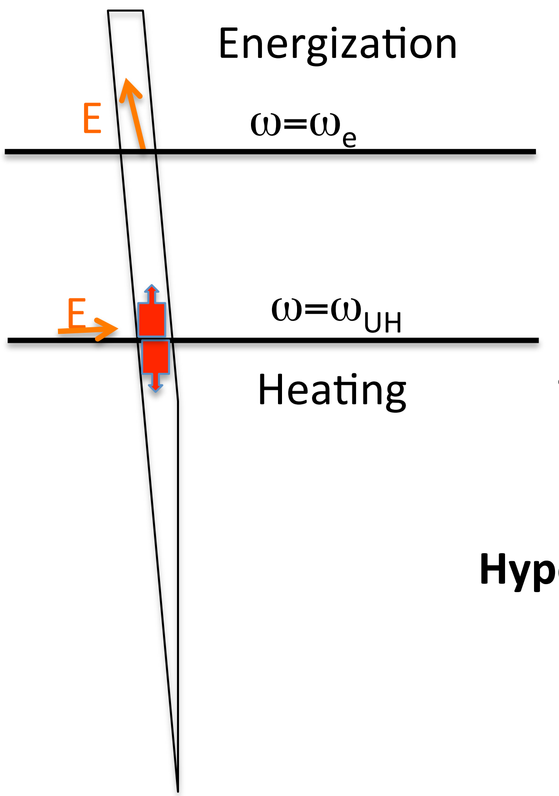
O-mode, 1V/m amplitude, electron temperature 0.4 eV, and different angles of incidence,

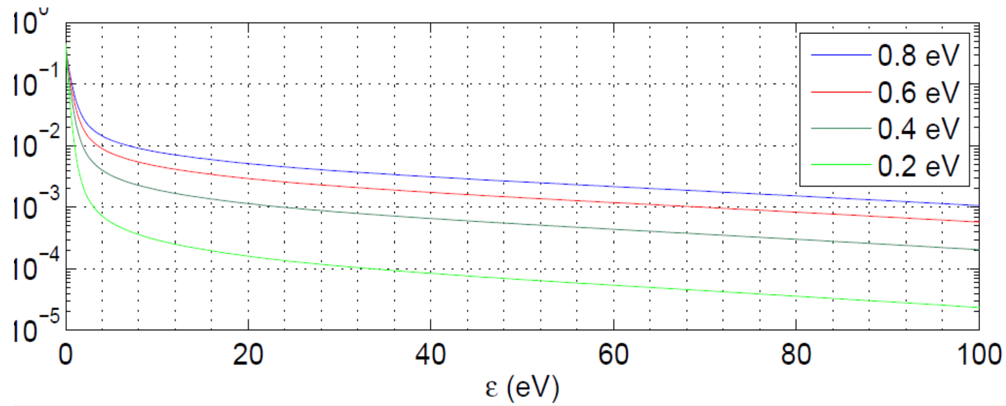




UH HEATING AND THE ROLE OF DOUBLE RESONANCE $\omega_{UH} \approx n\Omega_e$

Is it related to ECR acceleration and how do we account in the context of our DAIL model?



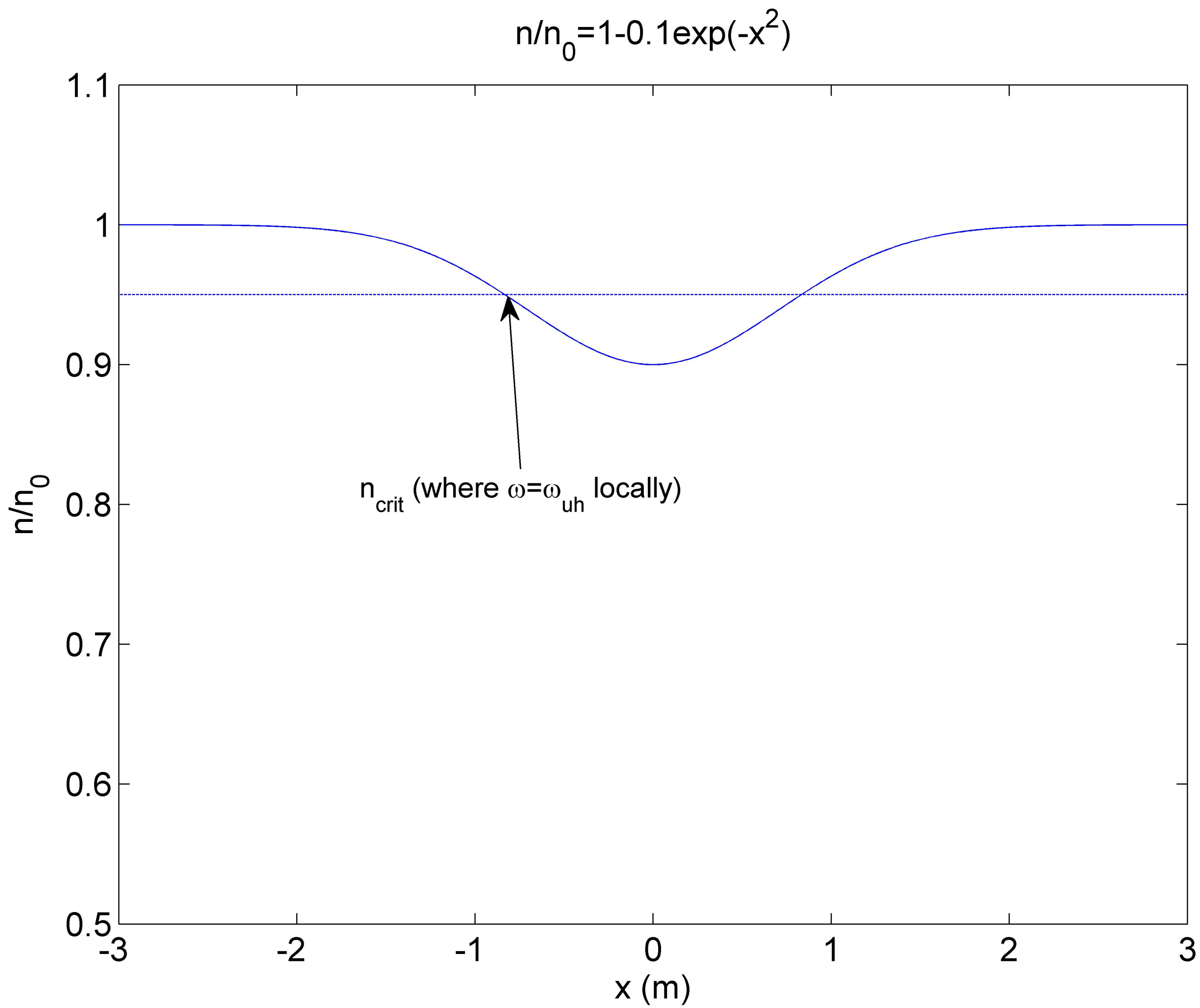


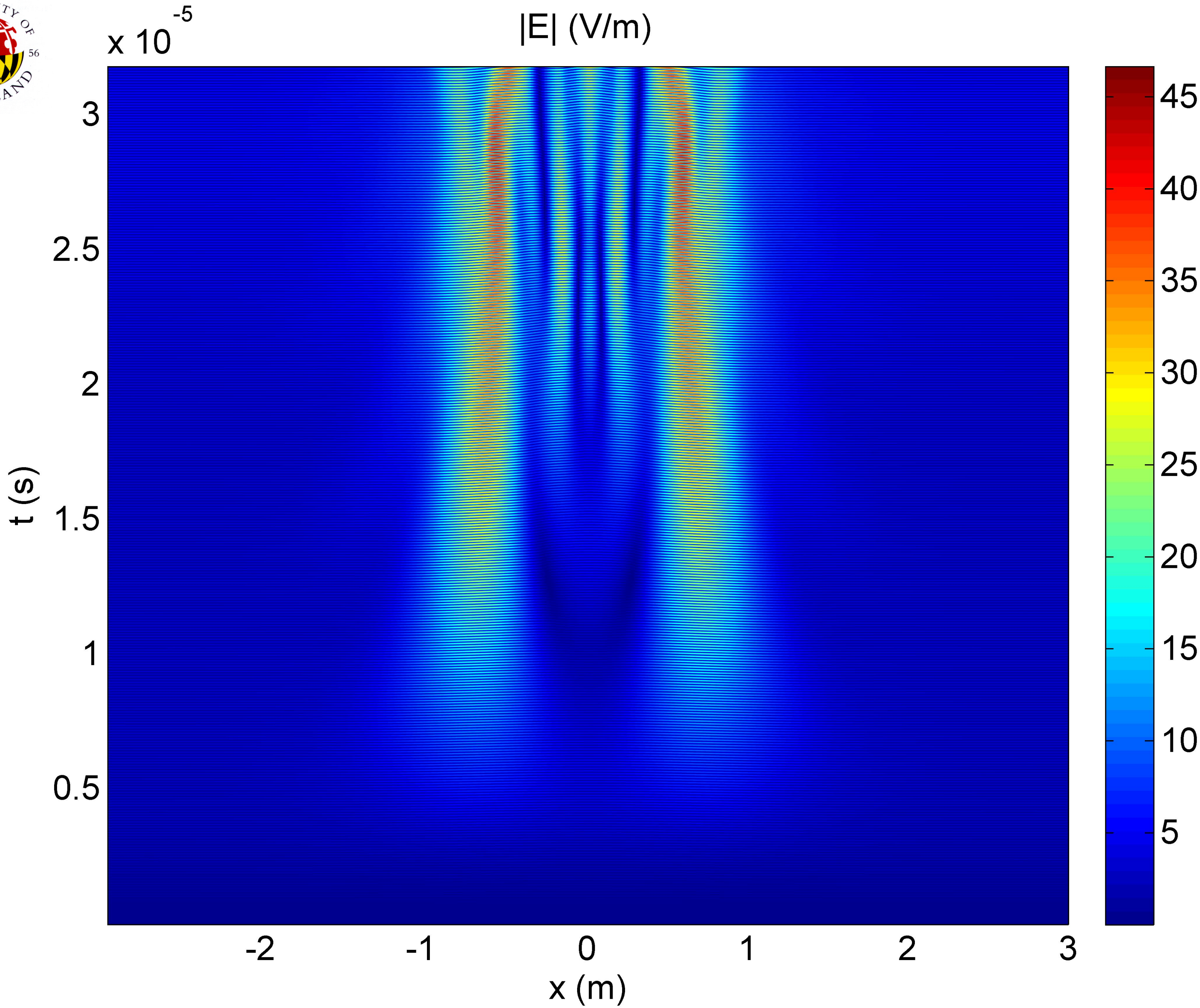
The extent of acceleration depends of heating

