Using Active Experiments to Probe Geo-space

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Third International Conference

The Mechanics of the Magnetospheric System and Effects on the Polar Region

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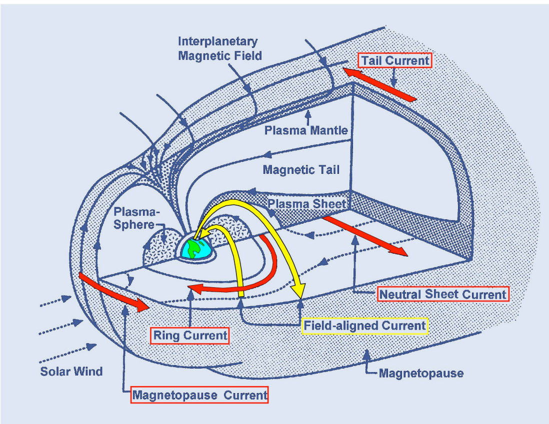
Acknowledge:
B. Eliasson, C.L. Chang,
G. Milikh, X. Shao, P. Bernhardt
B. Watkins, T. Pedersen, E.Mishin

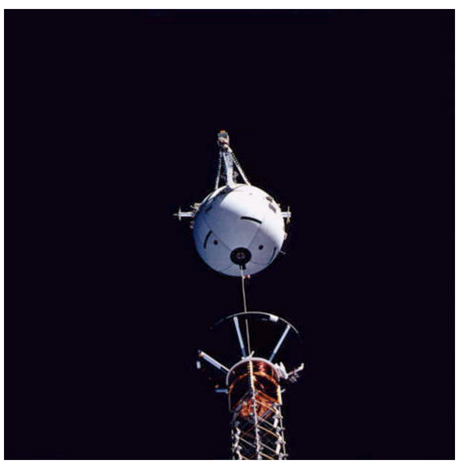
Torres del Paine, Patagonia, Chile
October 27-November 1, 2013

Active Experiments – Simulating Pieces of the Magnetospheric System

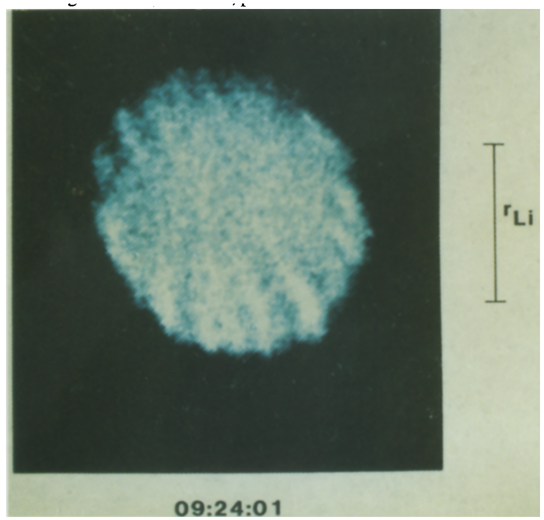


Study the response of the space environment to controlled disturbances (Injection of neutral gas, electron or ion beams, plasma clouds, charged spheres, shuttle engine exhaust, RF).

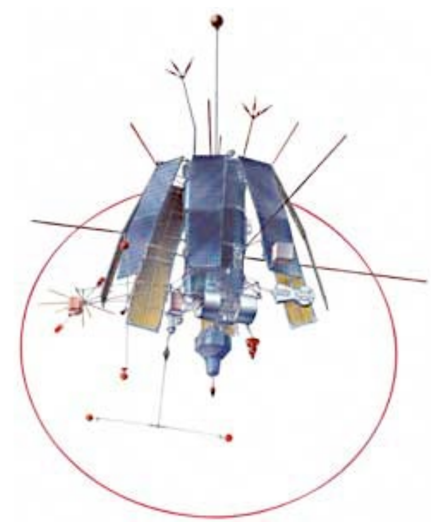
Using "Physics in Space" to understand and model "Space Physics" – Cause and Effect studies



Tether



AMPTE –Ba Cloud

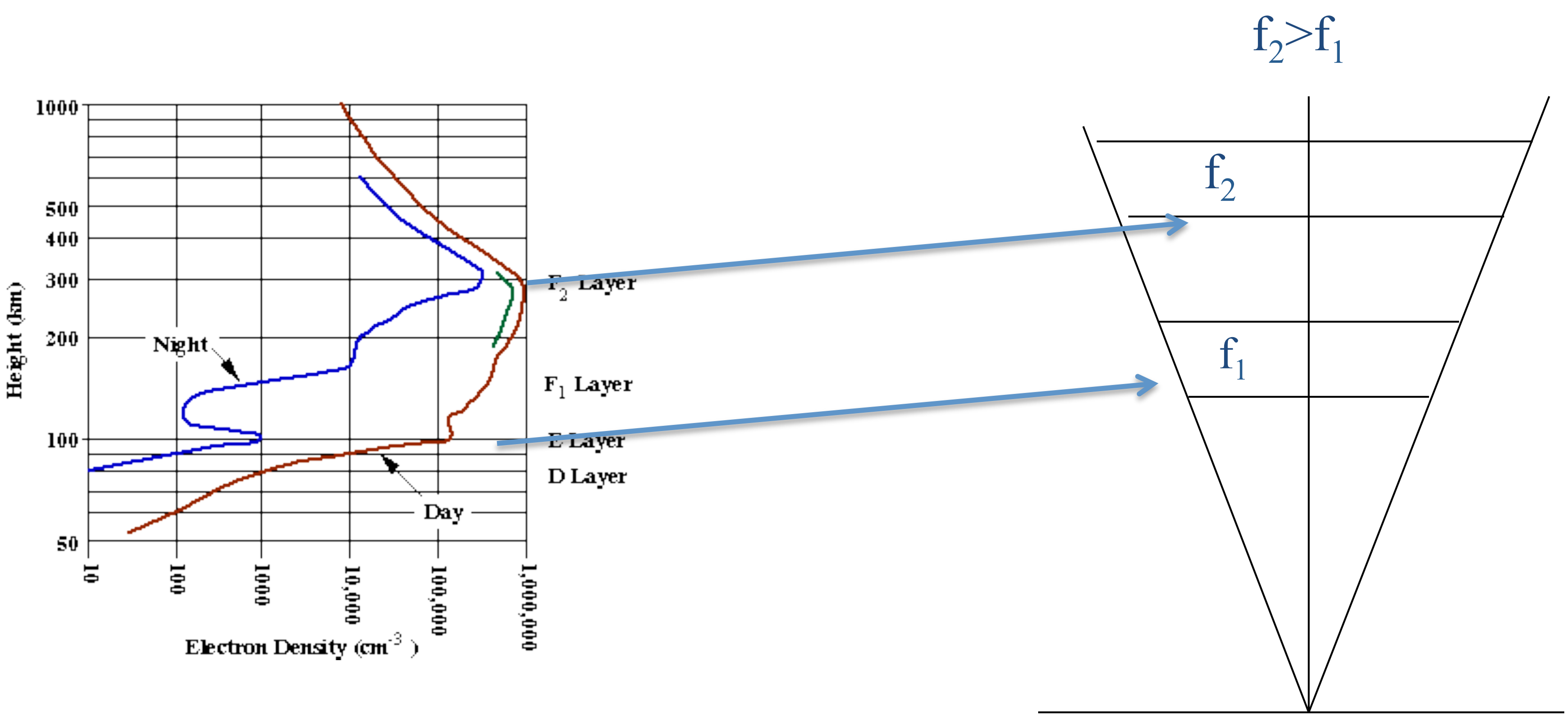


Activny - VLF

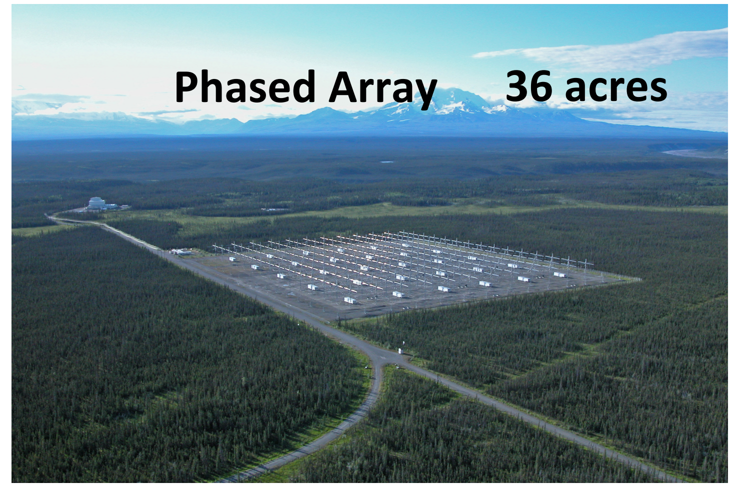
THE ALTERNATIVE-IONOSPHERIC HEATERS

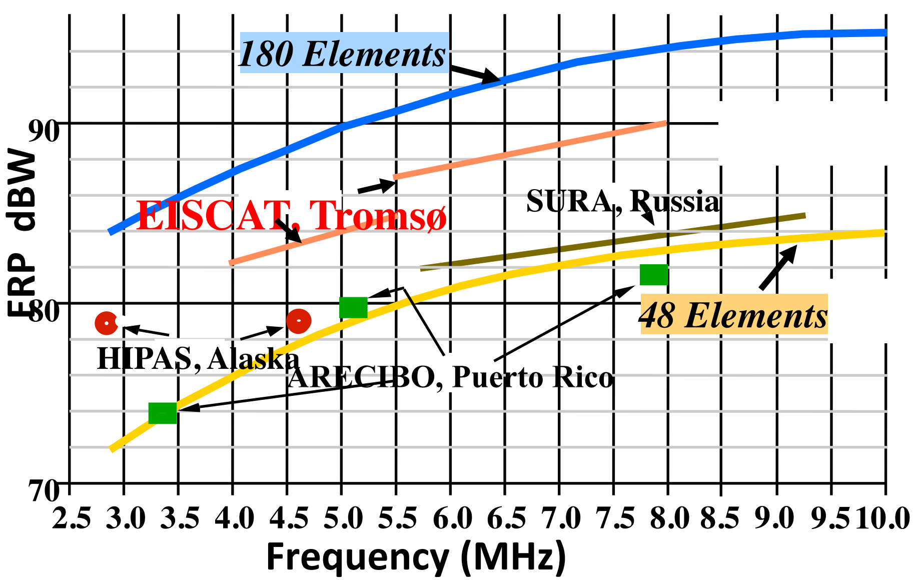
- **Ionospheric heater - Powerful HF transmitter (2.8-10 MHz) that induces controlled temporary modification to the electron temperature at desired altitude.**

- **Use in conjunction with diagnostics to study, in a cause and effect fashion:**
  - **EM propagation, plasma turbulence and instabilities**
  - **Response of magnetospheric plasma and Radiation Belts to controlled perturbations of the ionospheric plasma**



THE HAARP HEATER



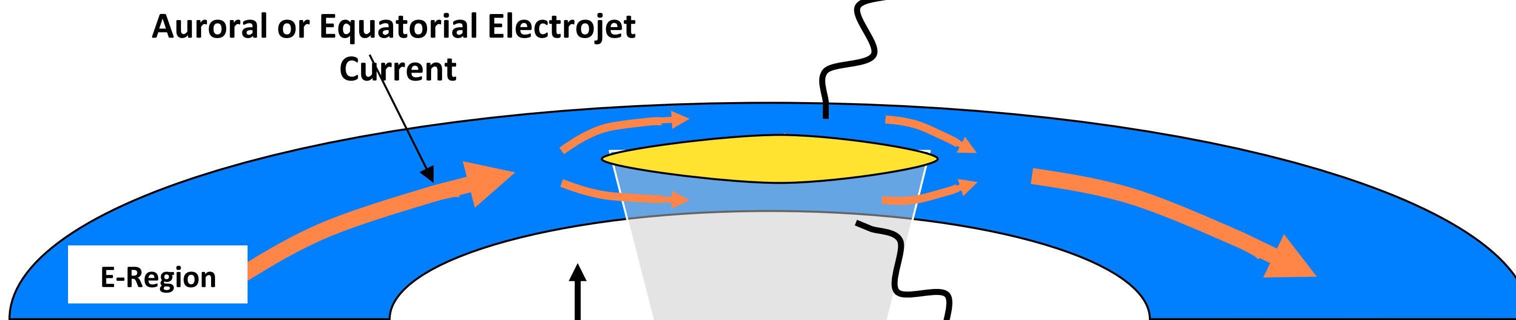


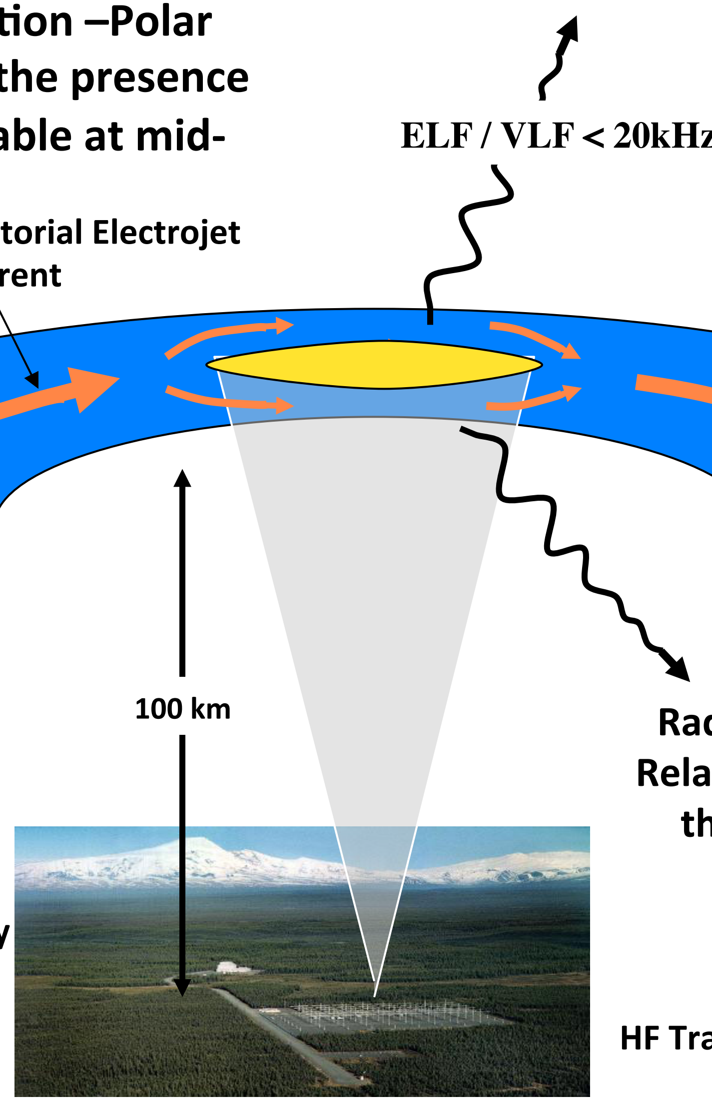
Discussion topics

1. Virtual ULF/ELF/VLF antennas
2. The Physics of Artificial Plasma Layers
3. Artificial Ionospheric Turbulence

HF Ionospheric Heaters as " VIRTUAL" ULF/ELF/VLF Antennae

Two techniques : 1. Current modulation –Polar Electrojet (PEJ) Antenna – Requires the presence of an electrojet current – not applicable at mid-latitude