Hypothesis: UH heating different under double resonance

Next : Two ongoing studies of UH heating

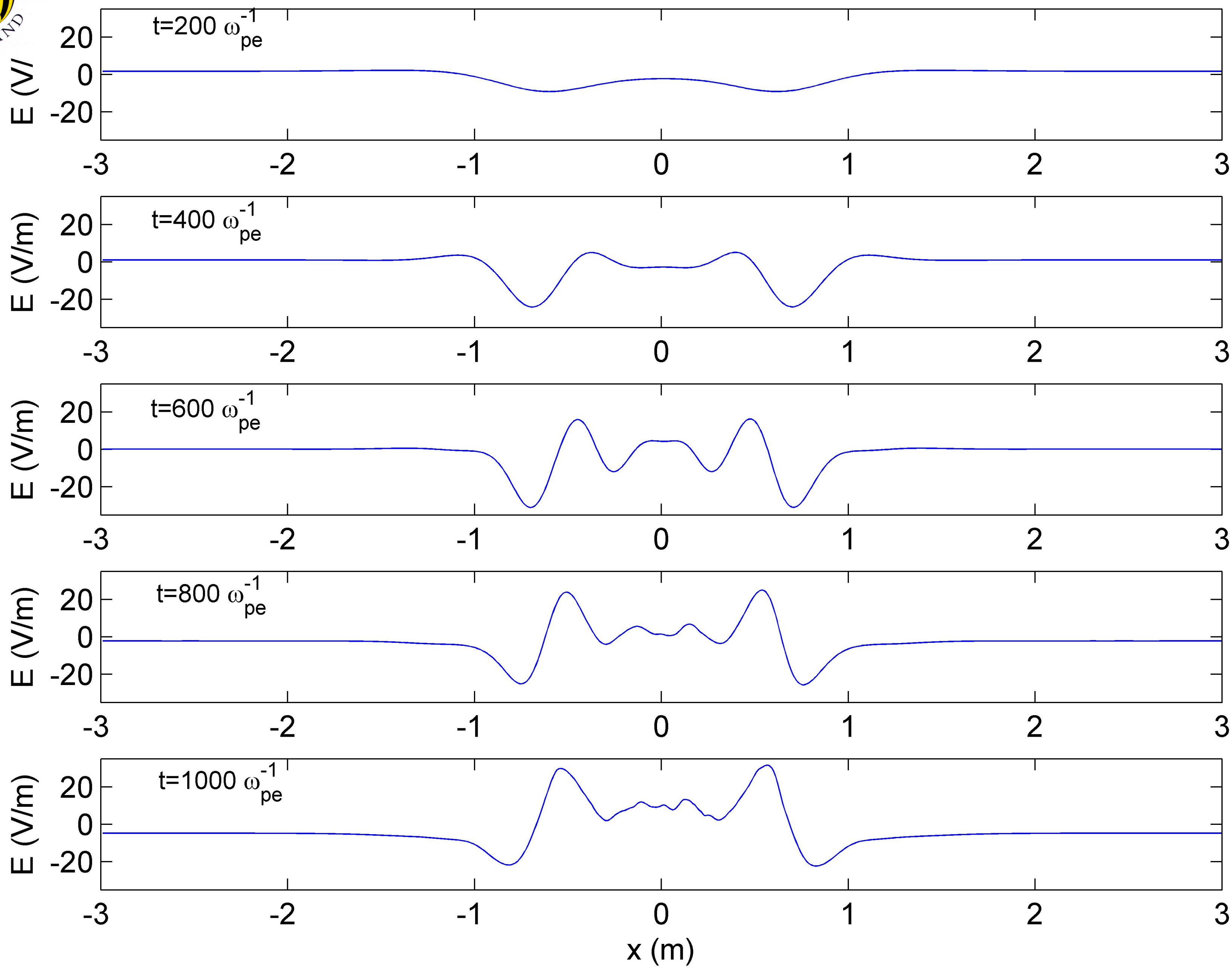
UPPER HYBRID – RESONANCE ABSORPTION





|E| (V/m)
x 10^-5
3
2.5
2
1.5
1
0.5
t (s)
-2
-1
0
1
2
3
x (m)
45
40
35
30
25
20
15
10
5

ω_{pe}=31.4×10^6 s^{-1}, ω_{ce}=0.248ω_{pe}, ω_{UH}=1.030ω_{pe}, ω=1.004ω_{pe}



STUDY ELECTRON HEATING DUE TO ES WAVE GIVEN BY $E_x=E_o \sin(kx-\omega t)$

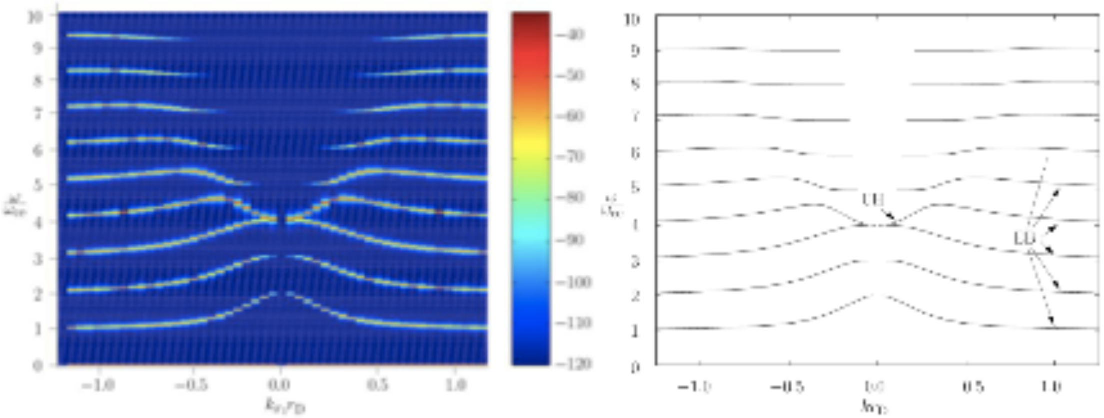


Figure 2: Power spectrum obtained from a Vlasov simulation (left) and theoretical dispersion diagram (right) showing the upper hybrid (UH) branch and several electron-Bernstein (EB) modes at the electron cyclotron harmonics for $\omega_{UH} = 4\omega_{ce}$. The wave energy is concentrated to the eigenmodes of the system. After *Eliasson* (2010).

Stochasticity analysis 10^4 particles

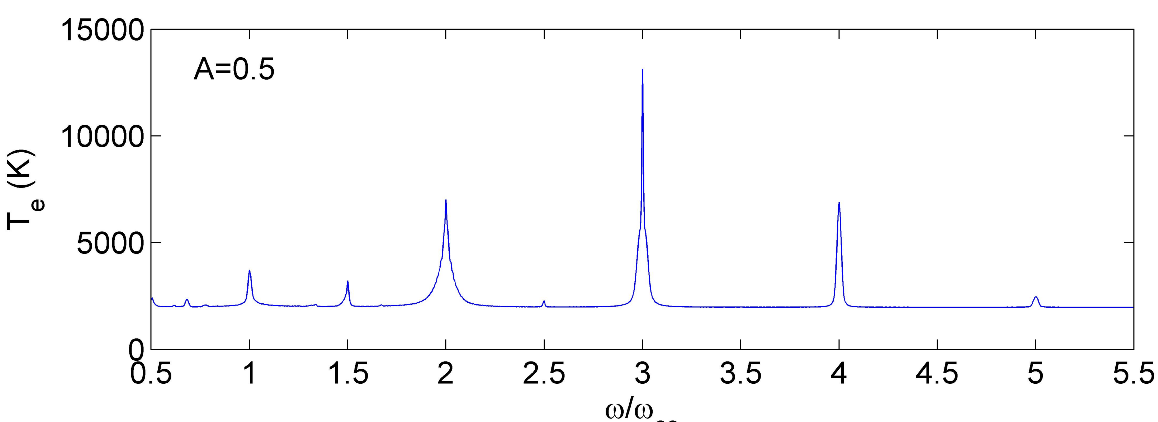
$$m\frac{d\mathbf{v}^j}{dt} = -eE_0 \sin(k_x x^j - \omega t)\hat{\mathbf{x}} - e\,\mathbf{v}^j \times B_0\hat{\mathbf{z}}$$

$$\frac{dx^j}{dt} = v_x^j$$

$$\frac{du_x^j}{dt} = -A\sin(u_y^j - \Omega t) - u_y^j$$

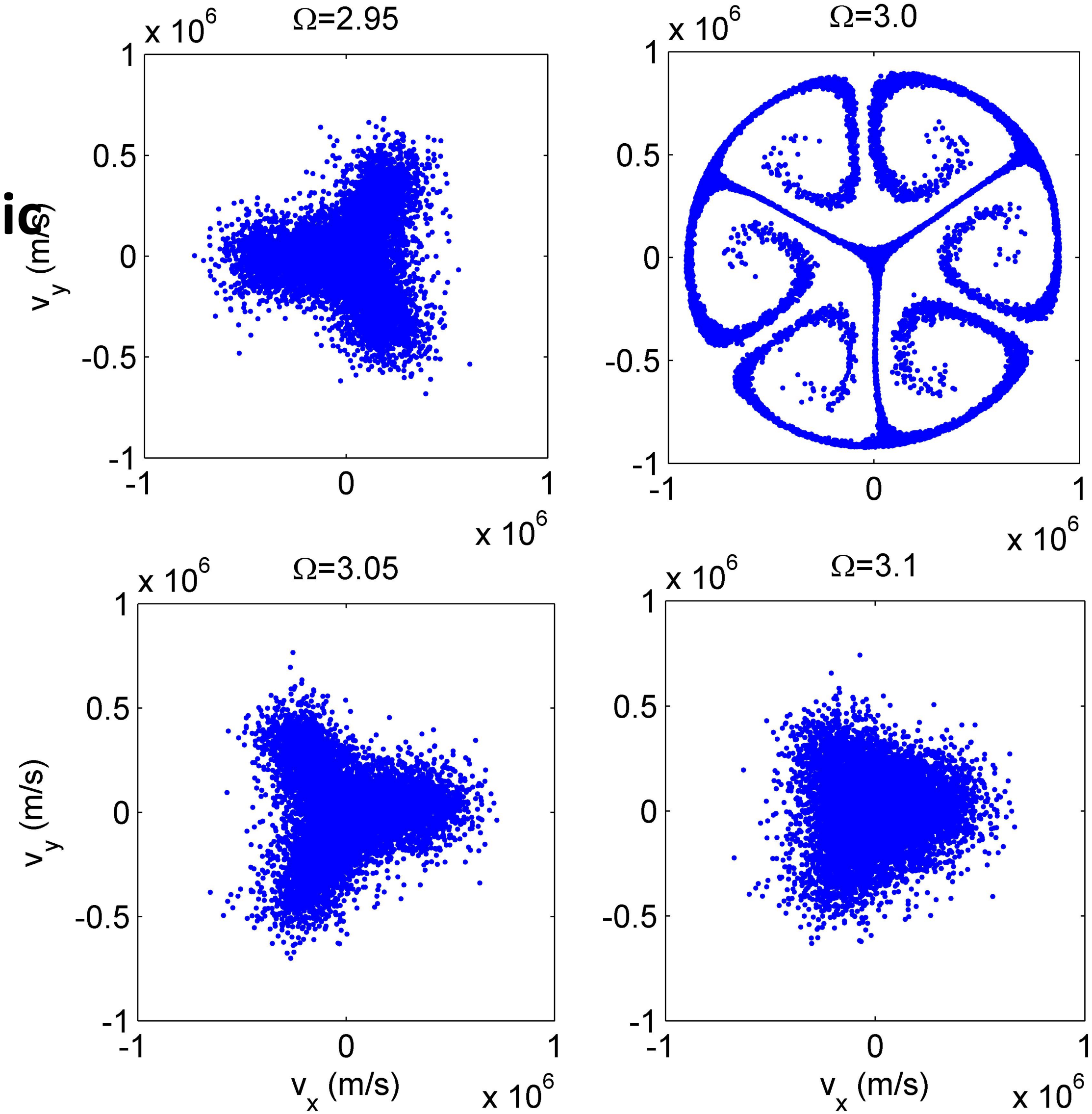
$$\frac{du_y^j}{dt} = u_x^j$$

$A=ek_xE_o/m\Omega_e^2$, $\Omega=\omega/\Omega_e$,
Velocity norm to ω/k, t->$1/\Omega_e$