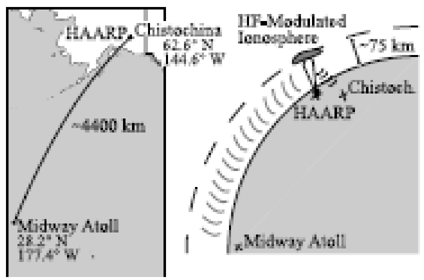
- **Natural Currents Flow in the Auroral and Equatorial Ionosphere at 80-100 km**
- **The HF signal (modulated at ELF/VLF) heats and thereby changes the local conductivity of the ionosphere**
- **The electrojet current is then caused to vary at the same ELF/VLF rate**
- **Propagating ELF/VLF signals are radiated by this 'virtual antenna'**

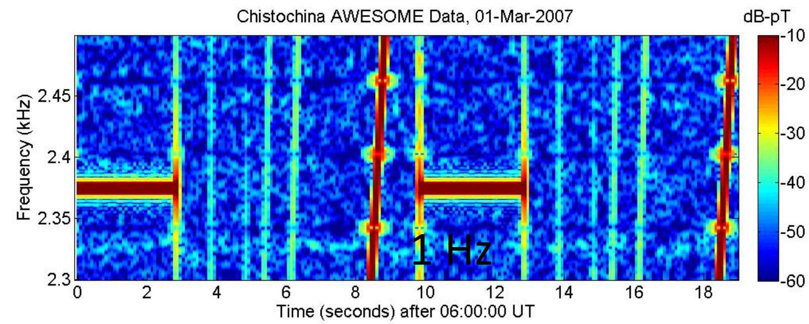
Radiated ELF Signal is Related to the Power of the HF Transmitter

HF Transmitter

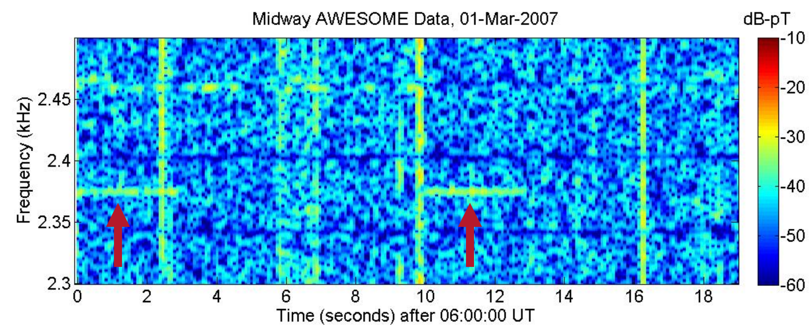
PEJ ELF/VLF Ground Detection

Moore et al.
GRL 2008
Stanford



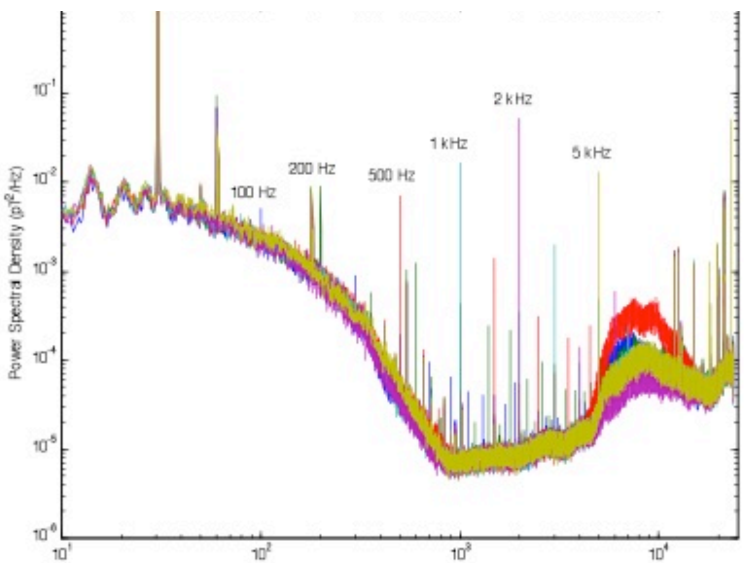


5400
km
away

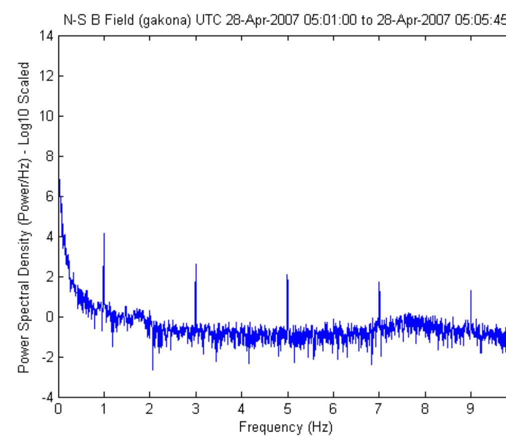


Midway

Underground sensors 230
km away



Papadopoulos et
al., 2003, 2008
UMD/BAE



PEJ ULF/ELF/VLF Upward Injection HAARP/DEMETER

Frequency .2 Hz

Closest distance 80 km

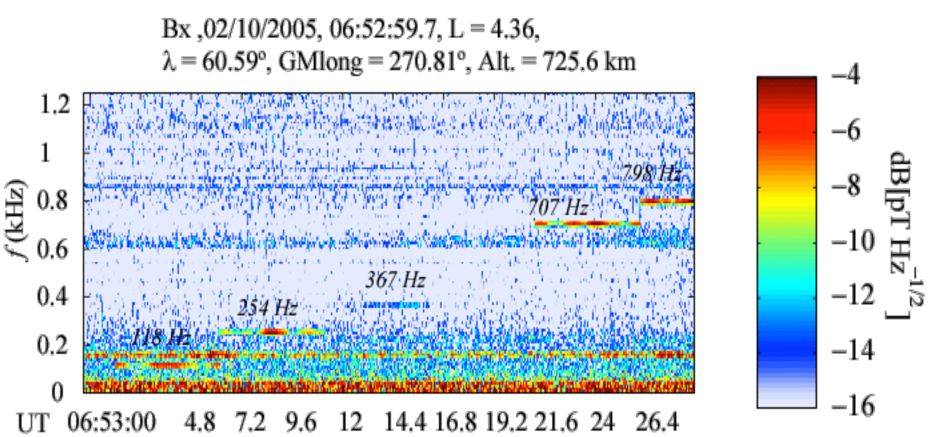
Detection time 25 sec

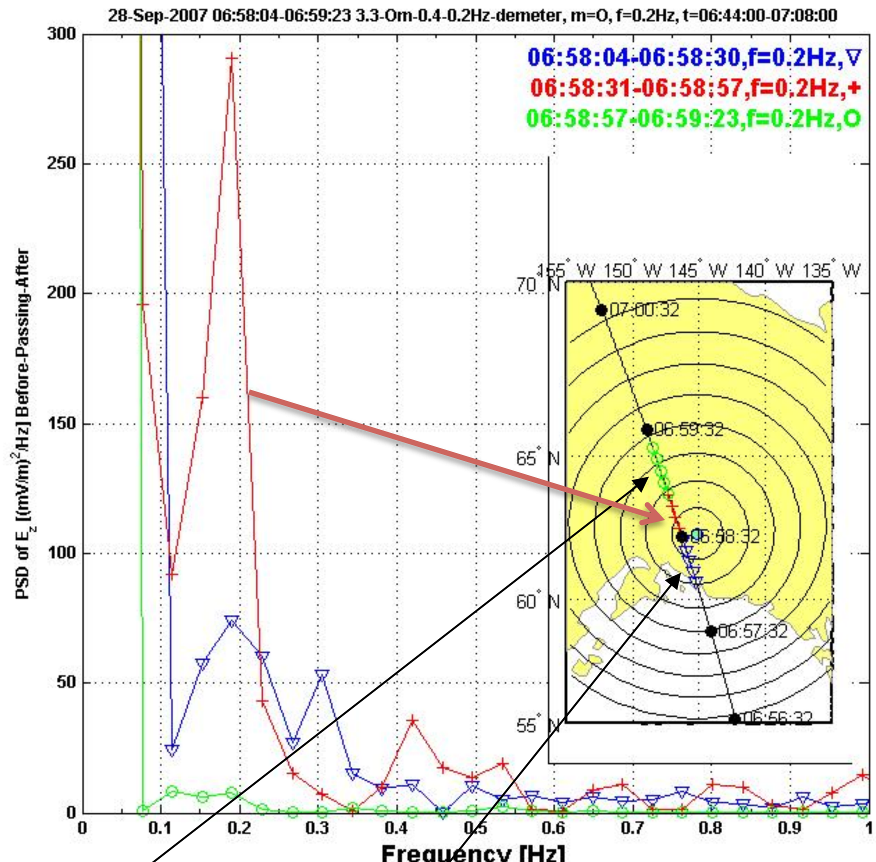
Detection distance 150 km

Maximum E ~10 mV/m

1.5 pT on the ground

DEMETER – 700 km





After

Before

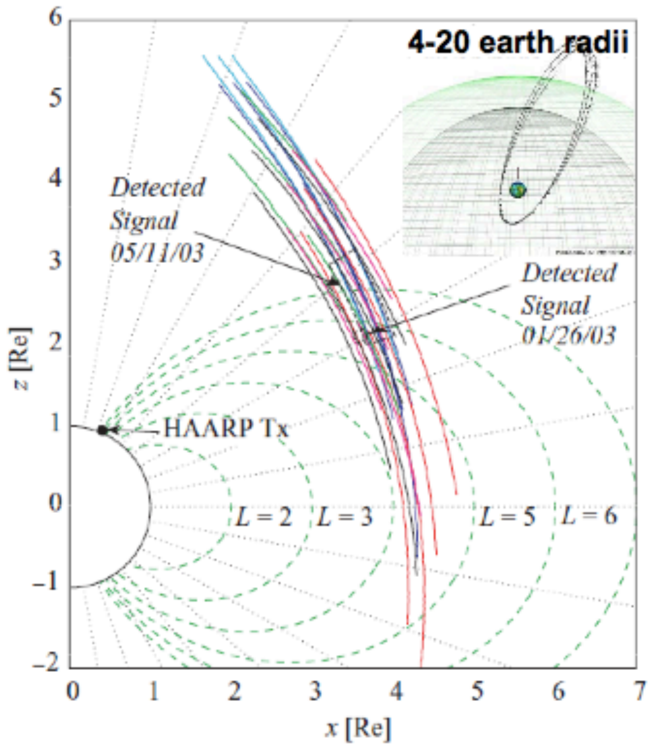
UMD/BAE

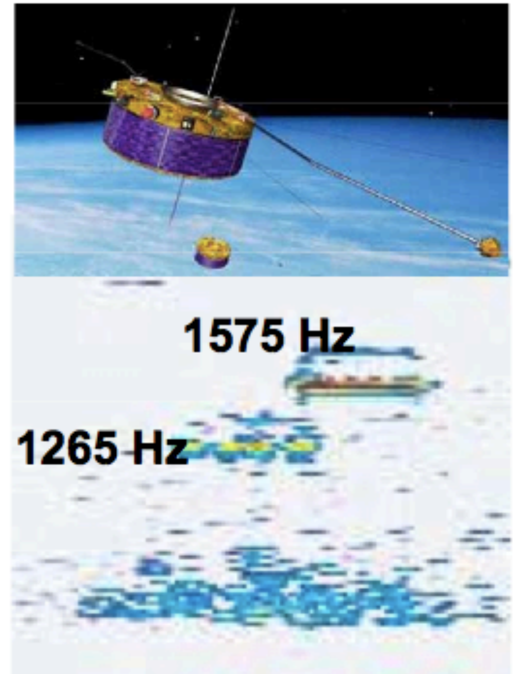
Platino et al., 2006

Stanford

Papadopoulos et al., 2008

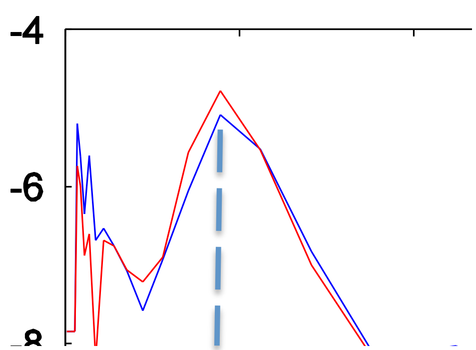
HAARP/CLUSTER





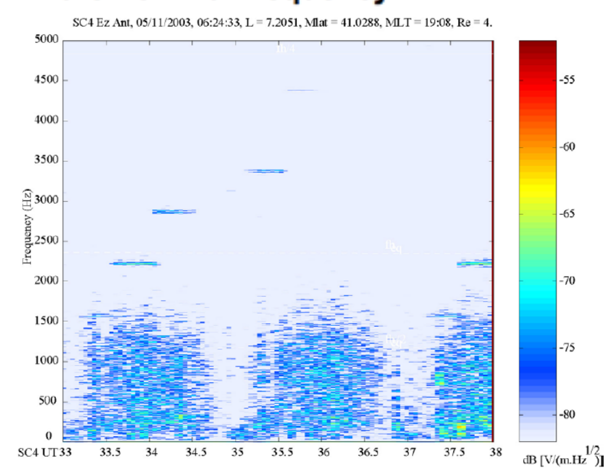
Sideband waves extend several hundred Hz above and below the nominal frequency

Platino et al. 2004



1 kHz

Milikh et al. 2012



F-Region ULF/VLF "Virtual Antenna – Ionospheric Current Drive (ICD)