3.5 V/m

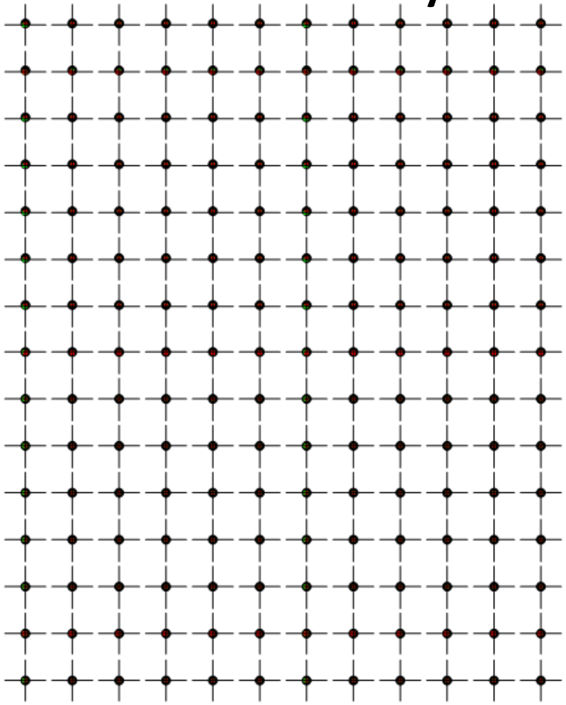
Strongly anisotropic Heating



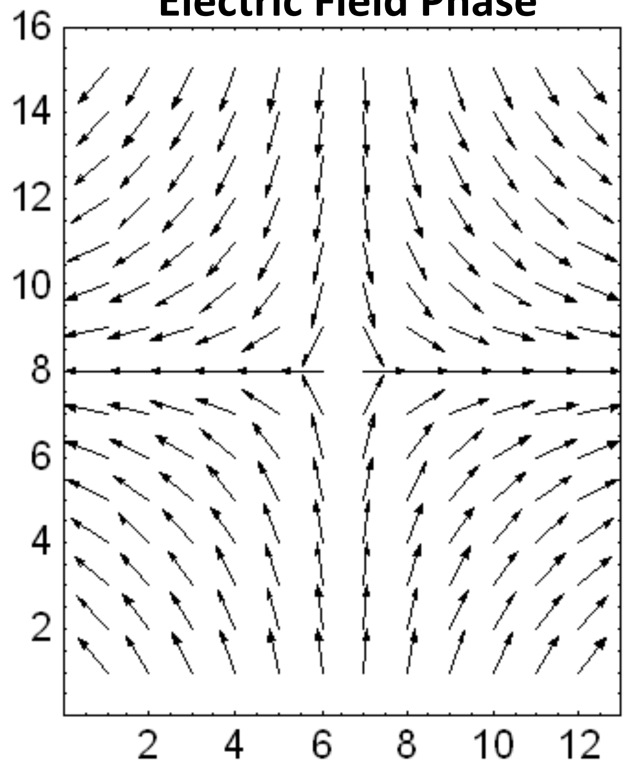
BERNHARDT

L=1 OAM Generation with HAARP

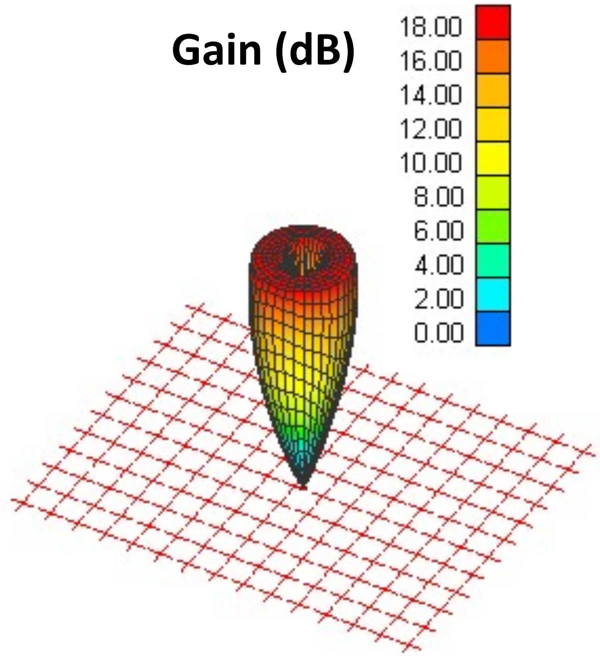
Antenna Array



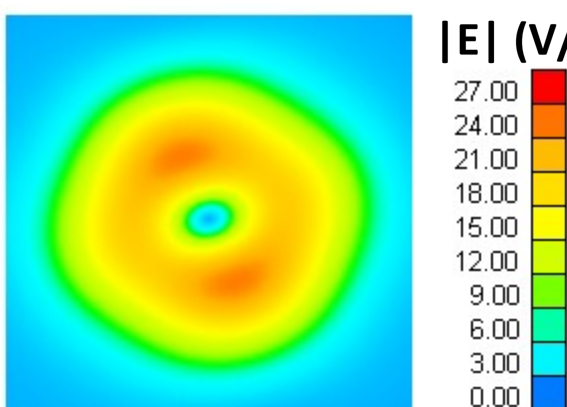
Electric Field Phase



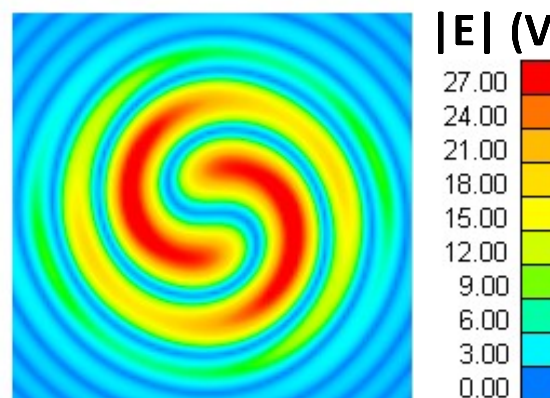
Gain (dB)



Average |E| (V/m)



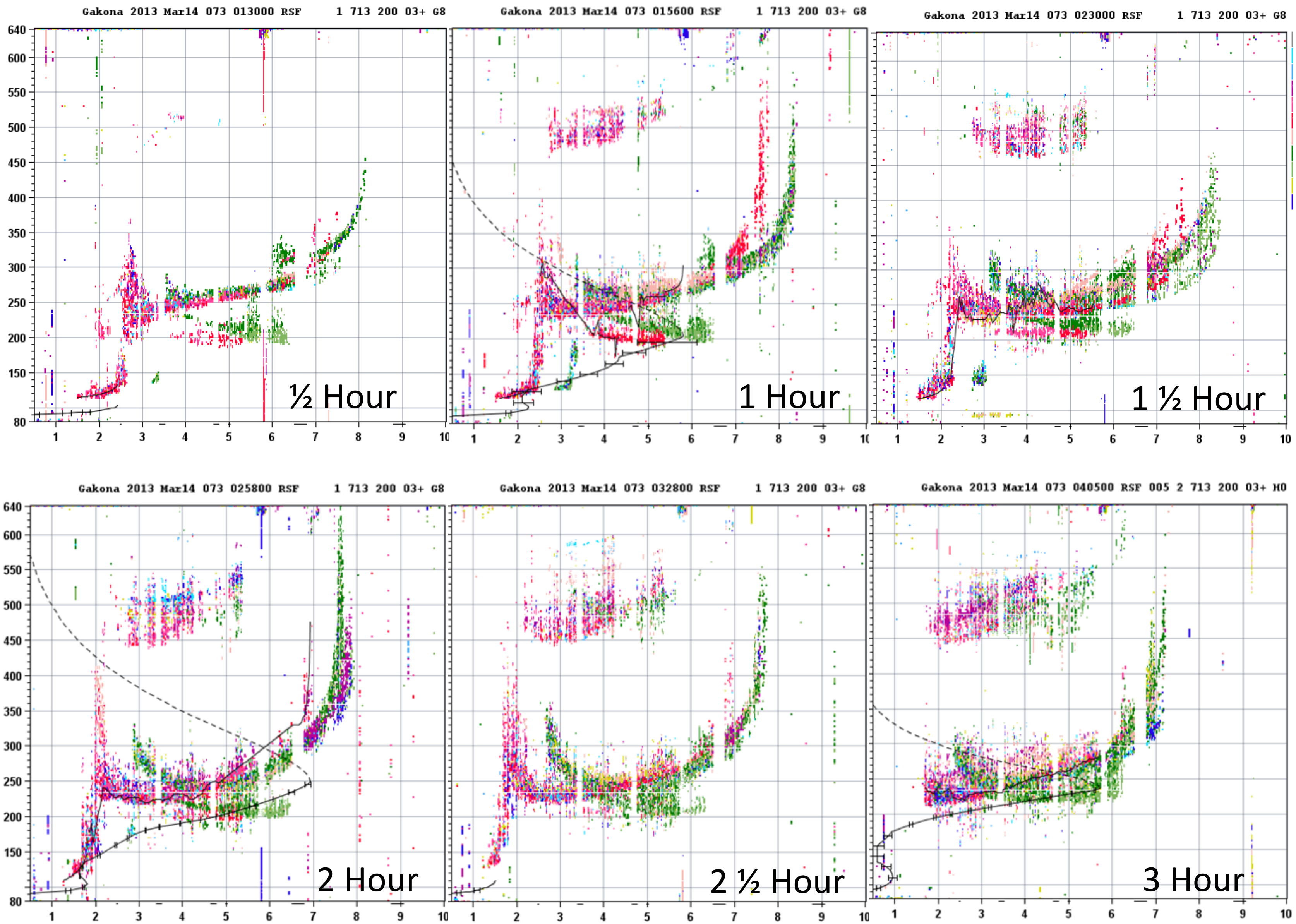
Instant |E| (V/m)



BERNHARDT

14 March 2013 01:30 to 04:00 GMT

Extended Artificial Ionization with 5.8 MHz Twisted Beam



SUPPELEMENTARY SLIDES

SEE Spectra

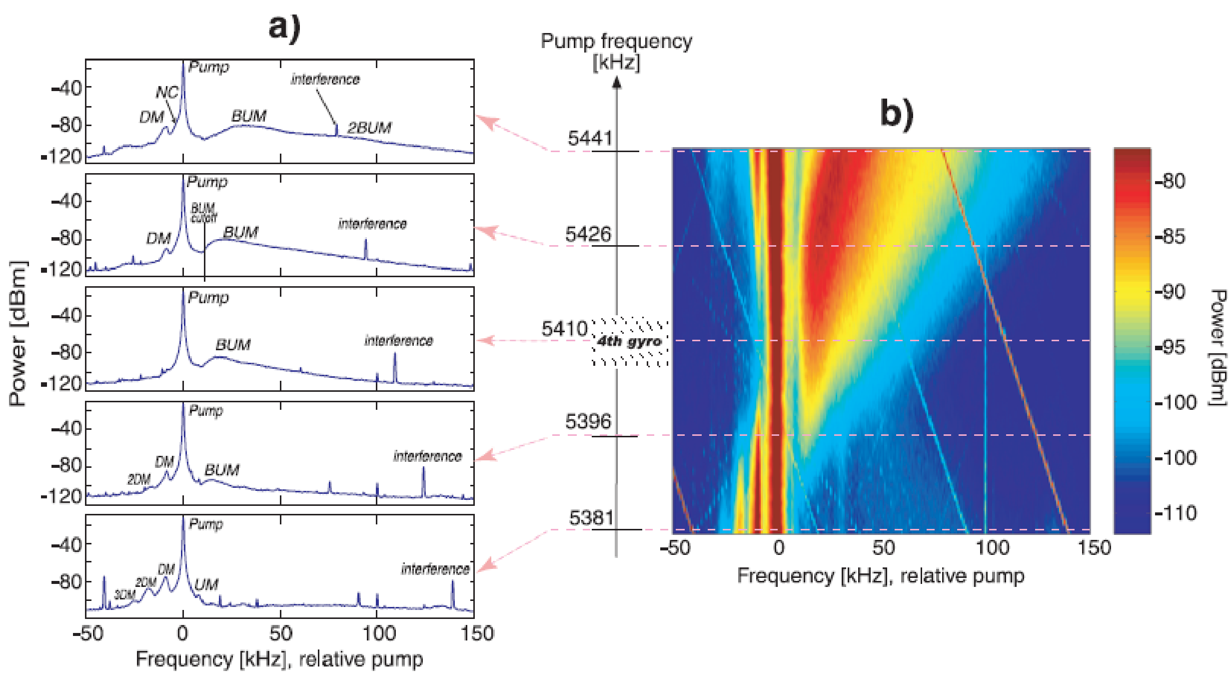
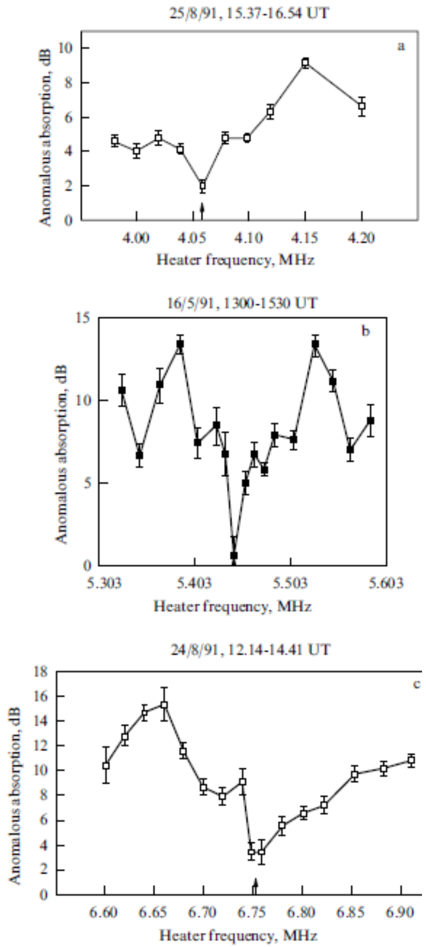


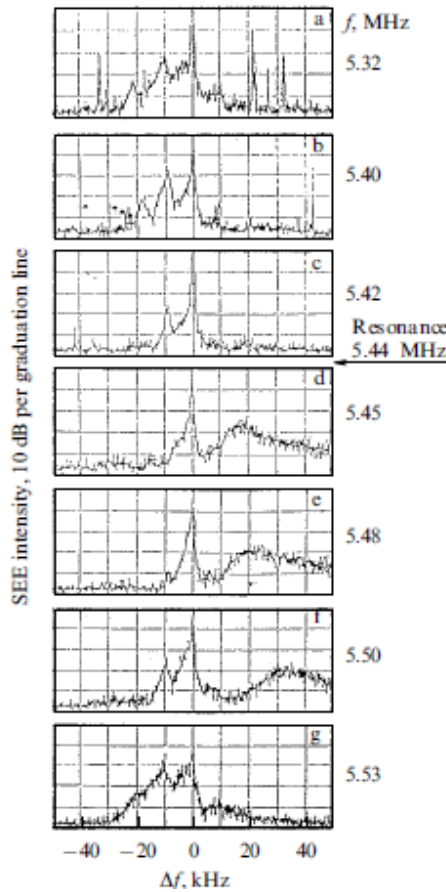
Figure 3. (a) The stack of five plots showing SEE spectra for the five different pump frequencies marked on the vertical axis in the middle of the figure. The standard SEE spectral features and the pump are labeled. These spectra are cross sections of the pump relative spectra versus pump frequency two-dimensional plot in Figure 3b. (b) The position of the cross sections are marked with dashed, magenta lines. The estimated range of the local fourth gyroharmonic is shown as a hatched region on the pump frequency axis.