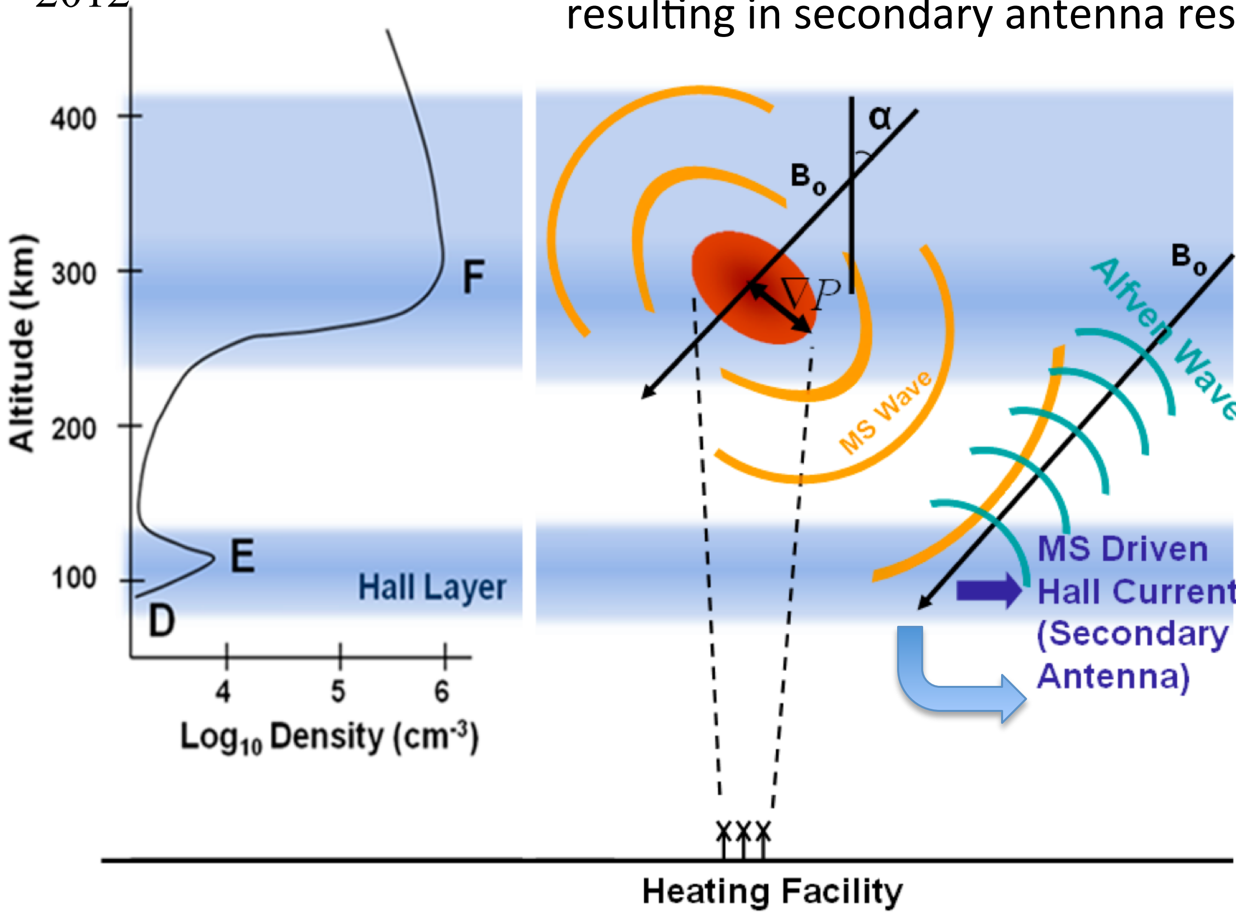
DOES NOT REQUIRE EJET – CAN BE IMPLEMENTED ANYWHERE AND ANYTIME

Papadopoulos et al. GRL 2011a,b
Eliasson et al., JGR 2012

Based on Modulated F-Region Heating Diamagnetic current)

Step 1: $$\Delta J = \frac{B \times \nabla \delta p}{B^2} \exp(i\omega t)$$ **Magnetosonic (MS) Wave**

Step 2: E field of MS wave drives Hall current in E-region resulting in secondary antenna resembling PEJ

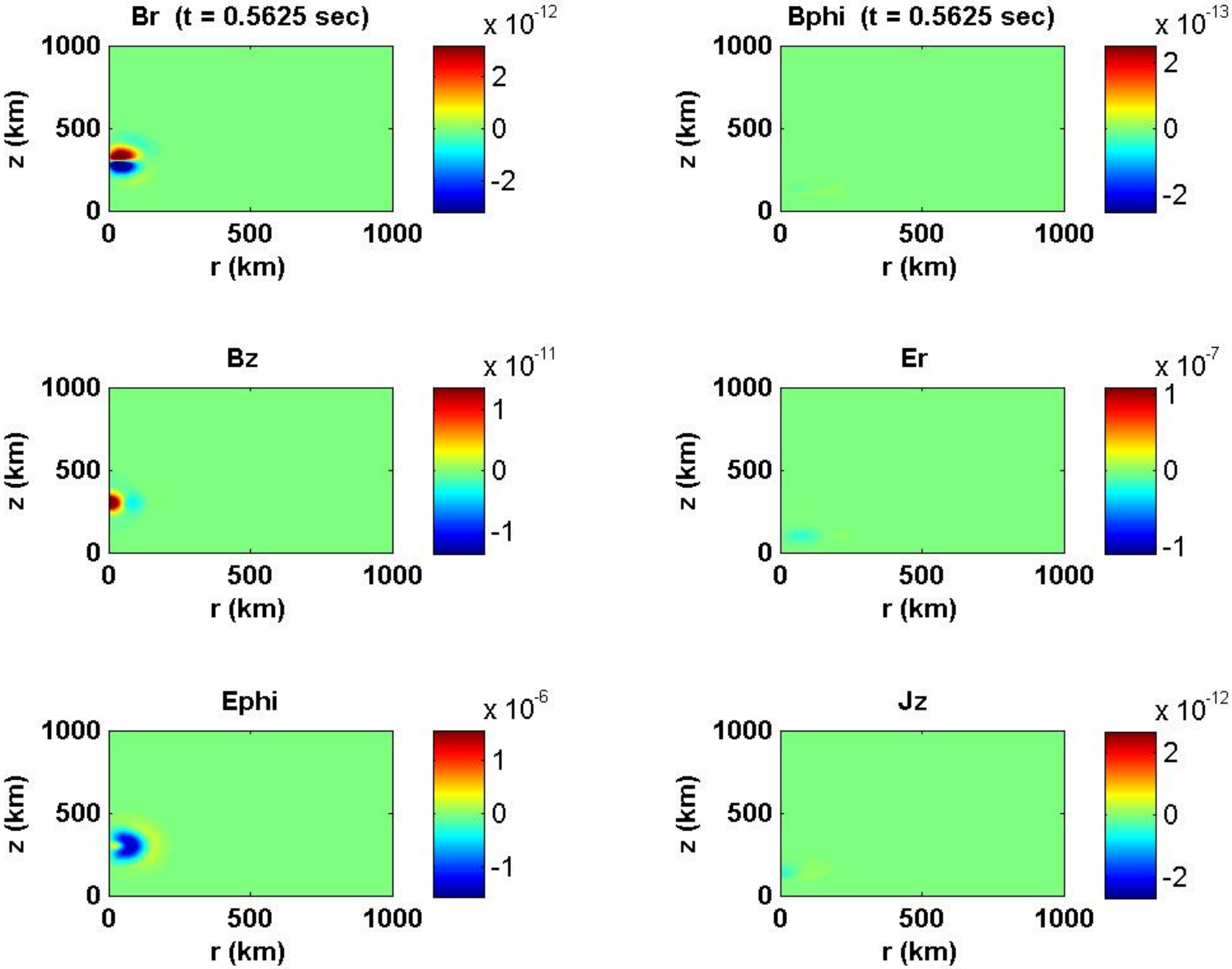


F- region cooling response does not allow frequencies higher than 60-70 Hz

Injects MS & SAW upwards and ELF in the Earth-Ionosphere Waveguide

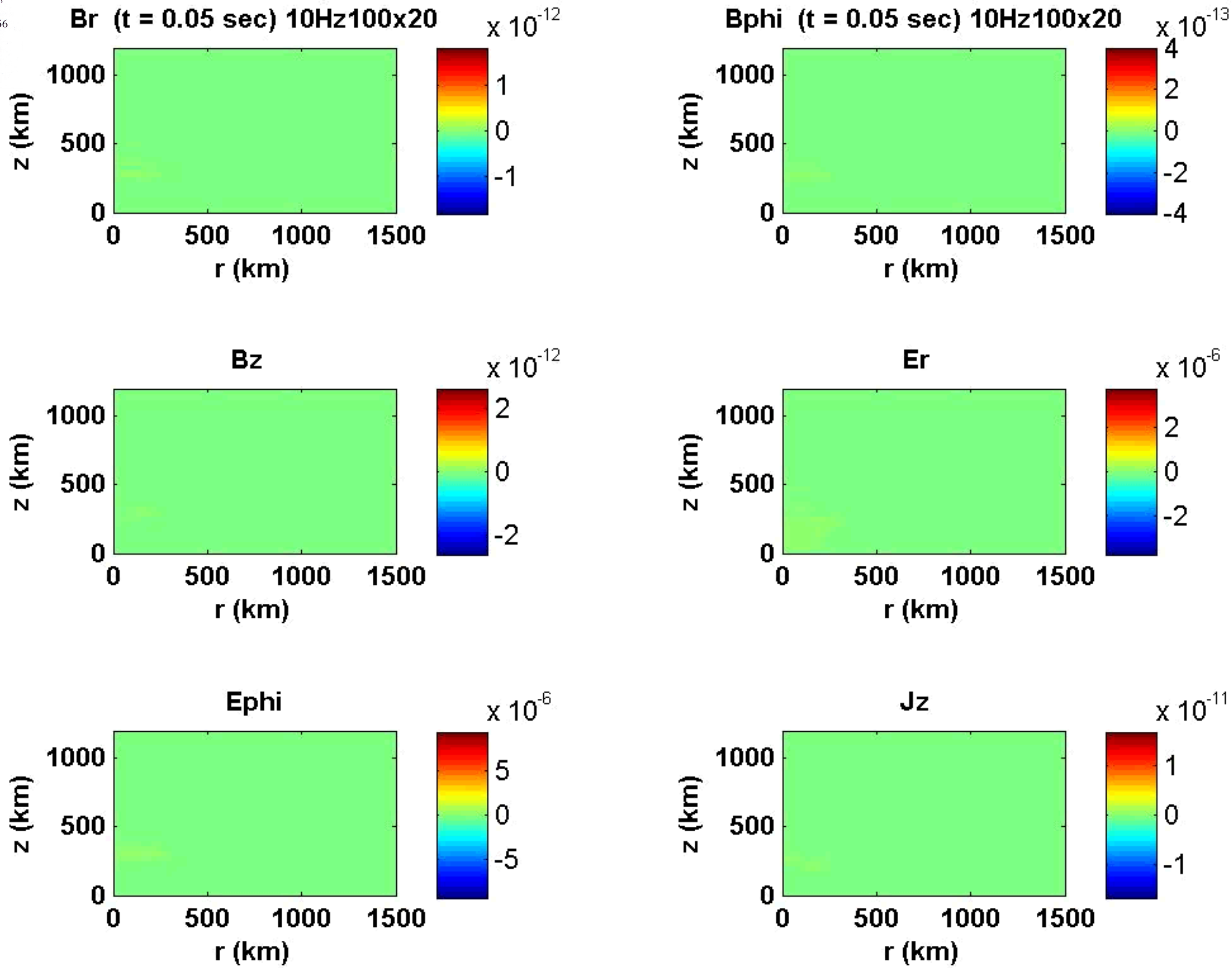
Cylindrical Coordinates

Papadopoulos et al. GRL 2011a



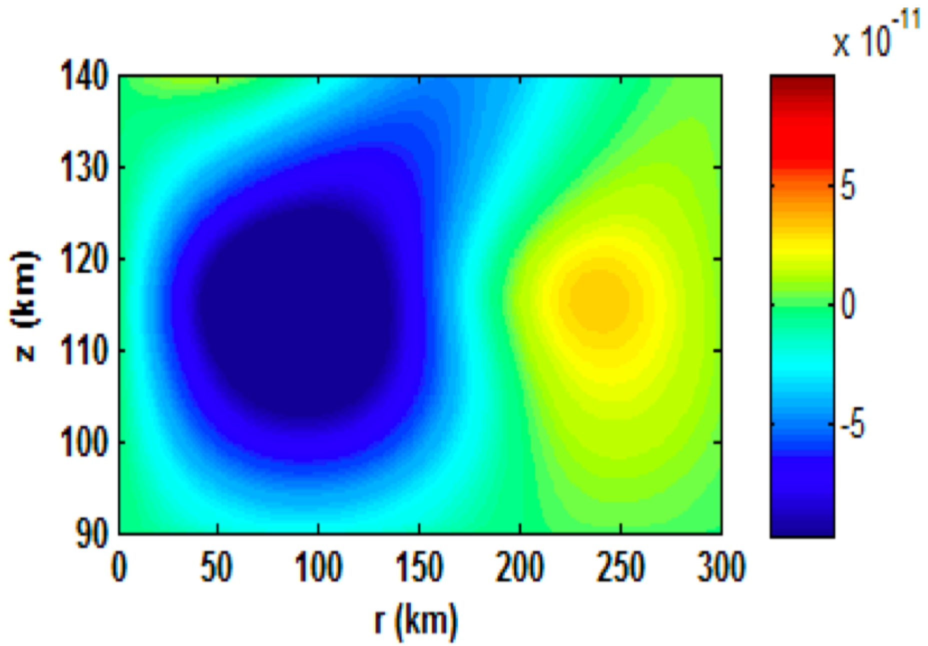
MS

SAW


Br (t = 0.05 sec) 10Hz100x20
x 10^-12
1
0
-1
Bphi (t = 0.05 sec) 10Hz100x20
x 10^-13
4
2
0
-2
-4
Bz
x 10^-12
2
0
-2
Er
x 10^-6
2
0
-2
Ephi
x 10^-6
5
0
-5
Jz
x 10^-11
1
0
-1
z (km)
1000
500
0
r (km)
0
500
1000
1500