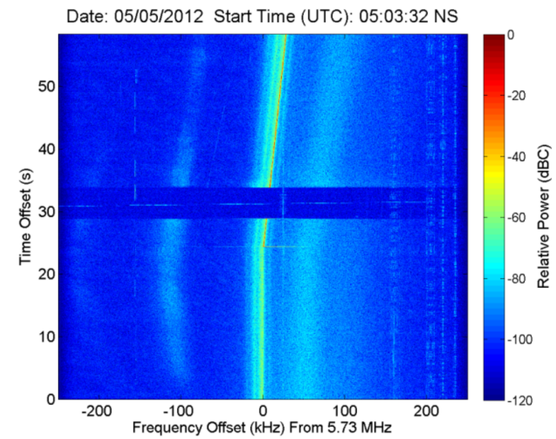
SuPer-Short Striations

Effects associated with $\omega \approx \omega_{uh}(z) \approx n\Omega_e$

Gurevich Physics-Uspekhi, 2007







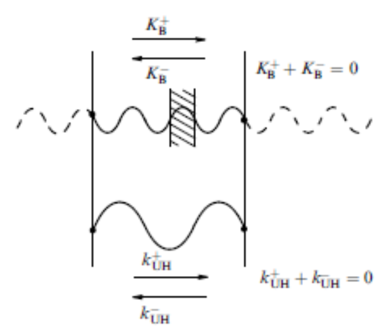
Paul's BUM

Need for four wave interaction – Pump, UH, EB, IA.

$$Pump(\omega, k_o = 0), UH(\omega_1, k_1), EB(\omega_2, k_2), IA(\omega_s, k)$$

$$\omega_1 + \omega_s = \omega = \omega_2 - \omega_s, \rightarrow \omega_2 > \omega$$

$$k_1 + k = 0 = k_2 - k, \rightarrow k = k_2 \approx O(1/r_e)$$

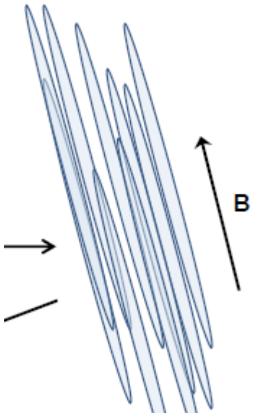


Suppression of anomalous absorption

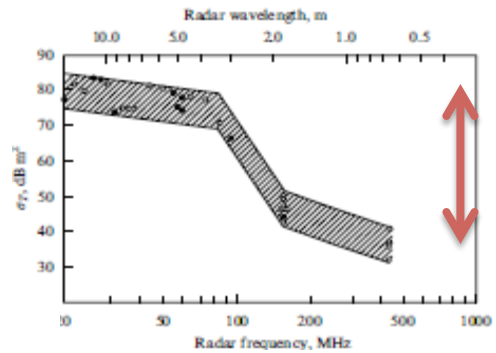
BUM

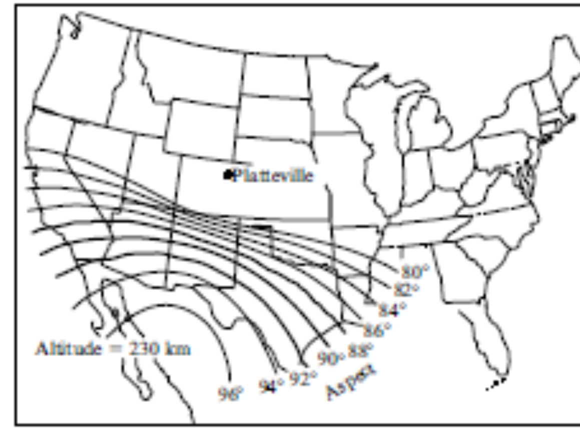
Generation of short scale FAI Super-Short-Striations (SSS)

Raising MUF to GHz



Platteville FAS:





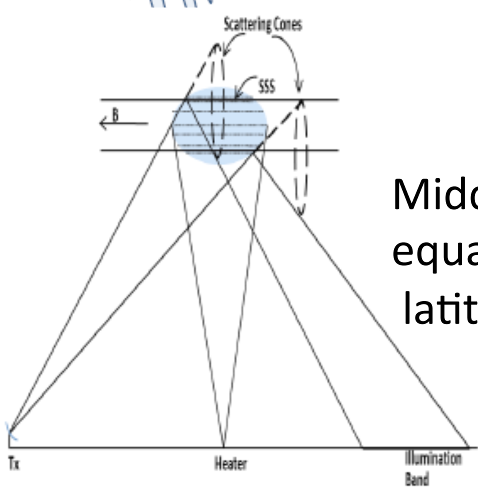


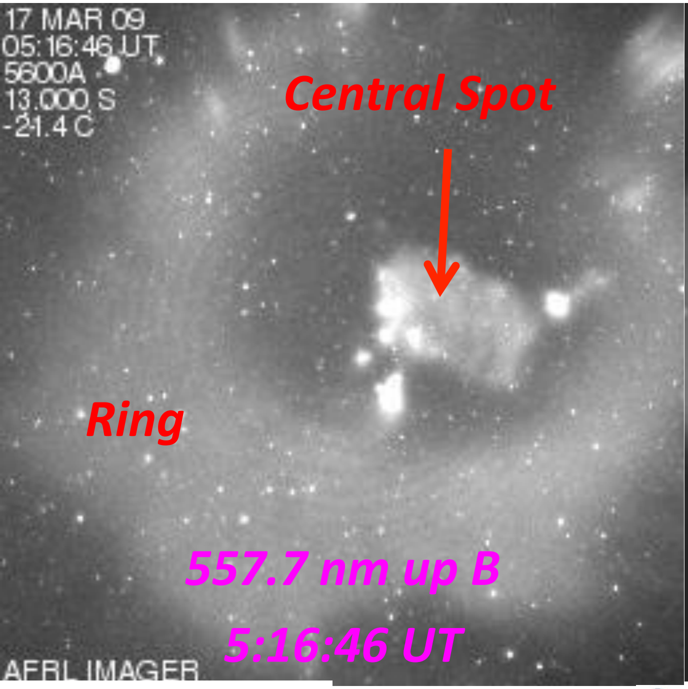
Fig. 1: Schematic of SSS FAS system at GHz.

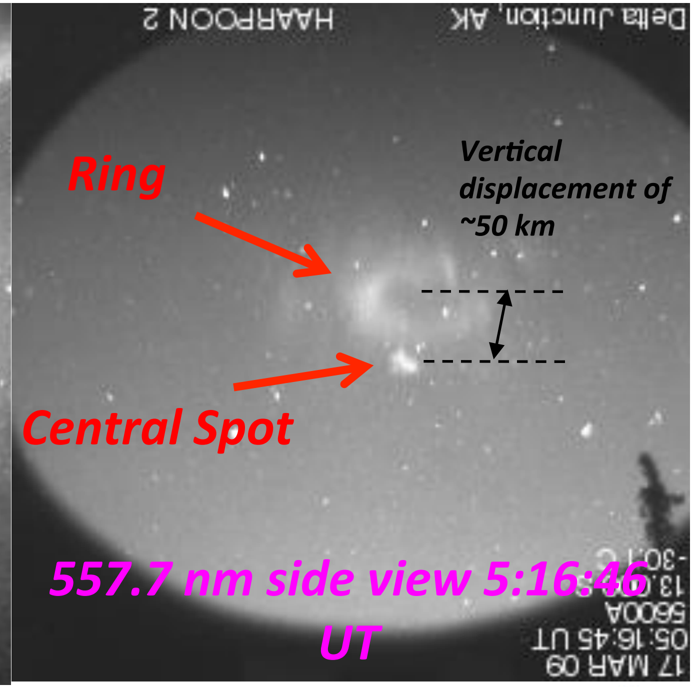
Middle or equatorial latitude

Potential answer from physics of ion cloud formation

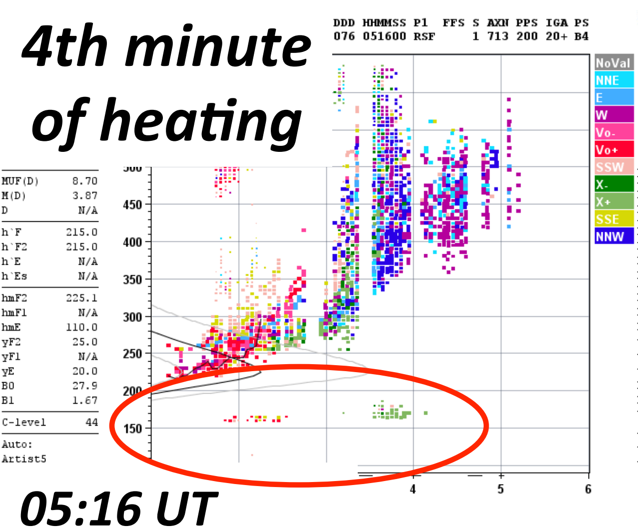
FAS Concept- Aspect scattering. RF transmitted from Tx along the 90° line are orthogonal to FAI and will be observed everywhere at the 90° line. Tx located in the 92° line observed at 88° and vice versa

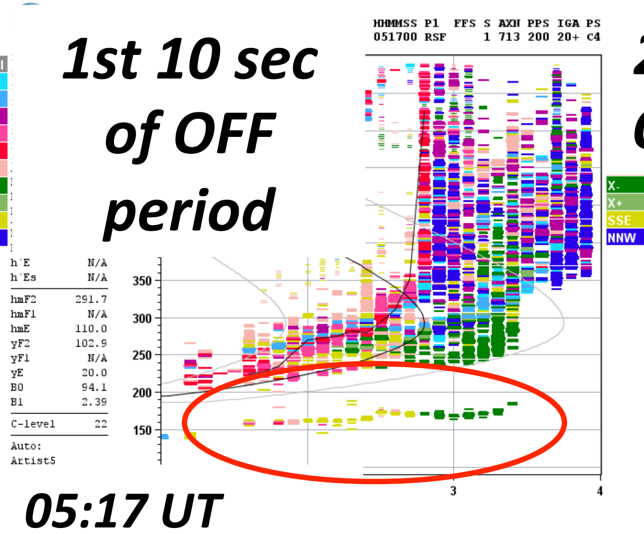
Mystery Solved by Multi-Site Optical Observations: March 2009

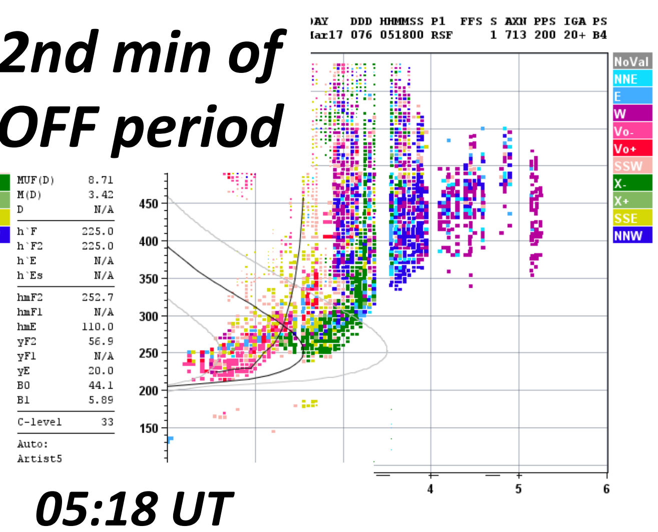




- Combined data sets indicate presence of artificial plasma sufficient to interact with heater beam
- At altitudes with no significant natural plasma!