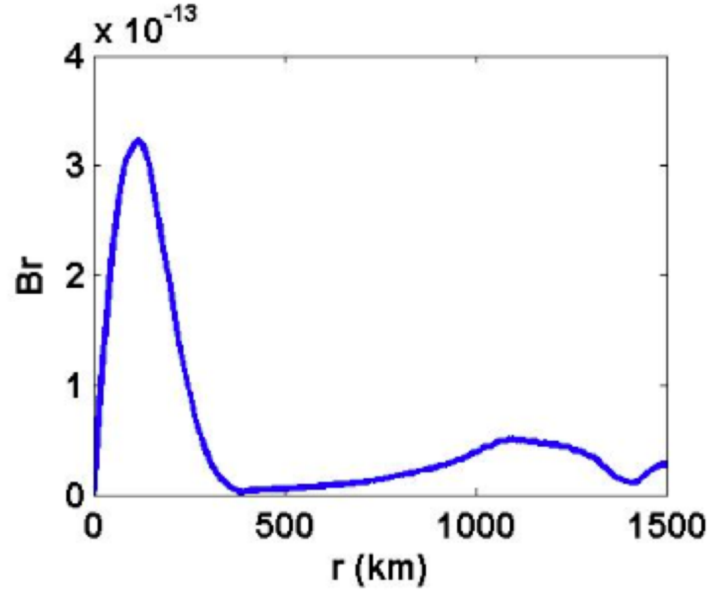
10 Hz

Secondary Antenna Current and Ground Field



J_θ

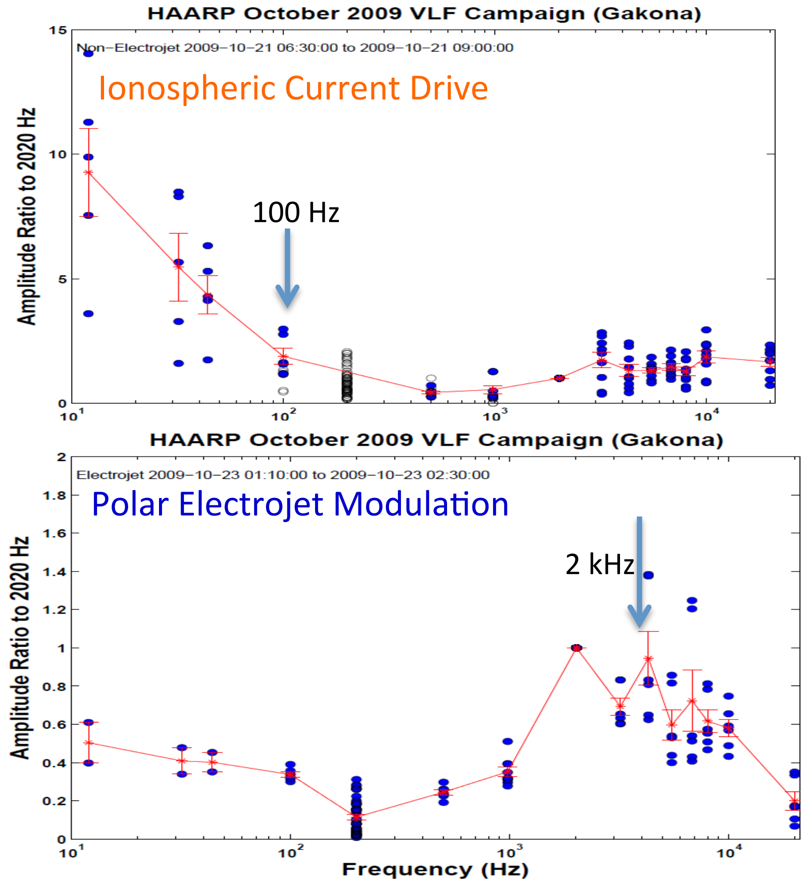
Skip distance

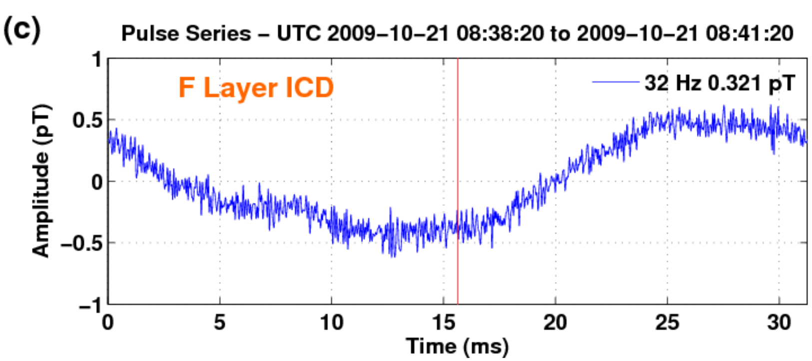


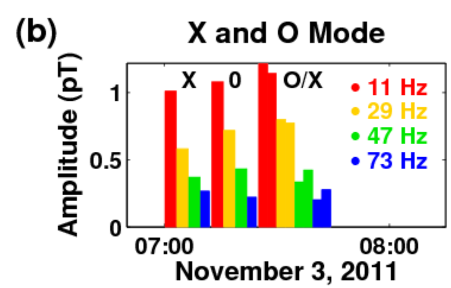
B_r

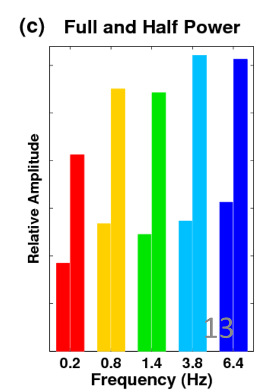
ICD PoP Ground Sensors

- Ionospheric current drive (***ICD***) produced ULF/ELF waves up to 50-70 Hz
  - F layer mod. - No electrojet
  - < 70 Hz, $1/f^a$ dependence
    - Upper freq. is limited by pressure relaxation time scale of the F layer
    - No O/X effect
- Polar electrojet modulation (***PEJ***) produced ULF/ELF/VLF waves 0.001Hz -20 kHz
  - D/E layers mod. - With electrojet
    - < 1 kHz: plateau
    - 2-8 kHz: peak efficiency
    - > 10 kHz: $1/f^a$ decrease
    - X mode dominant



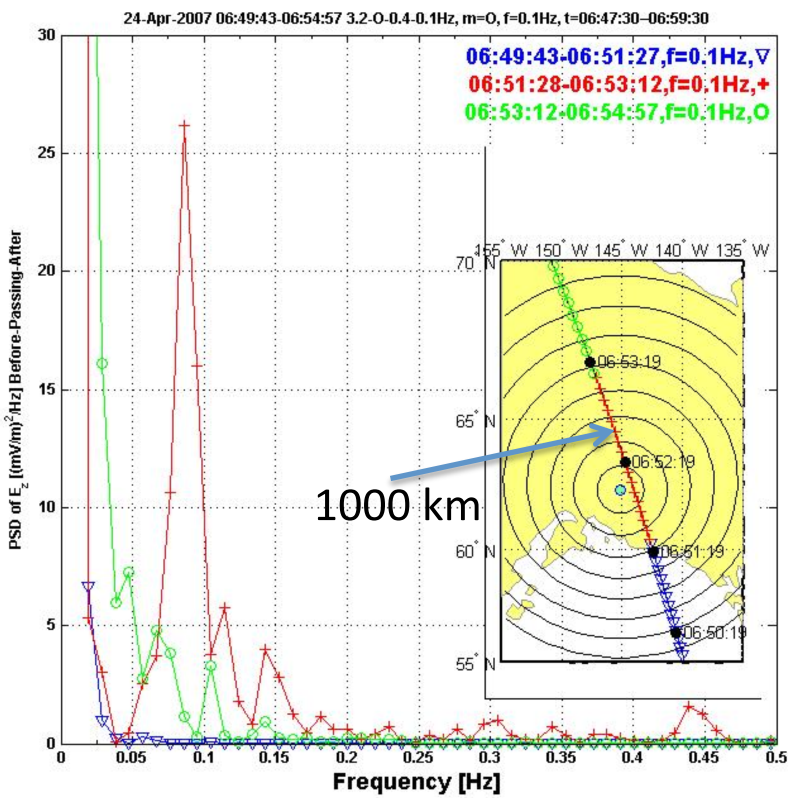


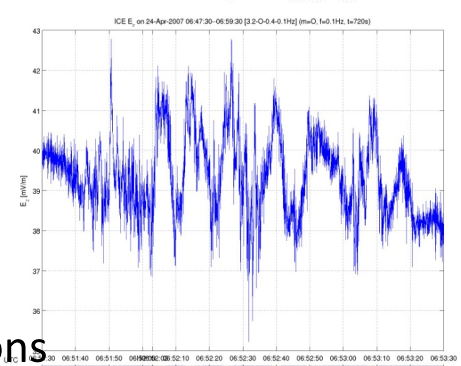




ICD Upward Injection HAARP/DEMETER

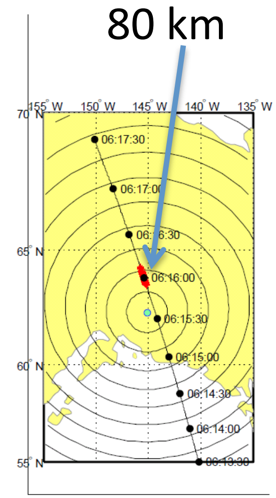
.1 Hz MS

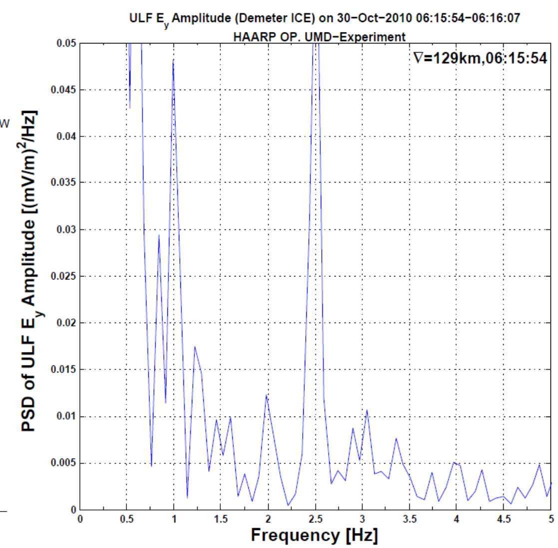


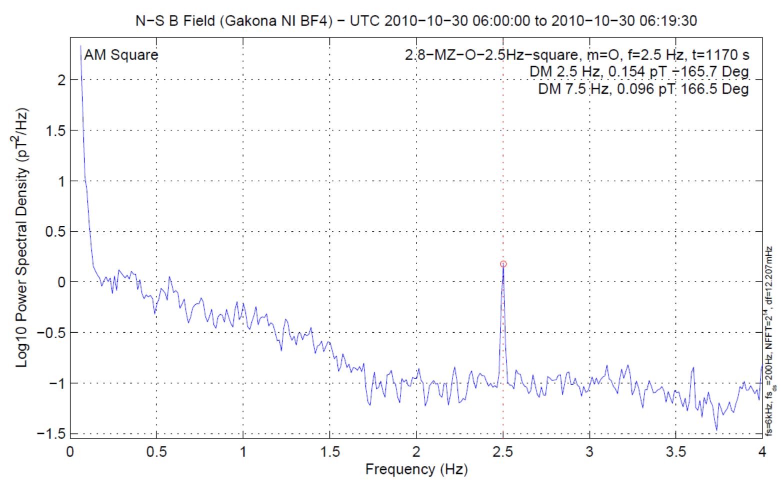


10 sec oscillations

2.5 Hz SAW



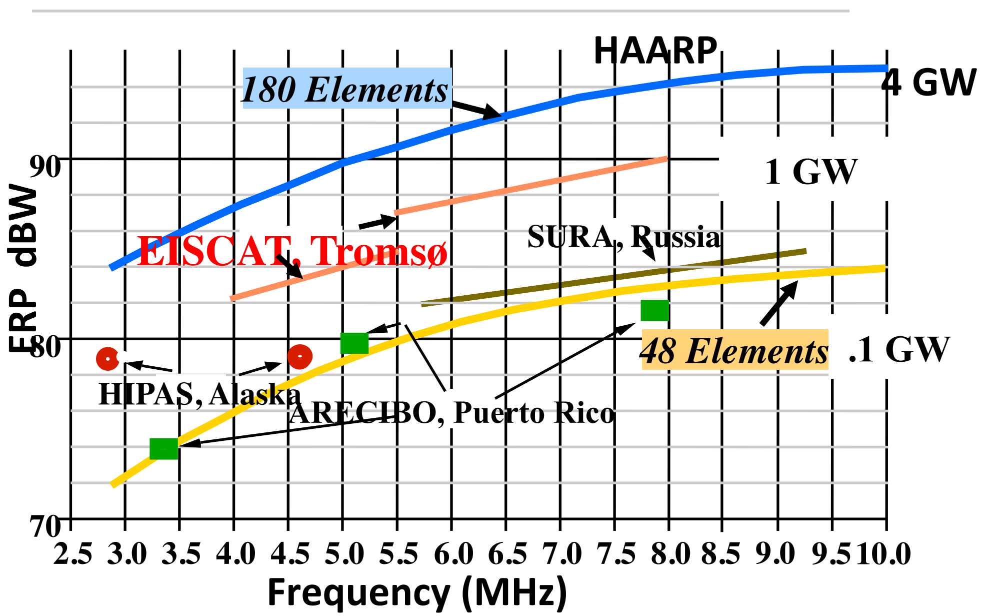




Cause and Effect Studies of the RB Physics

Use Ionospheric heaters (HF) to inject ULF/ELF/VLF waves in the L-shell that spans the heater.

Diagnose by Van Allen, Resonance, DSX, ePOP/ Cassiope, ERG, BARREL, Orbitals + microsats and ground instruments (ISR, sensors,…)



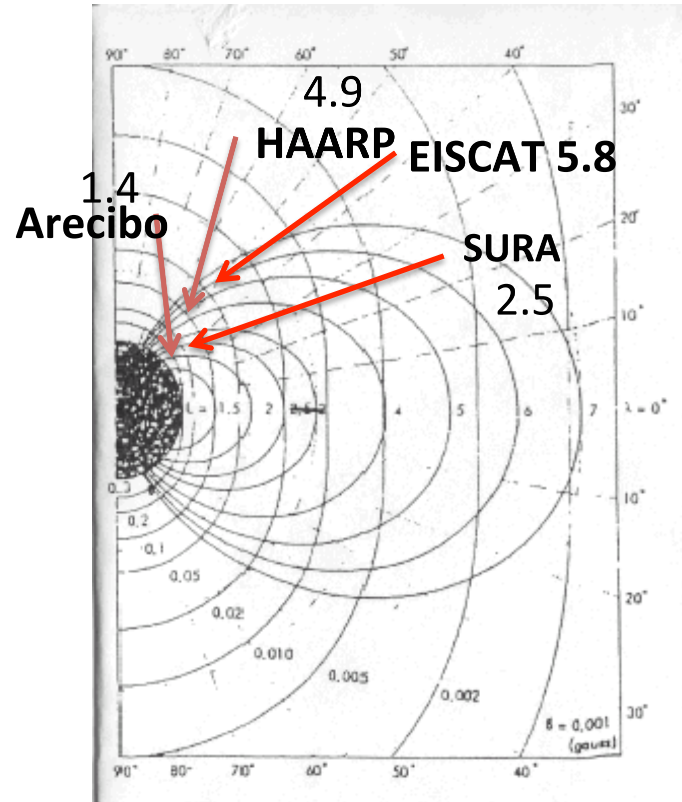


Figure 2-8. Constant-B surfaces in a dipole field.

HAARP

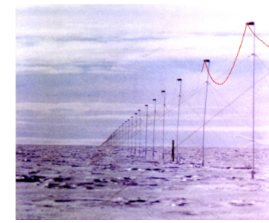
RECENT HAARP STUDIES

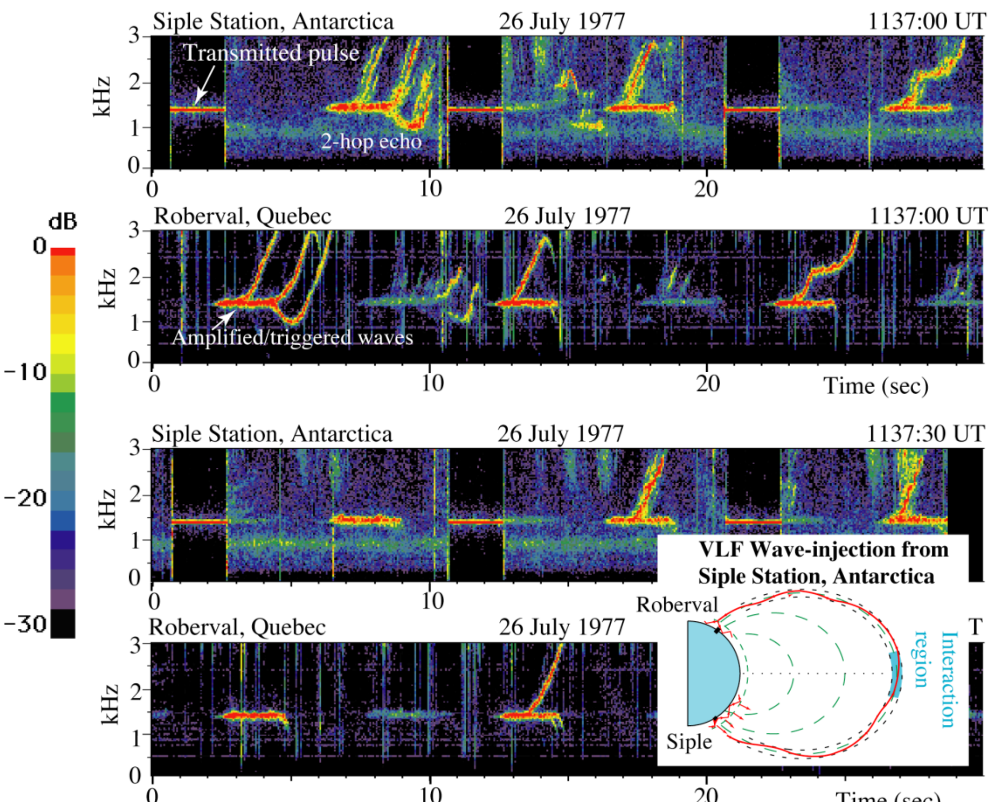
1. **The physics of artificially (Triggered) Emissions**
2. **Excitation of Ionospheric Alfven Resonator (IAR)**
3. **Properties of Alfvenic Duct-Pc1**
4. **Triggered ULF**

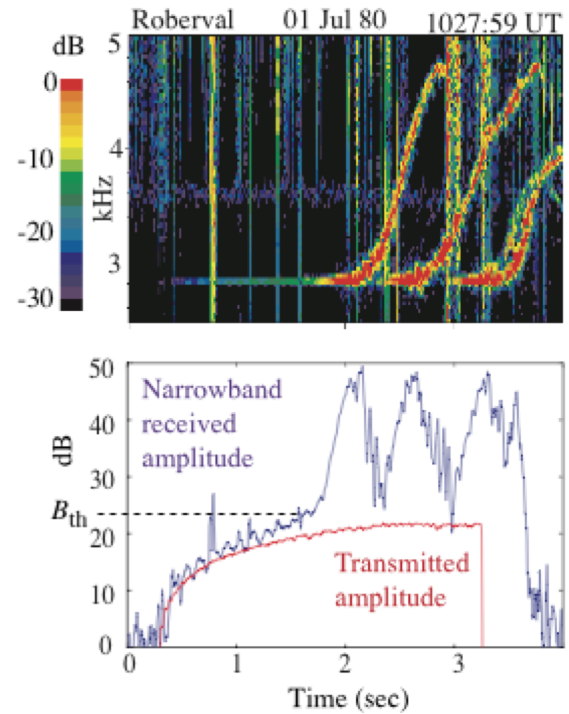
Artificially Stimulated Emissions (ASE)
Key RB Physics Issue – Physics of Chorus

Siple Station Antartica – (Stanford – NSF) Helliwell (1973-1987):

L=4.2, 1.5 MW, 42 km length antenna on 2 km thick ice sheet, Inject 3-6 kHz – limited bandwidth
Very difficult and inefficient to inject ELF/VLF with ground facilities







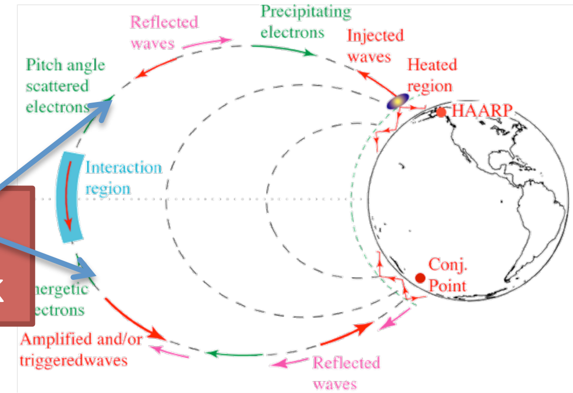
Triggered Emissions

HAARP Artificially Stimulated Emissions
Stanford University

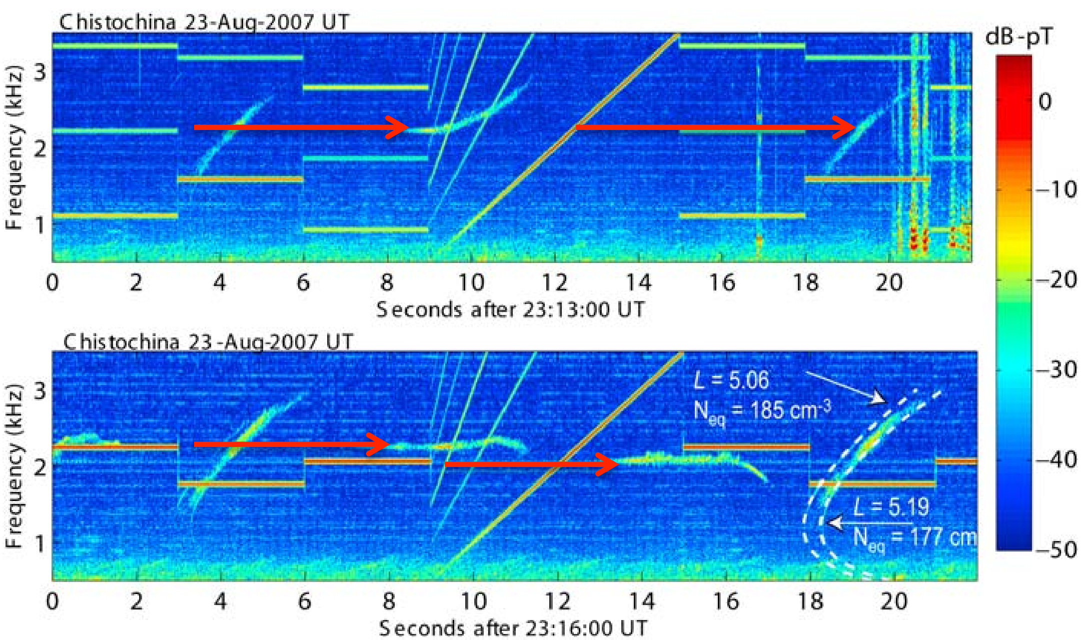
Triggered Emissions -Key non-linear issue in physics of RB (chorus, precipitation, wave-particle amplification, triggered EMIC, etc.) Role of trapped energetic particles.

Golkowski et al. JGR 2008, 2010

Resonance type diagnostic and feedback



2-hop echoes



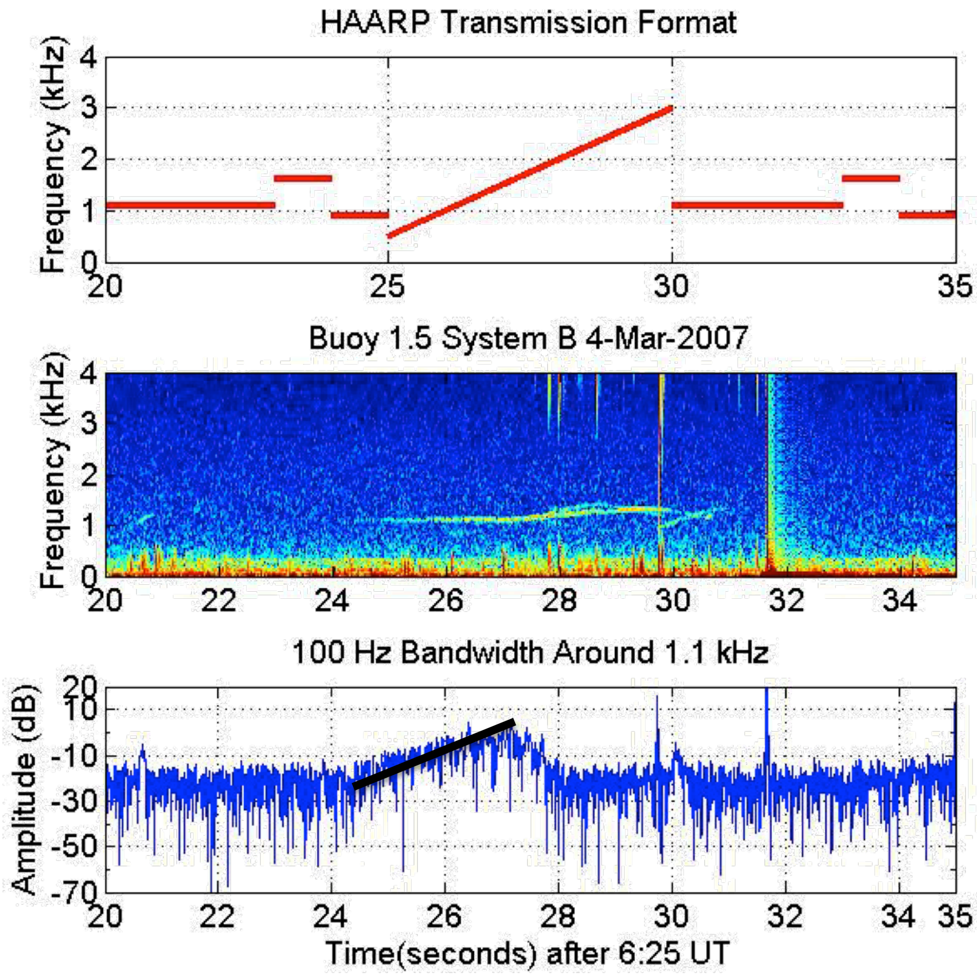
Conjugate

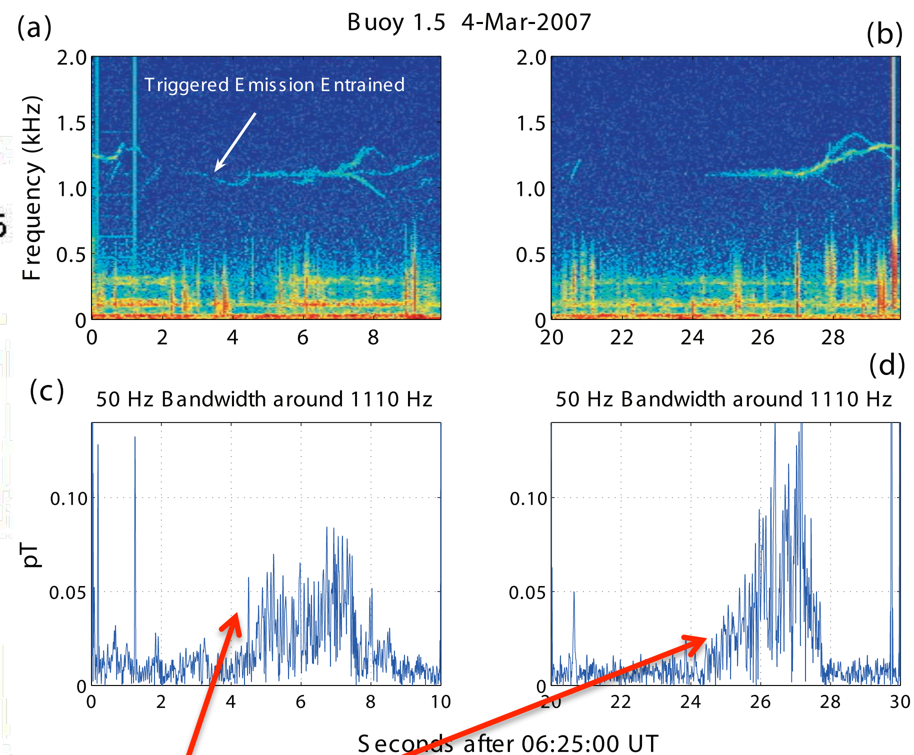
Buoy System

Pulses above 2 kHz have 2-hop echoes with triggered emissions
Pulses below 2 kHz and above 2.8 do not; ramps most often have echoes

15 dB/s Amplification & Triggered Emissions

Golkowski et al., JGR 2008, 2010





Only the pulse at 1100 Hz is amplified

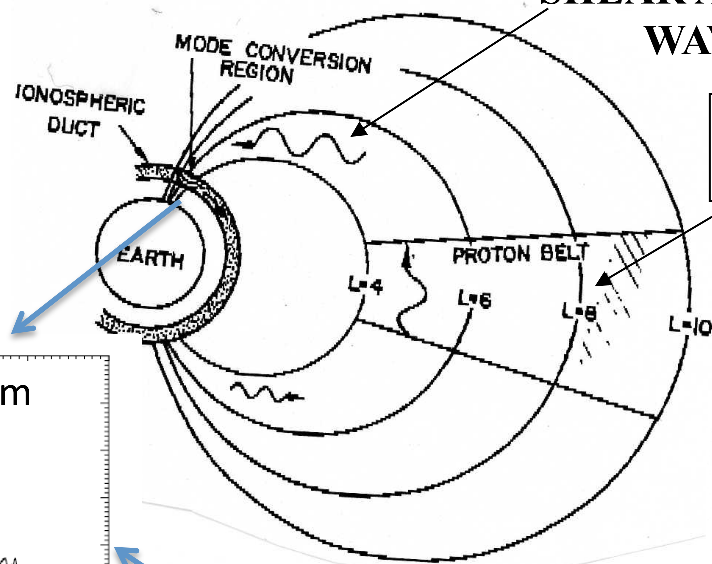
Definitive resolution of ASE requires long time diagnostics on field tube

Amplification with and without entrainment. RHS amplification steady below noise floor. LHS initial amplitude above noise due to previous echo (mode locking of coupled oscillators)

KEY TOPICS IN MECHANICS OF MAGNETOSPHERE

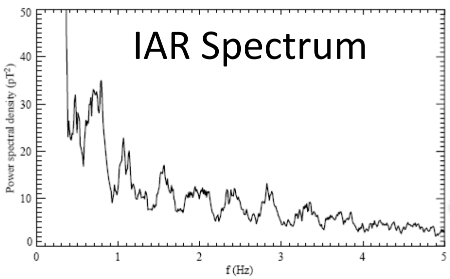
MI SHEAR ALFVEN WAVE COUPLING

Lateral Propagation as MS waves Pc1



SHEAR ALFVEN WAVE

Ion Cyclotron Instability



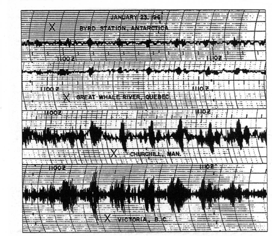
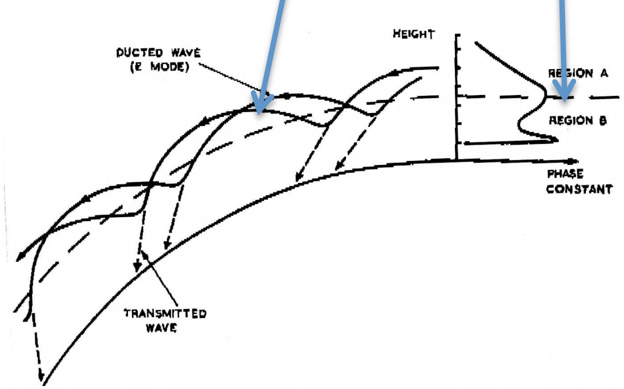