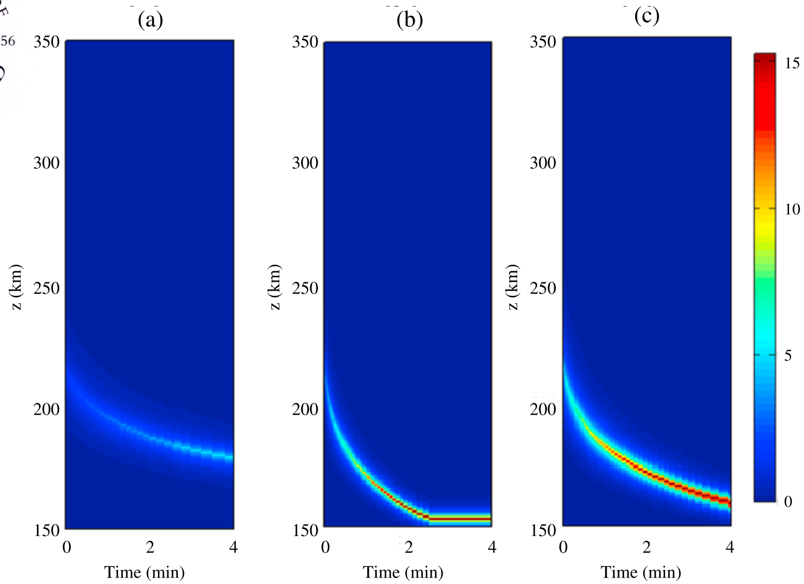
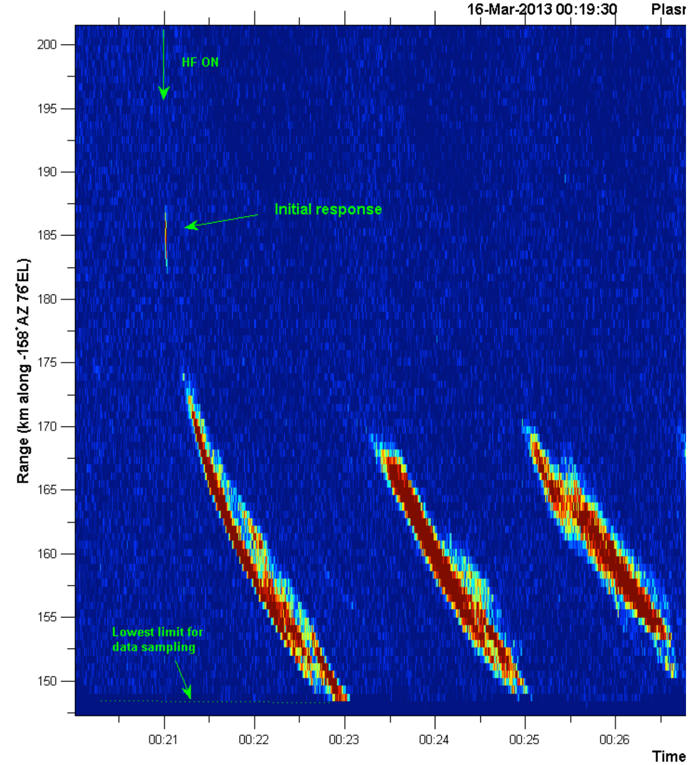
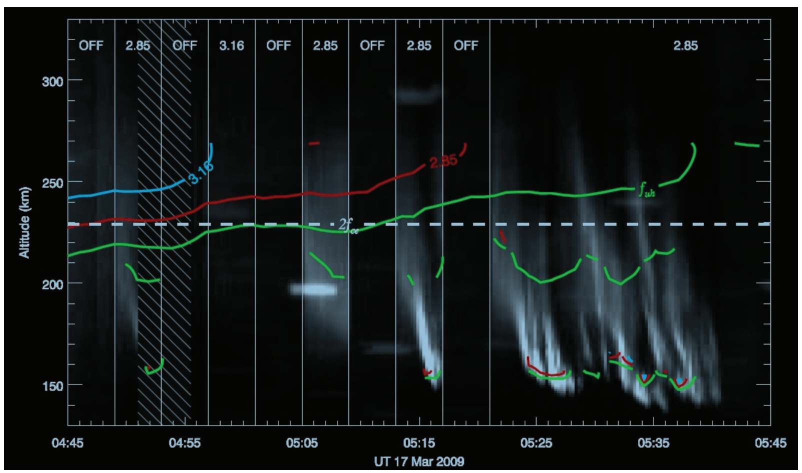


Figure 13. Green line emission as derived from simulation for different input wave amplitude and initial electron thermal energy: (a) E_0 = 1 V/m, T_e = 0.4 eV, (b) E_0 = 1.5 V/m, T_e = 0.4 eV, and (c) E_0 = 1 V/m, T_e = 0.6 eV.

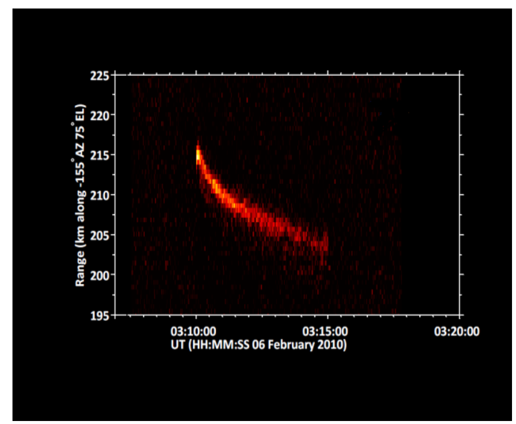
Plasma Line





Descending ion-line and plasma line structures observed with UHF radar during heating.

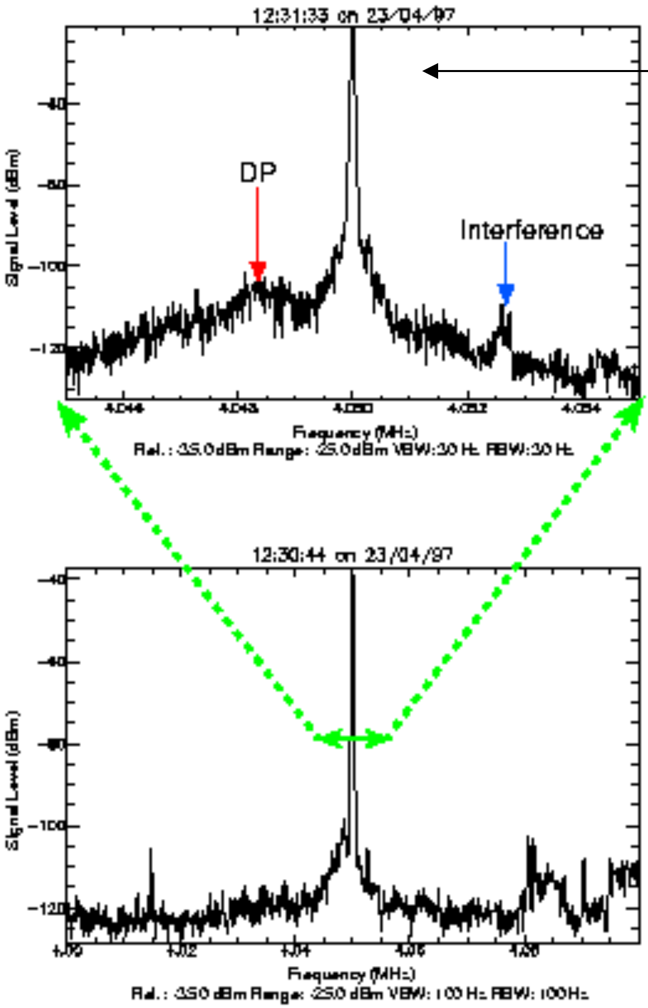
Watkins



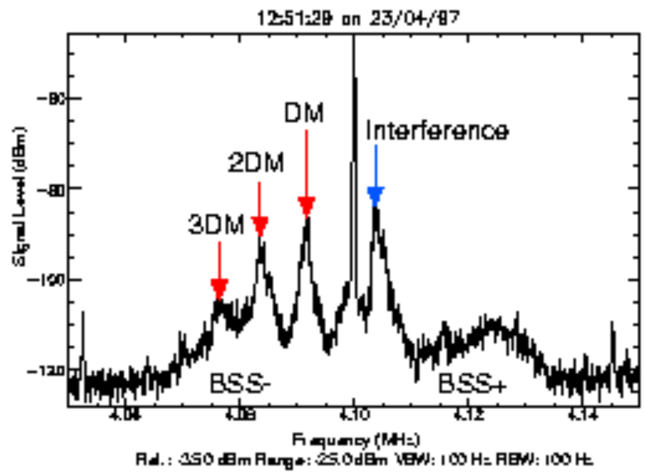
T. Pedersen et al. 2010

Ion Line

Stimulated Electromagnetic Emissions (SEE)



HF transmit frequency



are weak radio waves produced in the ionosphere by HF pumping.

Above Gyroharmonic

3rd Electron Gyroharmonic

Gyroharmonic ≈ 1.38 MHz
in F-layer

(Honary et al., Ann. Geophysicae, 1999)

SEE Spectra

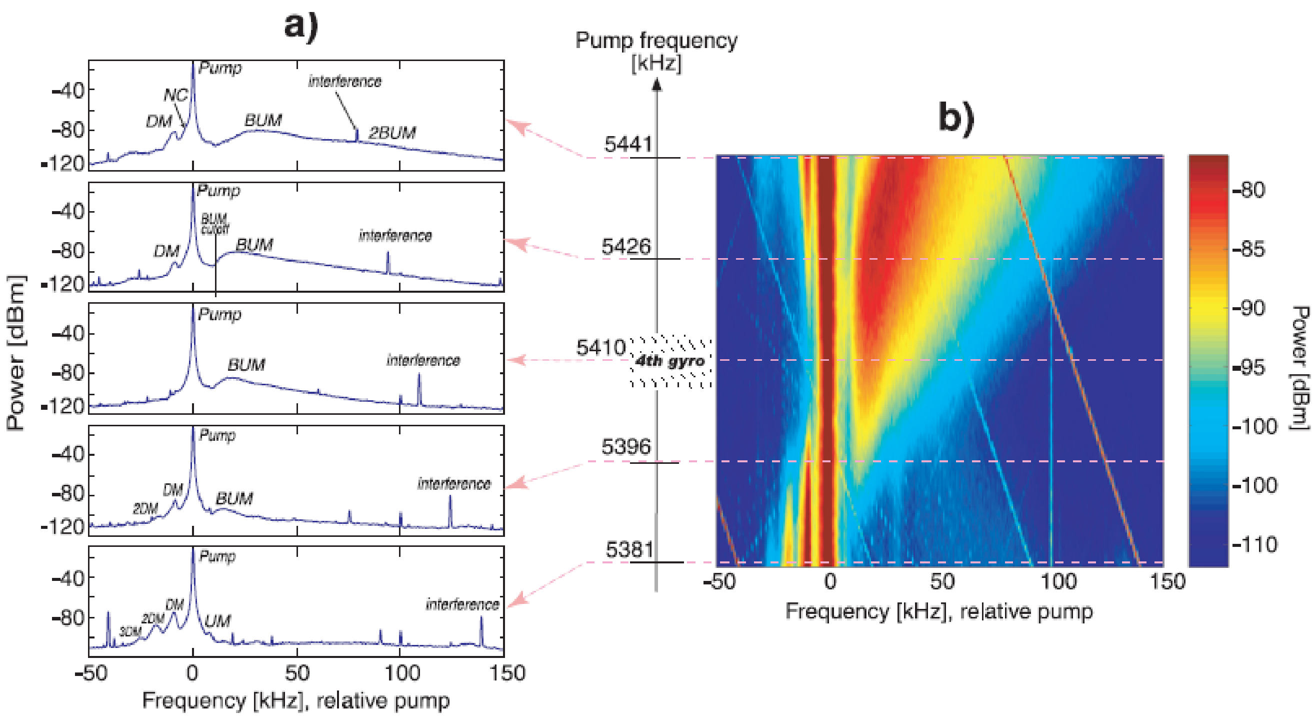
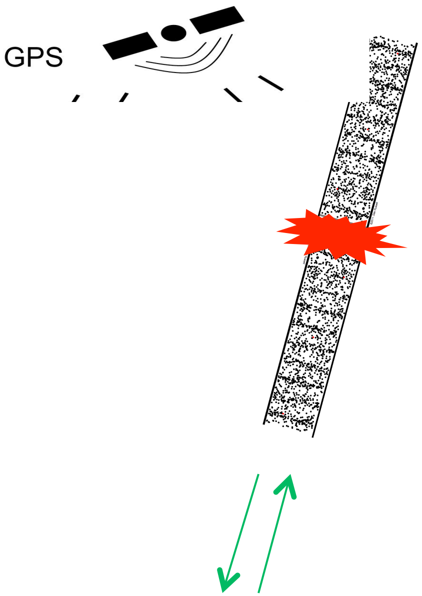
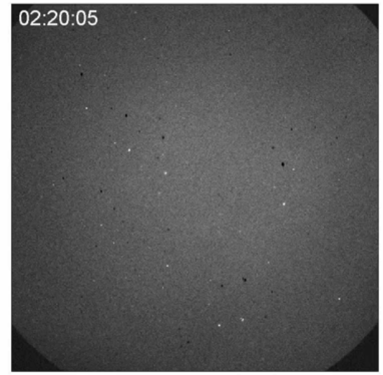


Figure 3. (a) The stack of five plots showing SEE spectra for the five different pump frequencies marked on the vertical axis in the middle of the figure. The standard SEE spectral features and the pump are labeled. These spectra are cross sections of the pump relative spectra versus pump frequency two-dimensional plot in Figure 3b. (b) The position of the cross sections are marked with dashed, magenta lines. The estimated range of the local fourth gyroharmonic is shown as a hatched region on the pump frequency axis.