Fig. 2.1. Example of Pc 1's (pearls) recorded at four stations simultaneously. (After J. E. Lokken, J. A. Shand, and C. S. Wright, DREP photograph 2751)

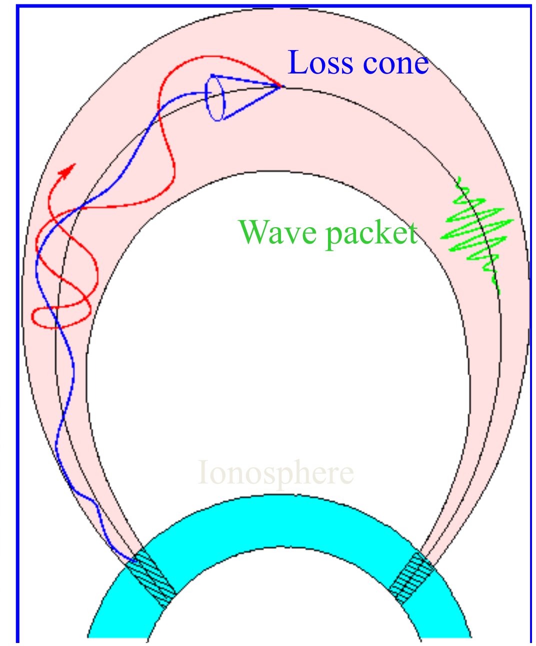
Ionospheric Alfven Resonator (IAR)

MS Duct



ALFVEN MASER

Trakhtengerts-Demekhov etc
Kennel-Petschek, Sagdeev

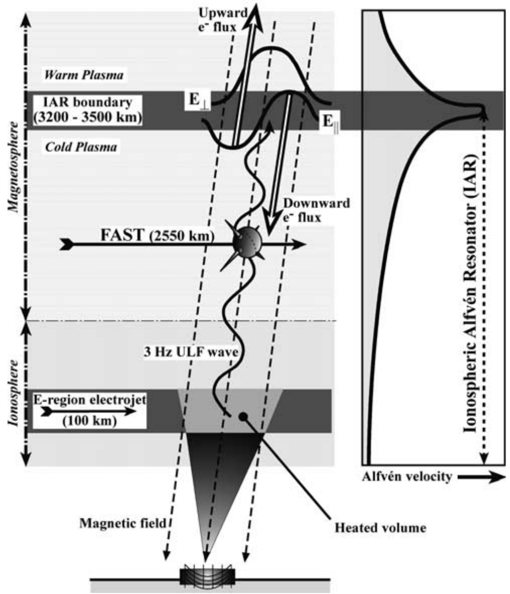


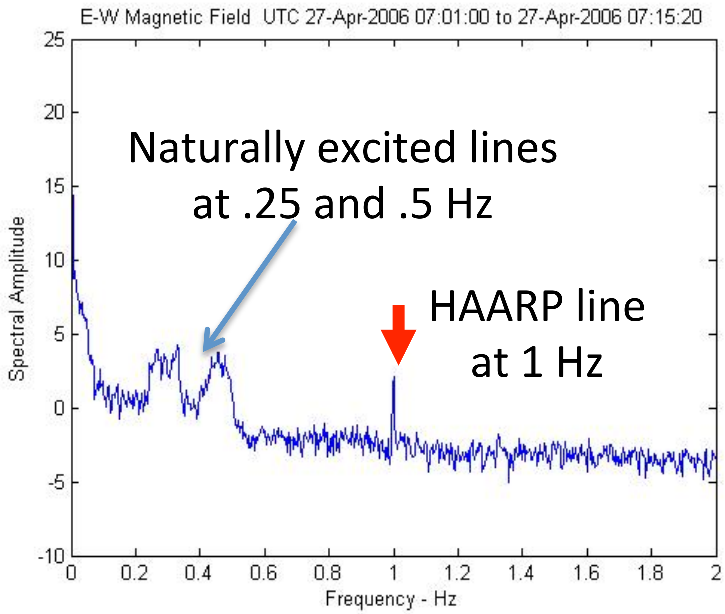
Active substance: Anisotropic energetic particles

Electro-dynamic system: Magnetic tube with cold plasma & ionosphere as mirrors

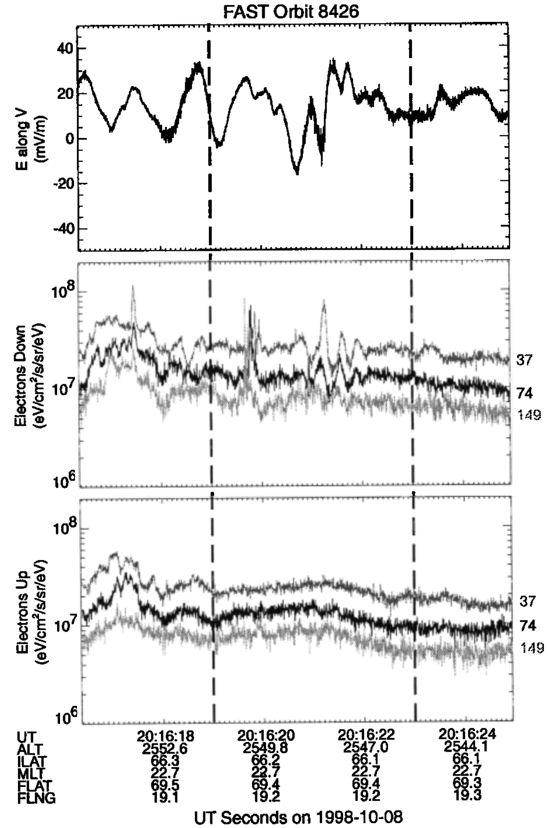
Operating modes: Whistlers & SAW

IAR Experiments





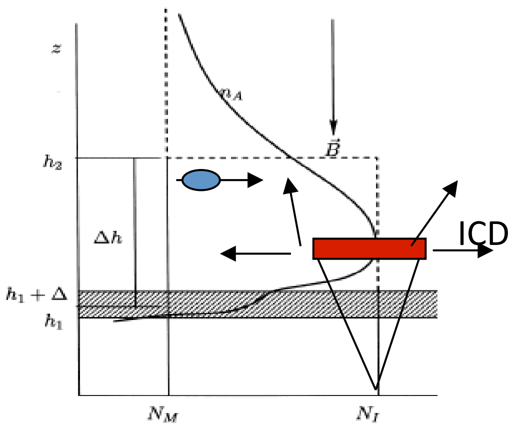
EISCAT/FAST Robinson et al., 2000



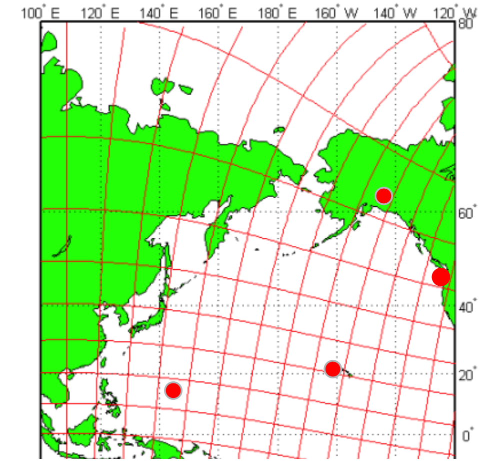
HAARP excitation of IAR
Papadopoulos et al., 2007

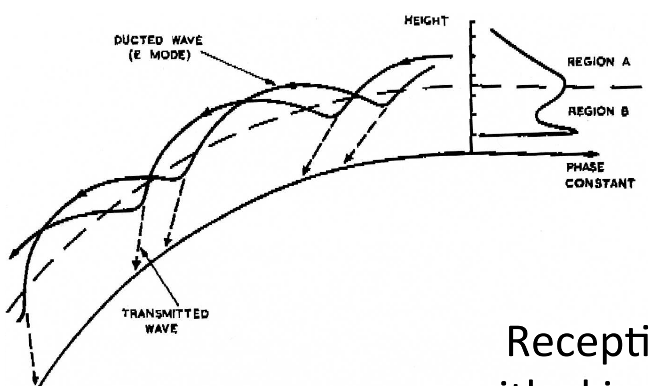
Q

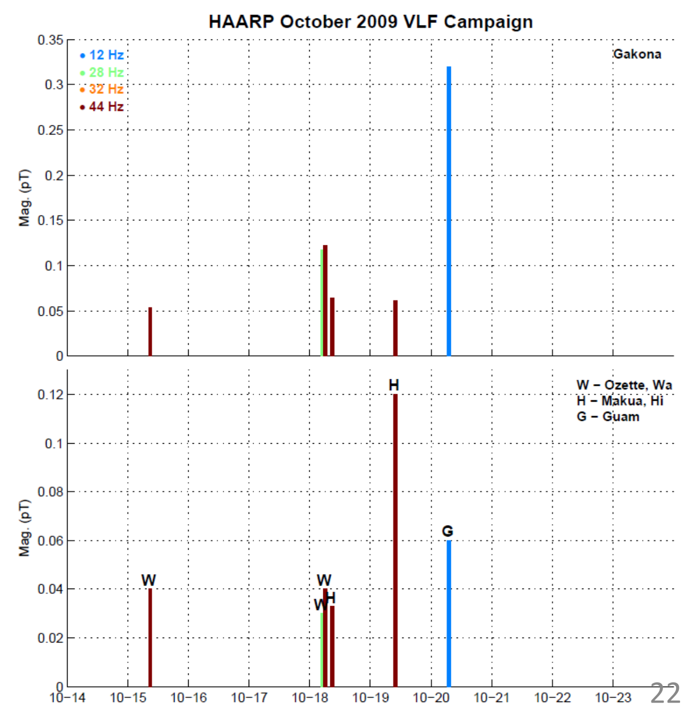
Physics of Pc-1 MHD Waves
Alfvenic Duct



- Distance from Gakona
  - Lake Ozette, WA (W)
    - 1300 mi
  - Hawaii (H)
    - 2900 mi
  - Guam (G)
    - 4800 mi
- Detection under quiet Gakona cond.
- No detection during electrojet days Oct. 22-23