Carozzi et al., JGR 2002

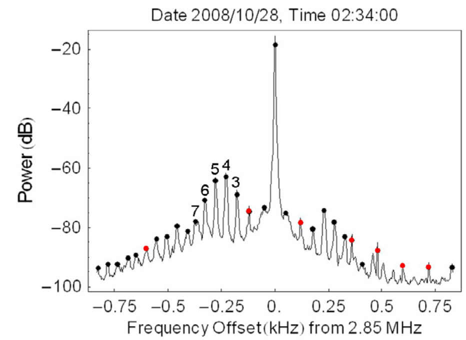
DIAGNOSTIC INSTRUMENTATION





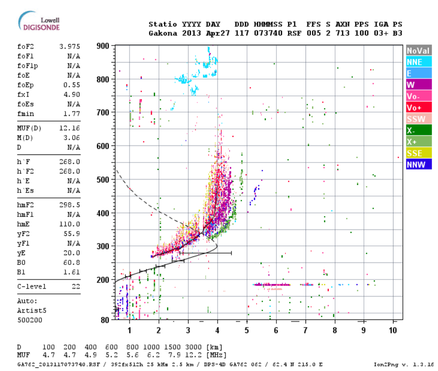
630 nm Artificial Plasma
Glow Discharge Ionization

Optics: All-sky imager ,Telescopic imager
Photometers ,14 ft Optical Dome
Tomography Chain ,Cordova -> Kaktovik

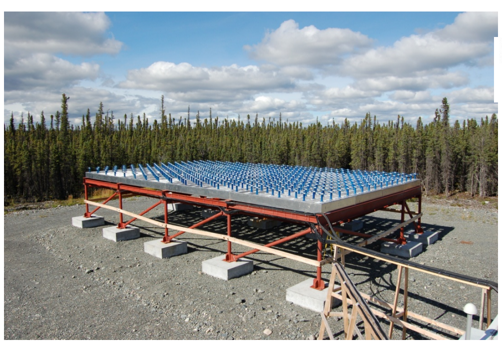


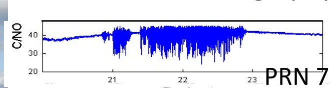
SEE

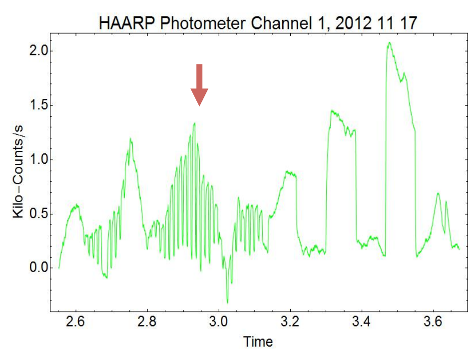
Eight channel HF receivers, NRL



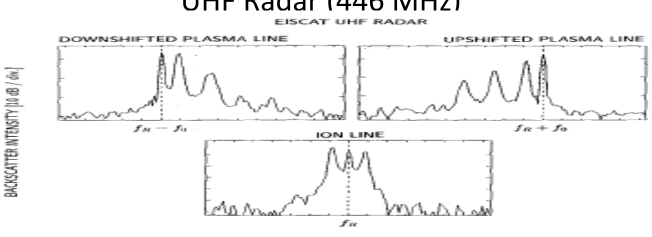
Ionosonde





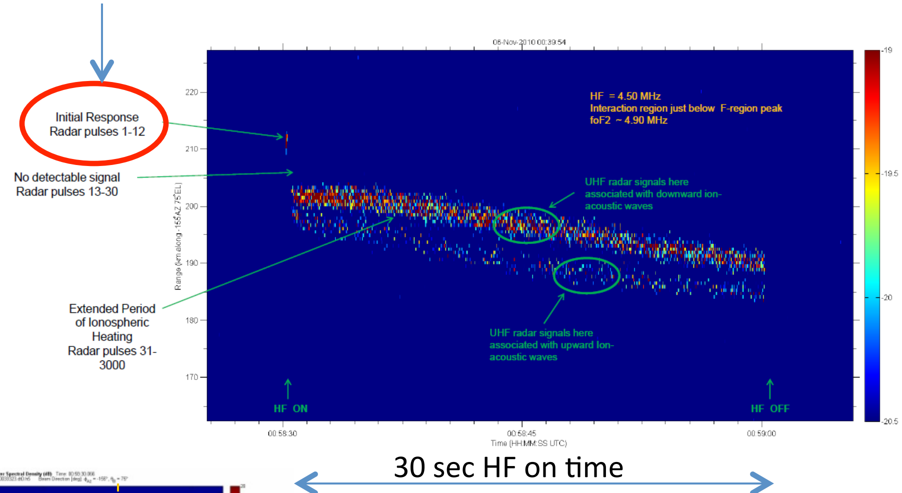


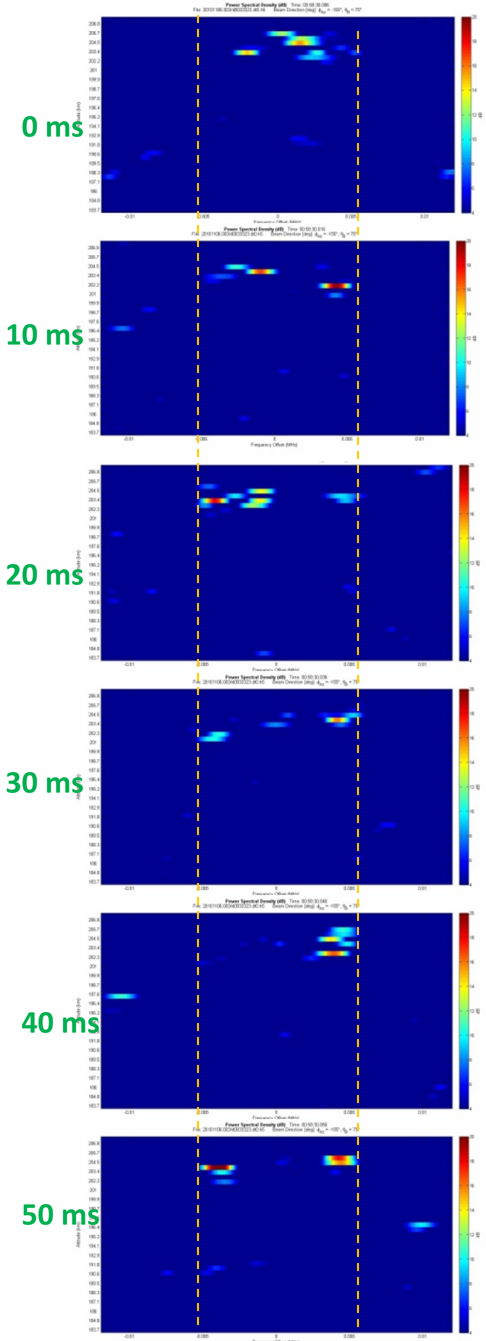
UHF Radar (446 MHz)

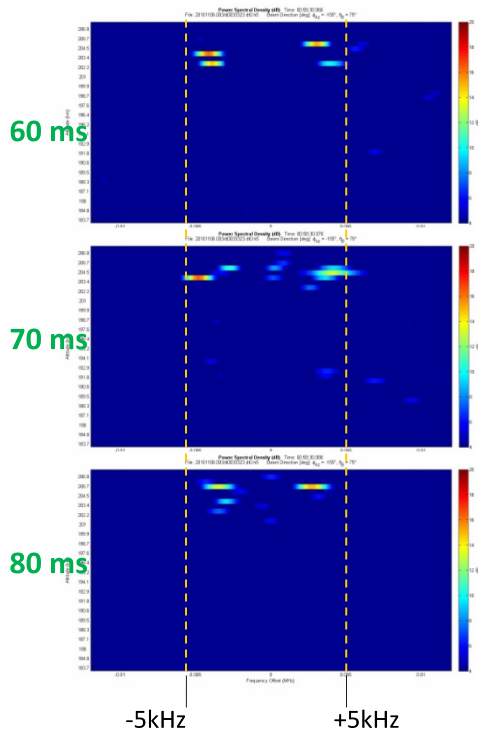


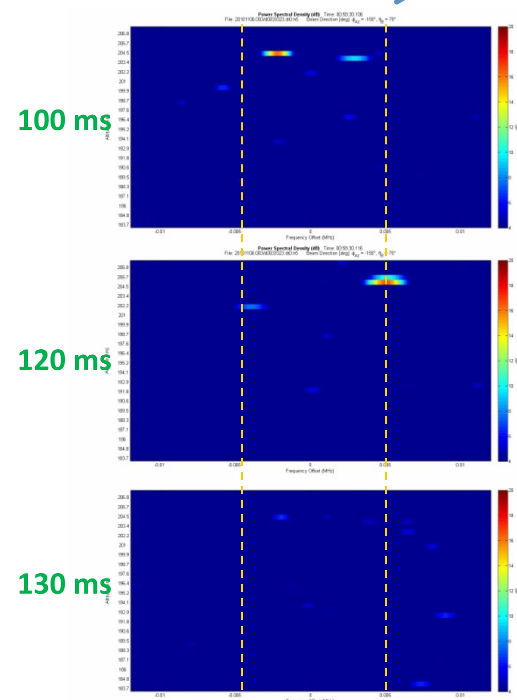
UHF Power Spectra During Initial Response Time

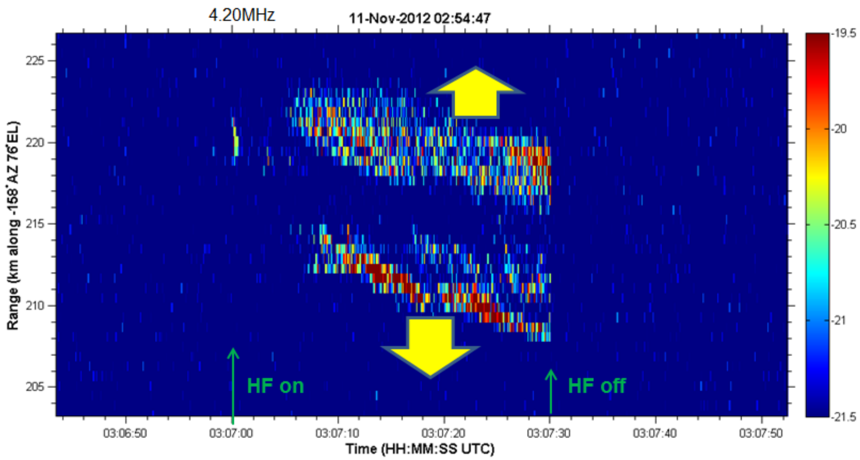
(First 12 pulses after HF turn on - 120 milli-sec)










4.20MHz
11-Nov-2012 02:54:47
Range (km along -158°AZ 76°EL)
225
220
215
210
205
HF on
HF off
03:06:50
03:07:00
03:07:10
03:07:20
03:07:30
03:07:40
03:07:50
Time (HH:MM:SS UTC)
-19.5
-20
-20.5
-21
-21.5