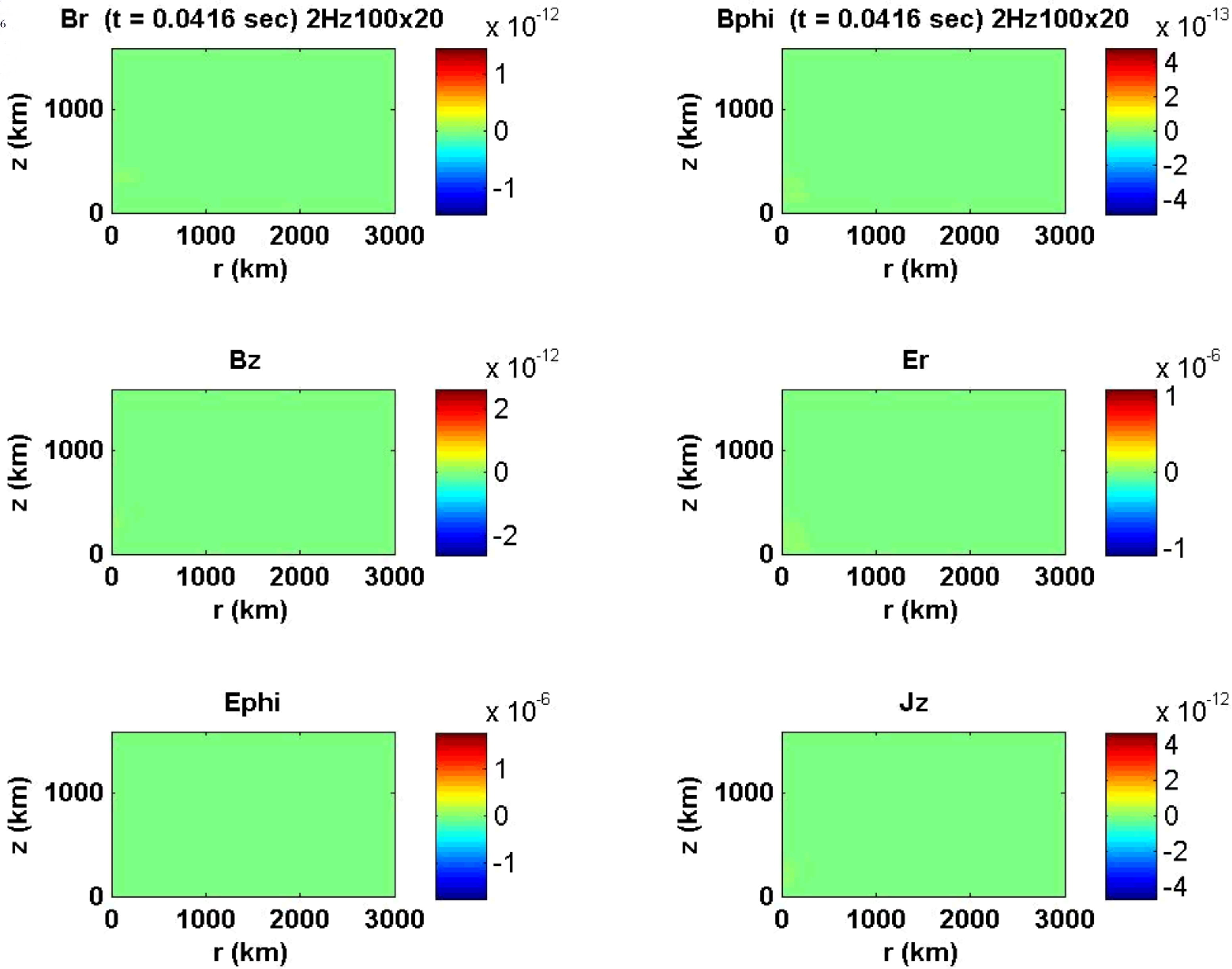




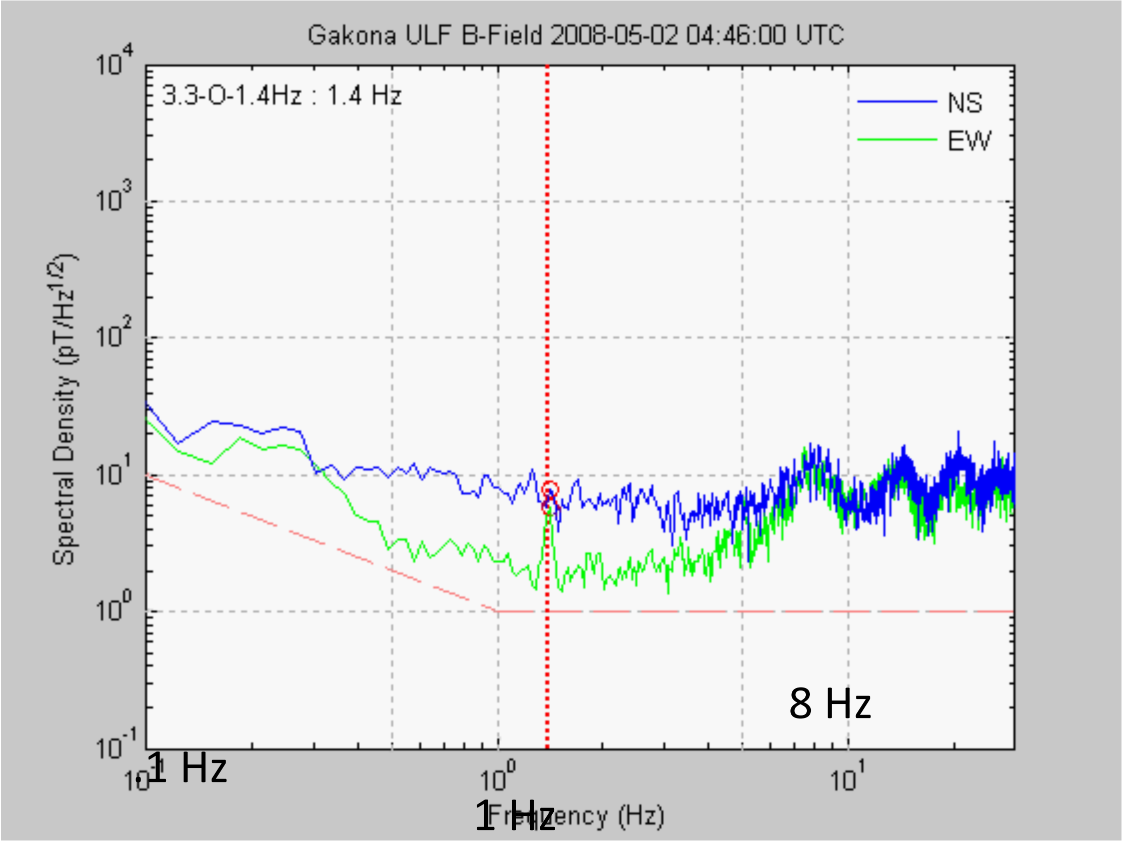


Reception consistent with skip distance effects

Eliasson, Chang, Papadopoulos, JGR 2012


Br (t = 0.0416 sec) 2Hz100x20
x 10^-12
Bphi (t = 0.0416 sec) 2Hz100x20
x 10^-13
Bz
x 10^-12
Er
x 10^-6
Ephi
x 10^-6
Jz
x 10^-12
z (km)
r (km)

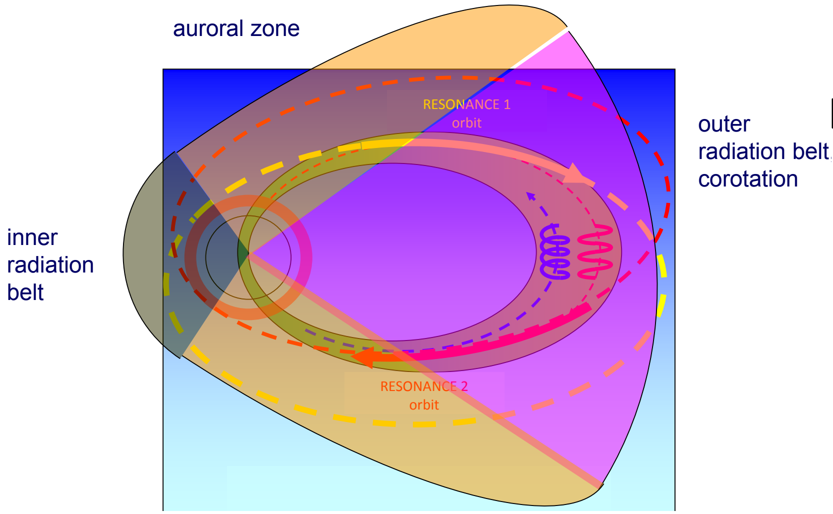
HAARP –Triggered ULF?



What is needed - Resonance

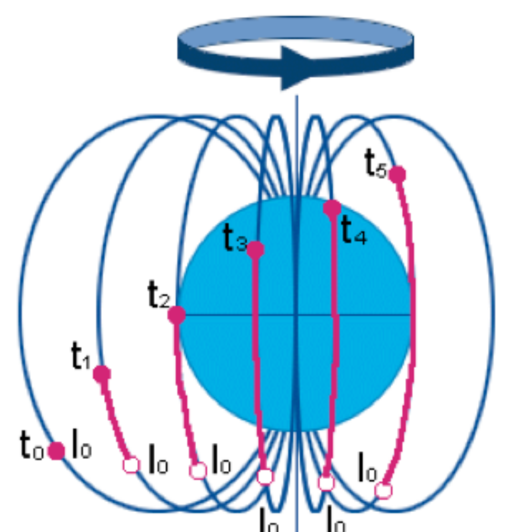
Pair of microsatellites (1A-1B; 2A-2B) in Magneto-synchronous orbit – Stay on same field line for 45-60 minutes. Launch Summer 2014 by IKI.

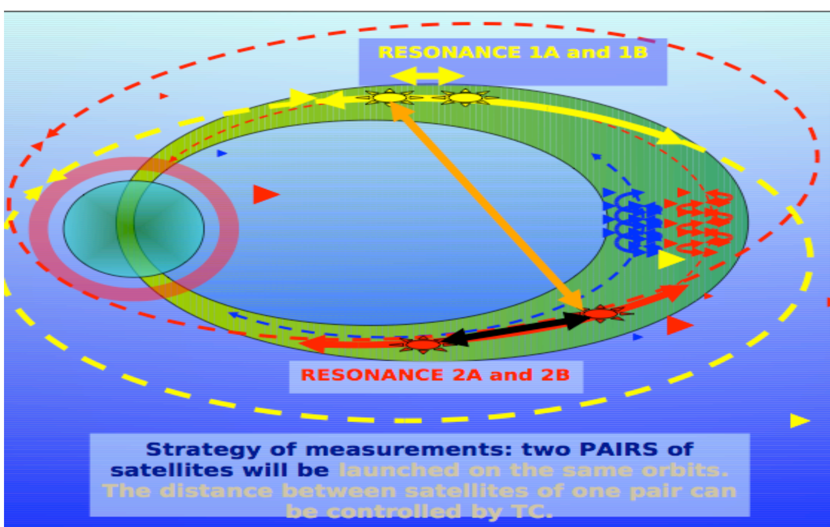
Zones along orbit



HAARP Coverage
H_p=500 km, H_a=27300
L=5.08, T= 8 hrs
43 min. within 20 km
3 hrs within 50 km
of HAARP flux tube

Apogee 28000 km, Perigee 500 km, Period 8 hours, Incl. +63.4 and -63.4





~ 1-10 km

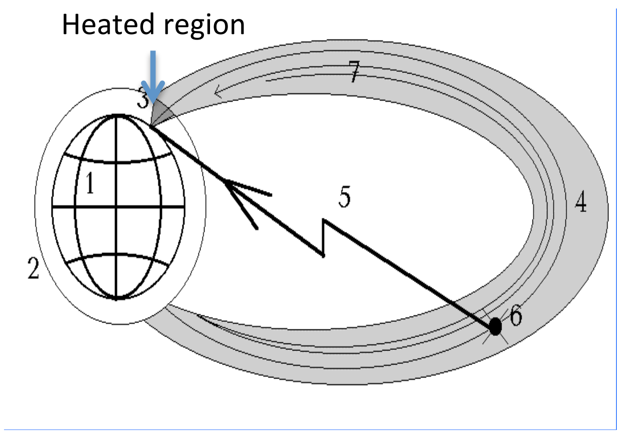
~ 5-15 x10^3 km

Electric and magnetic sensors
Wave analyzer and interferometer
DC – 10 MHz

Plasma sensors
Cold plasma
Suprathermal plasma
Energetic particles
Relativistic electrons

RB Physics Questions to be addressed by Active Probing

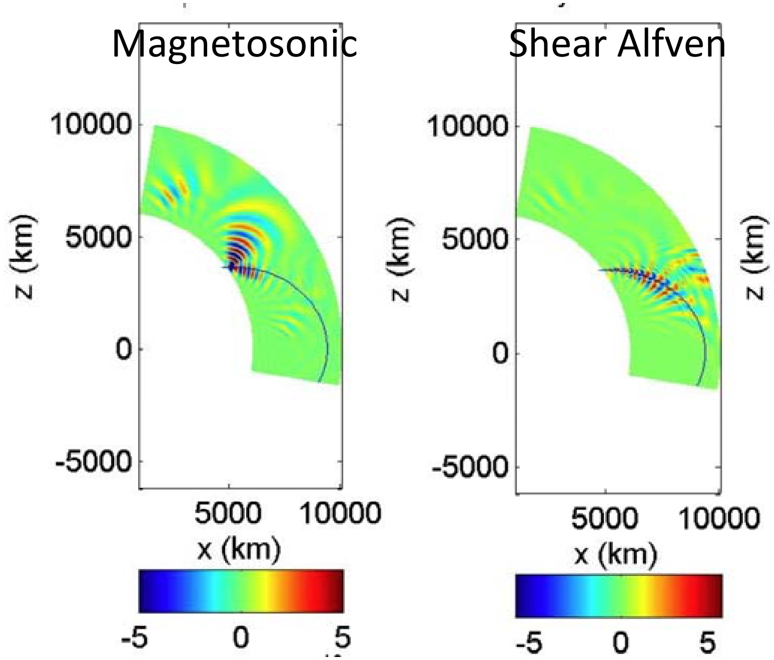
- What is the attenuation rate of Shear Alfven (SA) waves propagating towards the conjugates?
- Are there regions of mode conversion of SA waves to Electromagnetic Ion Cyclotron (EMIC) waves and what are the characteristics of the resonant conversion?
- What are the properties of the EMIC waves?
- What are the pitch angle scattering rates of relativistic electrons by EMIC waves?
- What are the pitch angle scattering rates of multi-MeV protons by SA waves?
- What are the properties of Field Line Resonances (FLR) in the inner RB?
- What controls the Ionospheric Alfven Resonator (IAR) structure and amplification?
- What is the non-linear physics of Artificially Stimulated Emissions (ASE) and how it relates to chorus?
- Is there an Alfven maser and what are the operational characteristics?
- Can FLR precipitate electrons?
- What are the properties of Alfvenic waveguide?

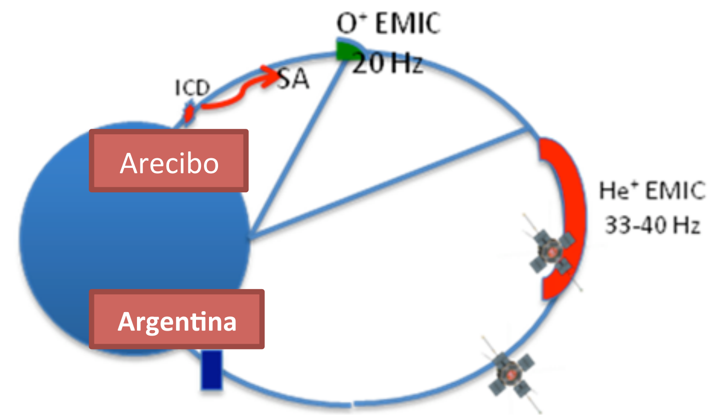


- Diagnose magnetospheric effects(ULF/ELF/VLF waves, energetic particles, plasma flows etc.), of heater operation with high spatiotemporal resolution
- Control heater operation based on transmitted data.
- Exploit dynamic feedback

INNER BELT PHYSICS STUDIES

Example of MHD Wave Propagation Studies in the Inner Belt Using Arecibo and Van Allen Probes





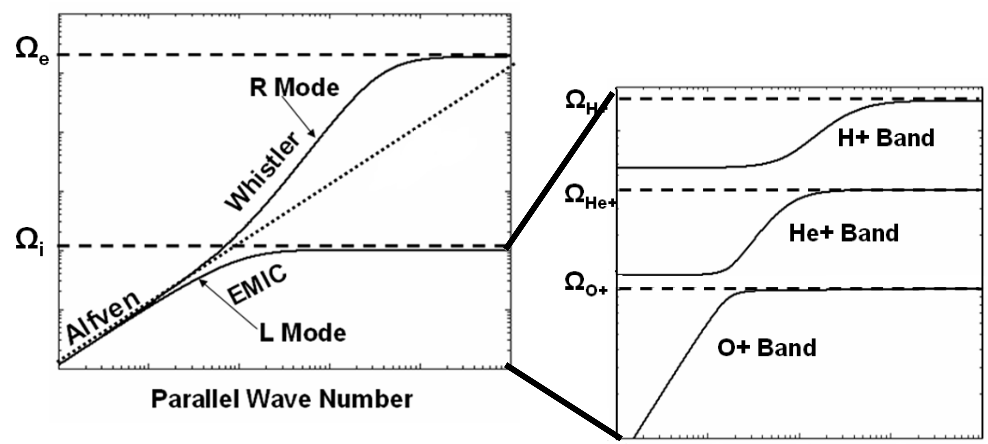
Simulation of MHD Wave injection using the Arecibo Heater

$$-k_z v_z = |\Omega_e| / \gamma$$

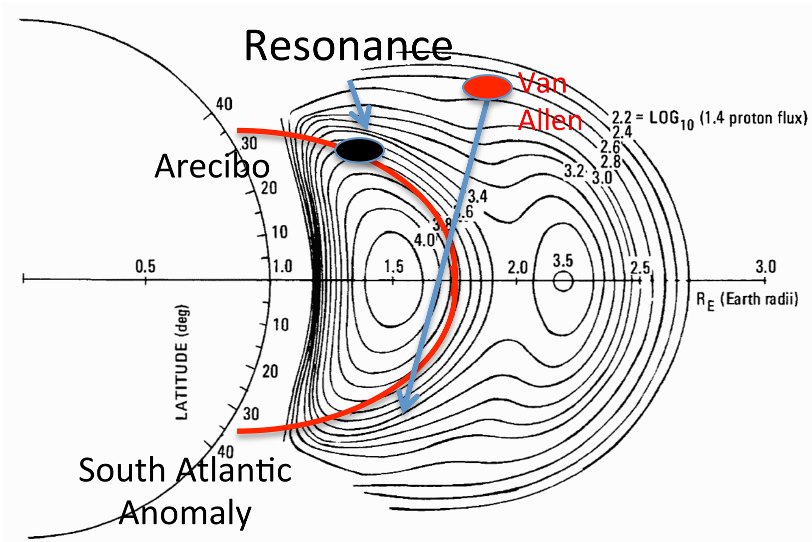
$$\frac{k^2c^2}{\omega^2} = 1 - \frac{\omega_{pe}^2}{\omega(\omega + |\Omega_e|)} - \sum_{j=1}^{3} \frac{\omega\omega_{pj}^2}{(\omega - \Omega_j)}$$

$$\frac{k^2c^2}{\omega^2} \to \infty \quad \text{for } \omega \to \Omega_j$$

As a result $1/k_z \to |\Omega_e| / \gamma v_z$ before reaching resonance $(1/k_z \to 0)$