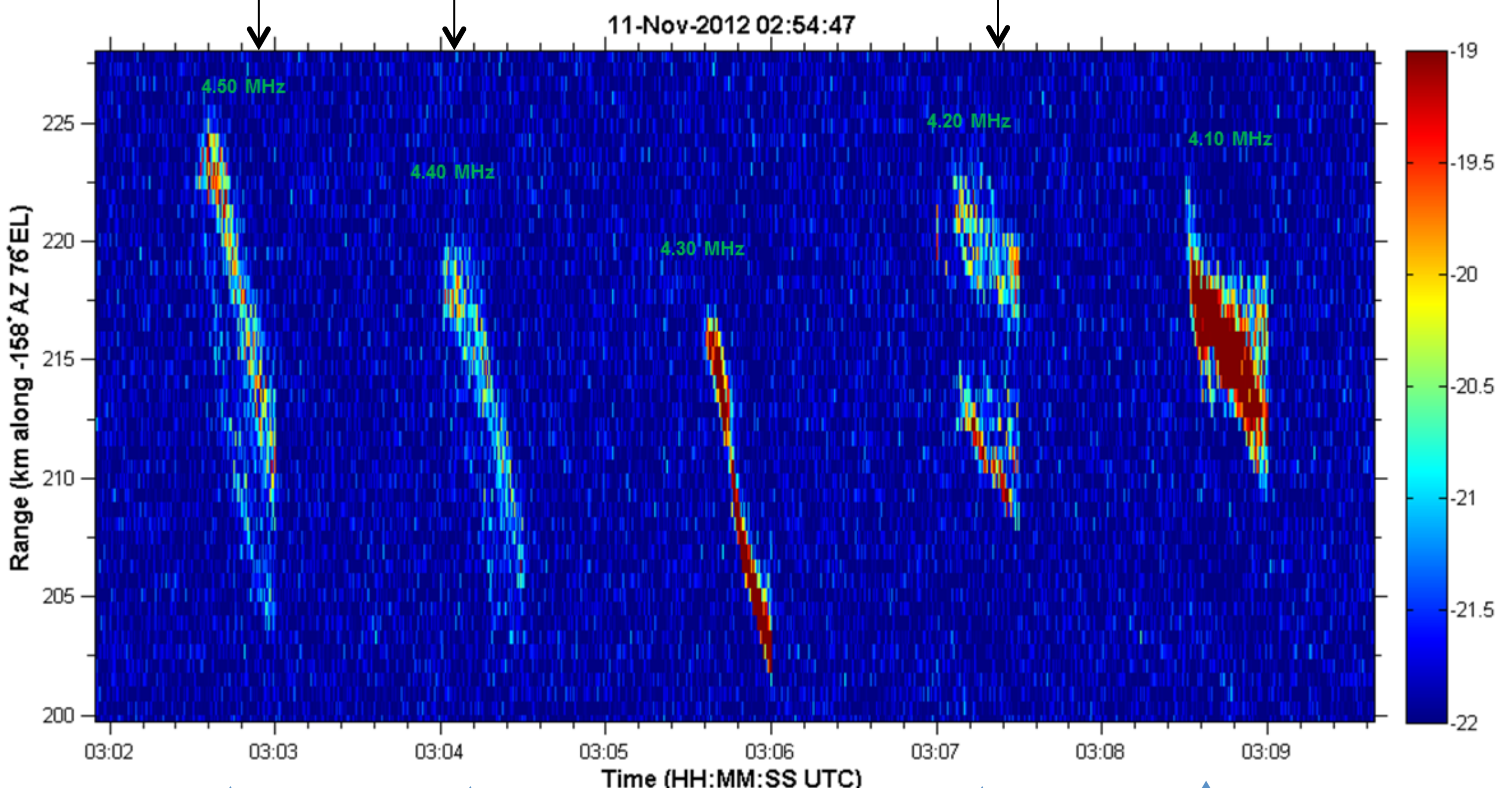
<u>Experimental results that suggest</u>:

Large-scale density changes maximized for HF frequencies far from gyro-harmonics

Results for 4 HF frequencies near the 3rd Gyro Harmonic   HF power cycled: 30secs on 60 secs off

Results for HF frequency far from gyro-harmonic

Results for HF frequency near 3rd gyro-harmonic



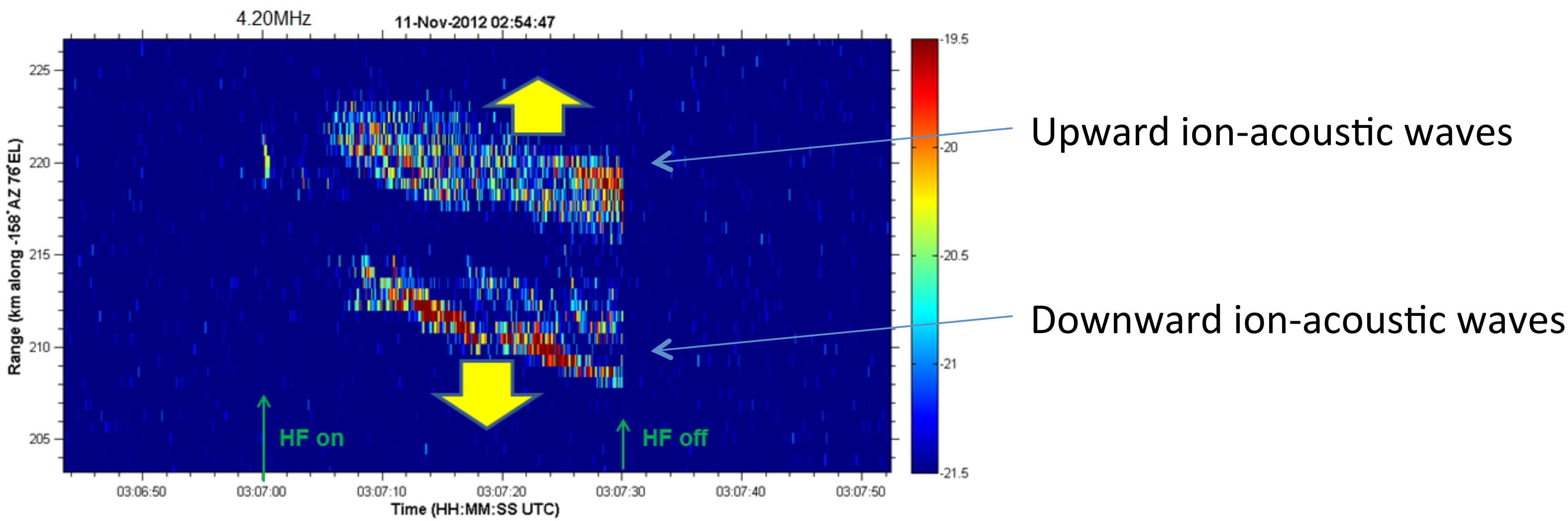
Drops ~20 km   ~700 m/s

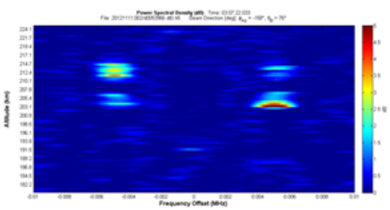
Drops 10 km ~330 m/
s

Topic 4: *UHF Radar Doppler Power Spectra Observations*

Enhanced Ion-Line Doppler Spectra for 4.20MHz (close to 3rd Gyro-Harmonic)

New Results: Two scattering structures with preferentially-directed ion-acoustic wave directions





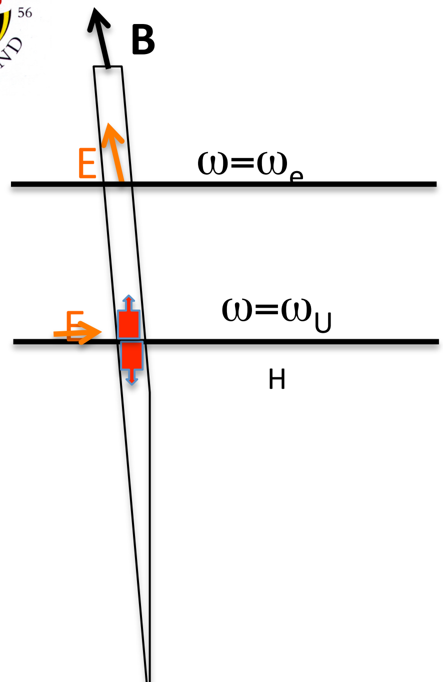
Power-height-time plot of HF-enhanced ion-line signals. Close to 3rd gyro-harmonic signals split into two layers. Doppler spectra (example to left) show strong asymmetries that indicate mainly upward propagating only ion-acoustic waves in the upper layer. The downward layer is associated with primarily downward propagating ion-acoustic waves..

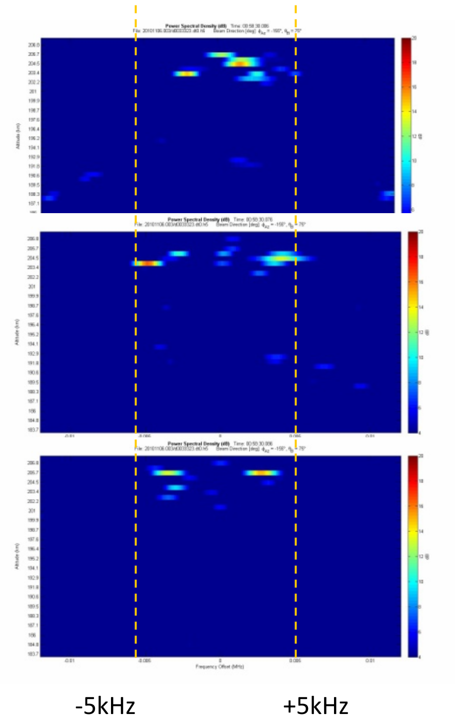
HF Power Cycle

30 secs on

60 secs off

The above spectral asymmetries are interpreted to be the result of electron flow upward and downward from the HF interaction region as indicated by the yellow-colored arrows.





Multi-time and length scale code (DAIL code suite- Eliasson et al. JGR 2012): (i)El. Accel in SLT, (ii)Transport model for accel. El.,(iii) ionization (iv) Chemistry package (recomb.,excit…)

Input: (i) HF E at 100 km (ii) Ambient density (iii) T_e

Output: (i)Temporal evolution of density and optical emissions (ii) Supra-thermal EDF

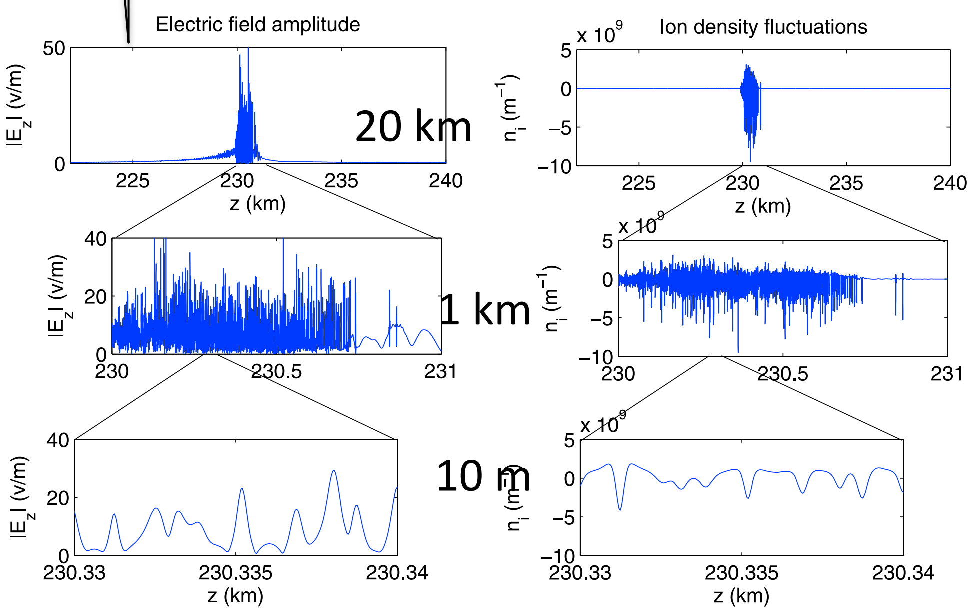
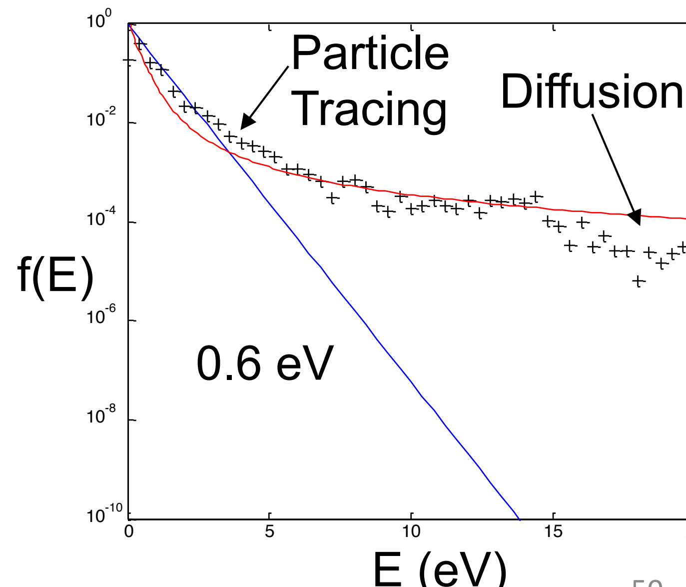
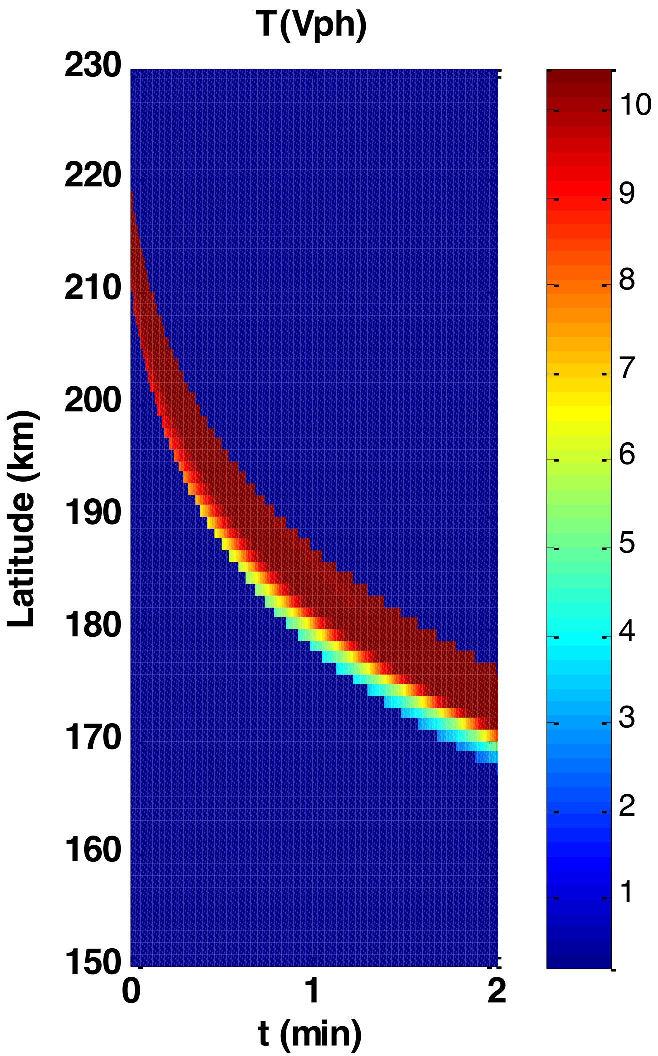
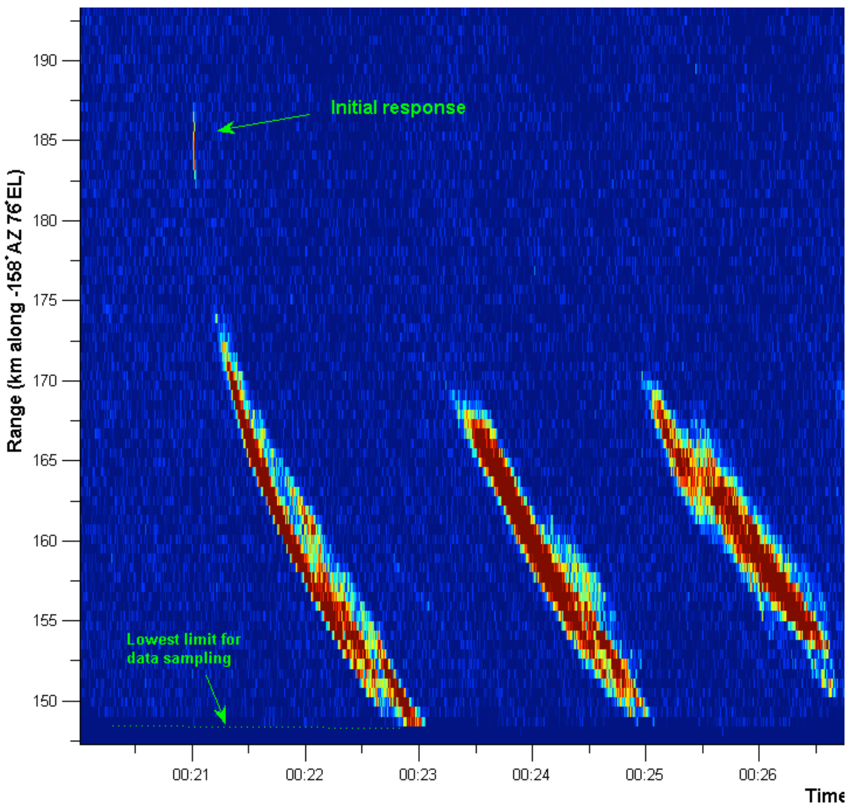


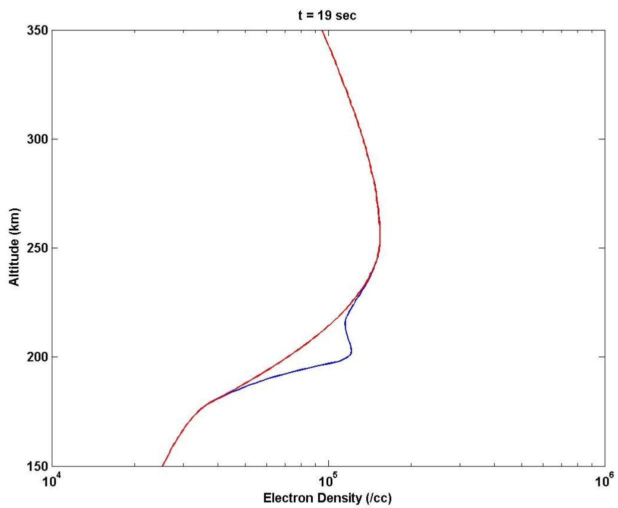
Figure 2. The amplitude of E_z and slowly varying ion density fluctuations n_i at various altitudes, for $E_O = 1.5$V/m.

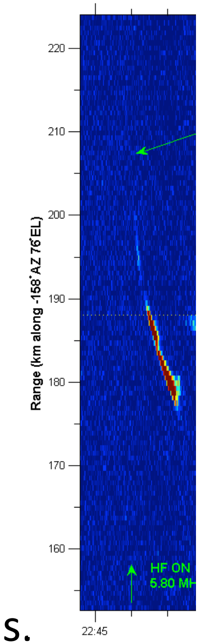


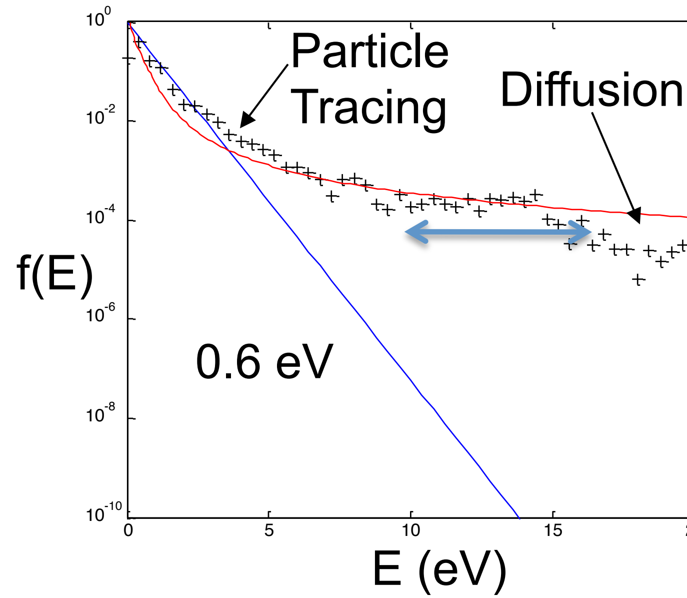

T(Vph)
Latitude (km)
t (min)
230
220
210
200
190
180
170
160
150
0
1
2
10
9
8
7
6
5
4
3
2
1


Initial response
Lowest limit for
data sampling
Range (km along -158˚AZ 76˚EL)
190
185
180
175
170
165
160
155
150
00:21
00:22
00:23
00:24
00:25
00:26
Time

PLASMA LINE ENHANCEMENT







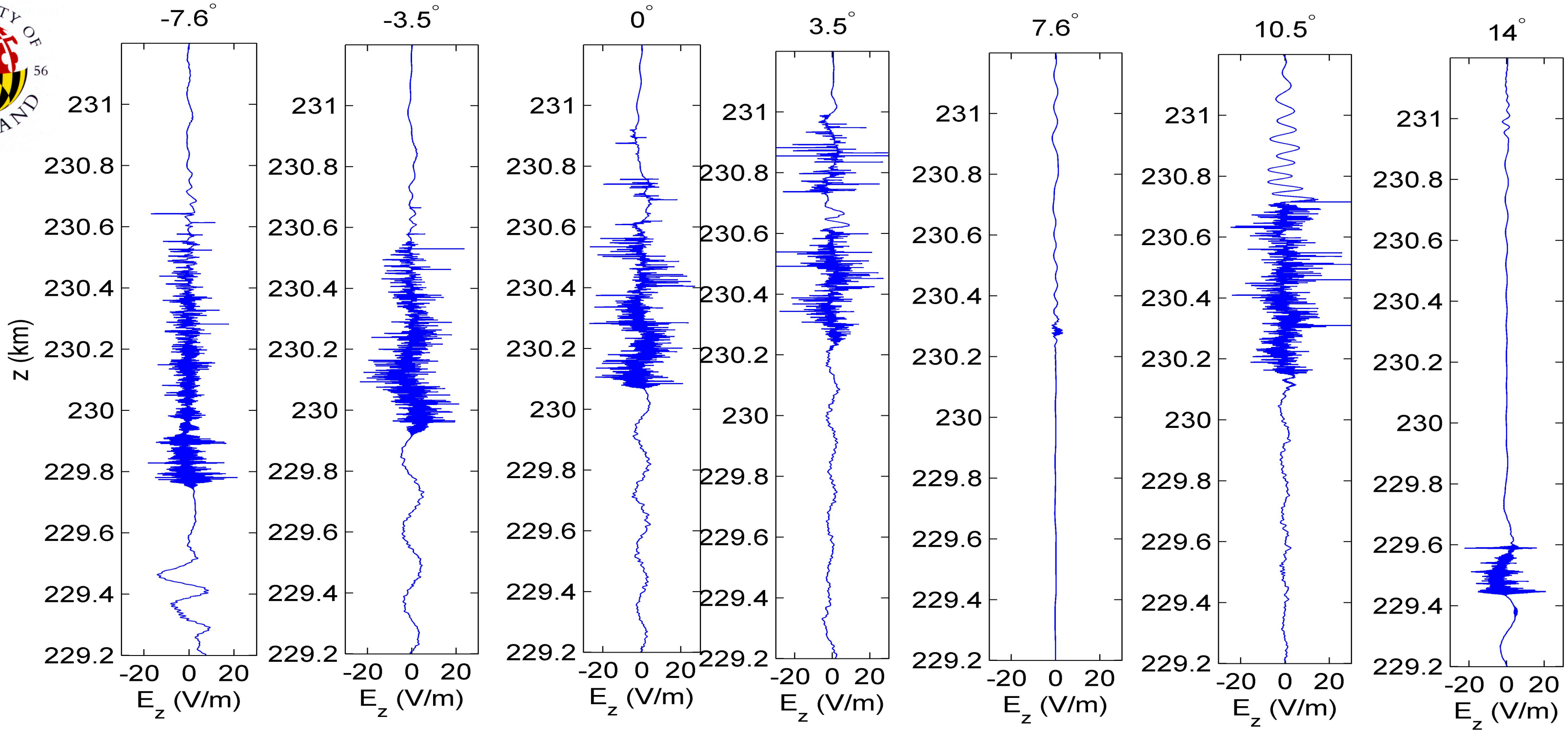
Enhancement due supra-thermal tails. Similar to Arecibo enhancement by photoelectrons but much stronger. The ionizing wave includes large T_e/T_i plasma and hot electron tails. Enhancement stops at low altitude when collisional damping dominates over Landau.

Classic signature of non-equilibrium plasma with supra-thermal tails

$$\frac{<E^2>}{8\pi} \approx \frac{8ne^2}{\omega_e}\int_{k_1}^{k_2} dkk \frac{F_T(\omega_e/k)}{\left|F_e'(\omega_e/k)\right|}$$

$$R \prec \frac{V_T^2/V_e^2}{/n(V_E/\alpha V_e)} \to (\lambda_R/\lambda_D)^2$$

$$\text{if } \nu < \omega_e u_{ph}^2 F'(u_{ph})$$



O-mode, 1V/m amplitude, electron temperature 0.4 eV, and different angles of incidence, B field *at 14-◦.* to the vertical line (same parameters as JGR 2012).

E_z amplitude *t=1* ms for different angles of incidence. The case *,7.6-◦.* corresponds roughly to the Spitze angle *,8.1-◦.*. Also at *,−7.6-◦.* there is an accumulation of electrostatic waves due to absorption (called southward process by Mjolhus 1990). The O mode turning point is at z=231.0 km and the upper hybrid resonance layer at z=223.8 km (outside the range of the plots).