Active SAW Probing of Inner RB Using the Arecibo Heater/Van Allen or Resonance



Proton Energy	Resonance Frequencies
30 MeV	6-16 Hz
50 MeV	5-15 Hz
100 MeV	3.5-9.5Hz

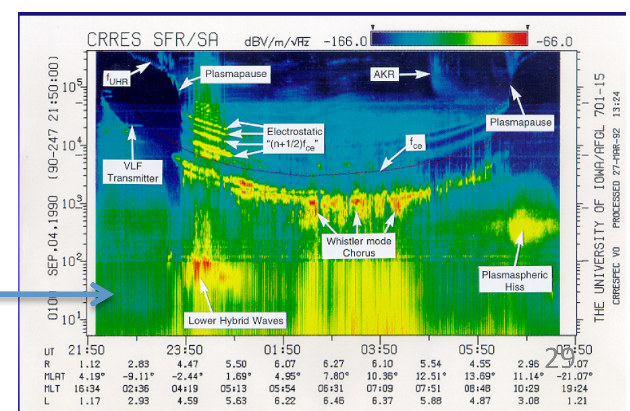
Focus on SAW for protons and EMIC for electrons

Typical inner belt proton lifetimes:

10 MeV – decades

50 MeV – century

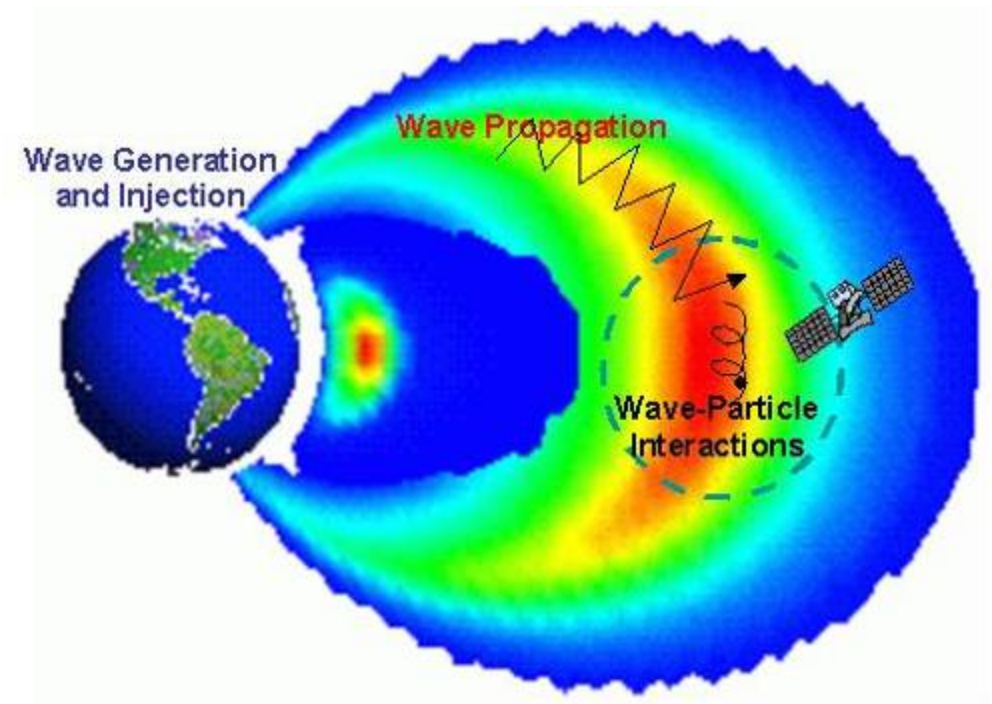
No SAW activity
Stacking



SUMMARY

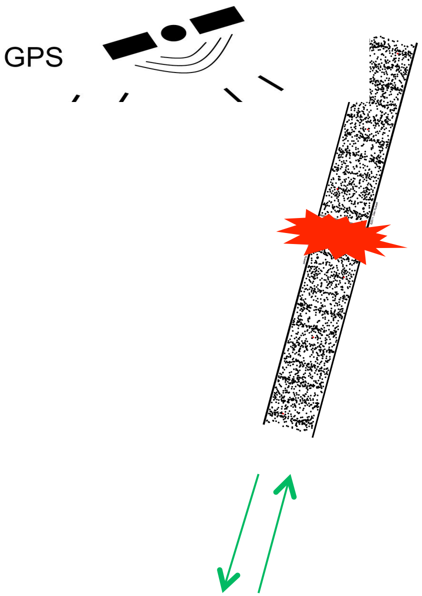
ACTIVE HEATER INJECTION EXPERIMENTS WITH WELL PLANNED SATELLITE COVERAGE COMPLEMENT CURRENT PASSIVE INVESTIGATIONS AND CAN RESOLVE MAJOR RB PHYSICS SCIENTIFIC OBJECTIVES SUCH AS

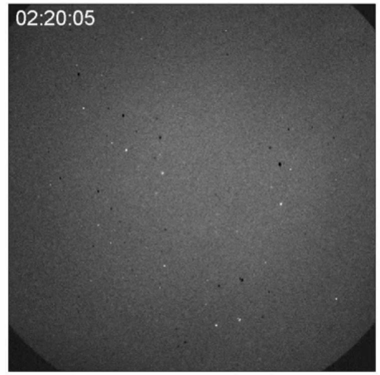
- **Wave Generation/Injection Efficiencies**
  - **Dependence on Frequency, Waveforms**
  - **Dependence on Geophysical Conditions**
- **Wave Propagation Characteristics**
  - **Ducting Conditions**
  - **Wave Amplification & Attenuation Processes**
  - **Dependence on Frequency, Waveforms**
  - **Dependence on Geophysical Conditions**
- **Wave-Particle Interactions**
  - **Effects of Waves on Particle Motion /Scattering**
  - **Efficiency of Precipitating Particles out of the Belts**
  - **Dependence on Geophysical Conditions**



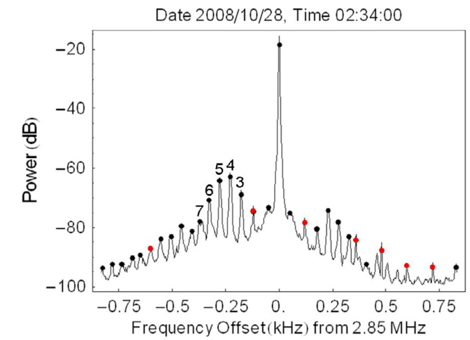
THE PHYSICS OF ARTIFICIAL IONIZATION

DIAGNOSTIC INSTRUMENTATION





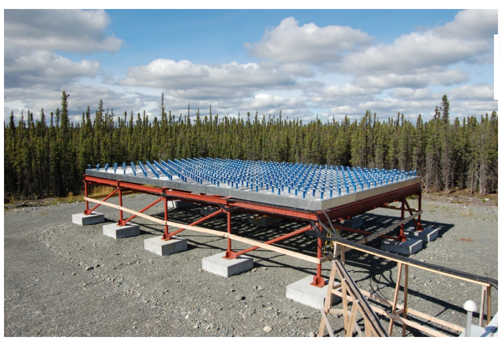
630 nm Artificial Plasma
Glow Discharge Ionization

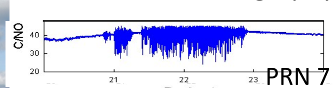


SEE

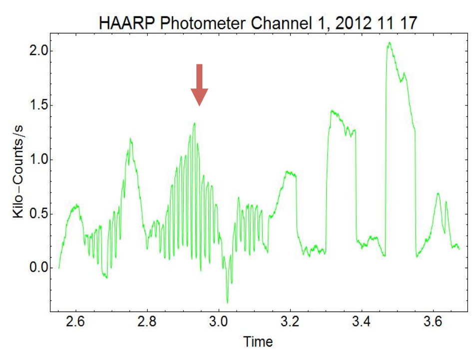
Eight channel HF receivers, NRL

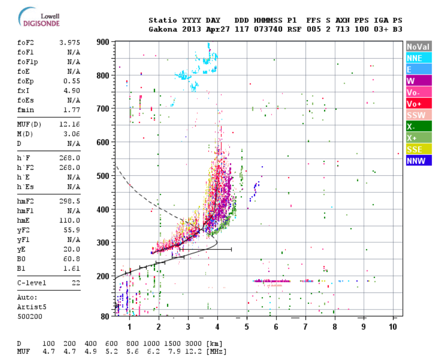
Optics: All-sky imager ,Telescopic imager
Photometers ,14 ft Optical Dome
Tomography Chain ,Cordova -> Kaktovik





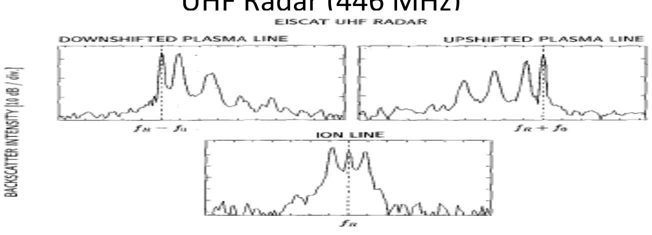
PRN 7



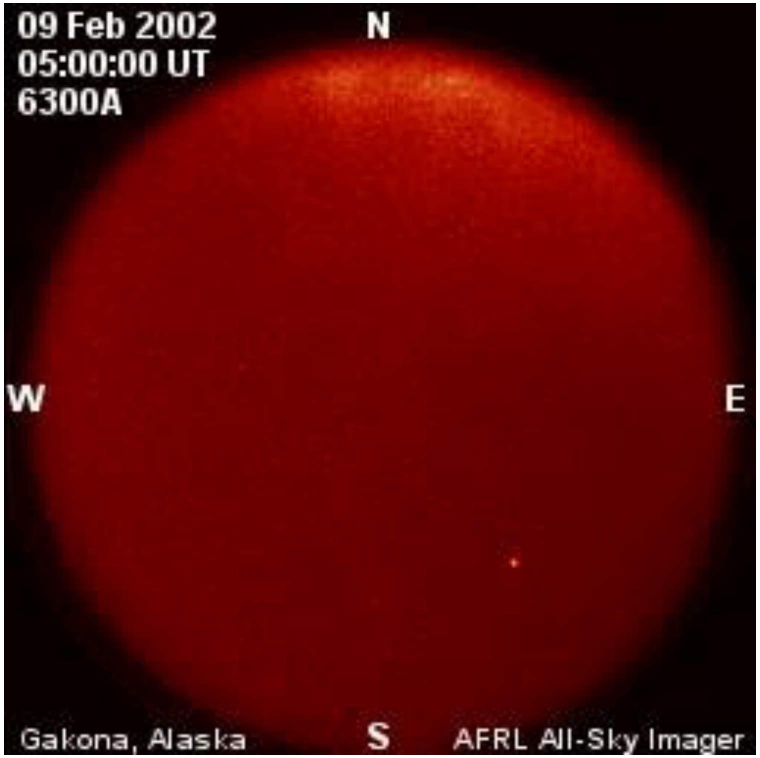


Ionosonde

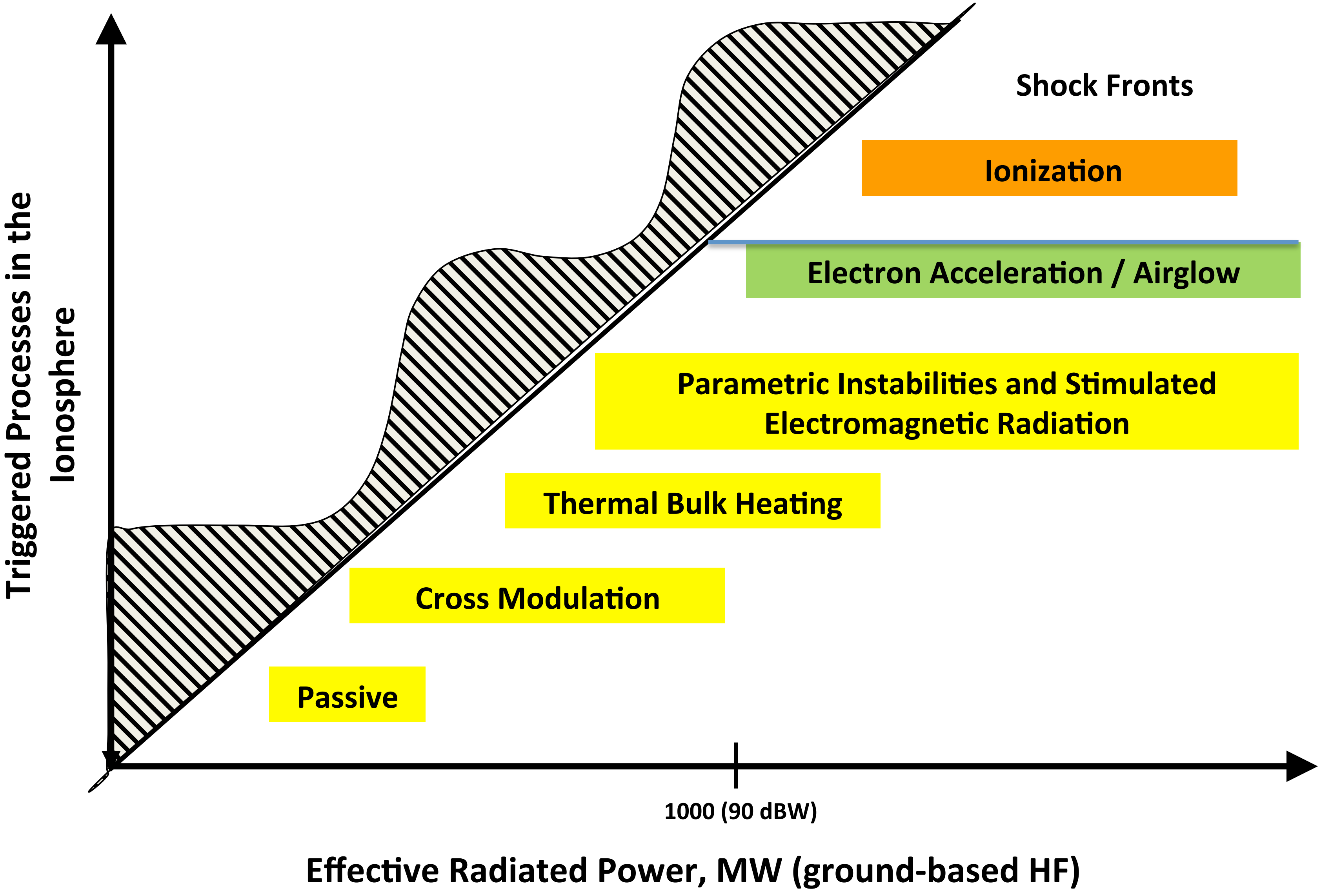
UHF Radar (446 MHz)



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



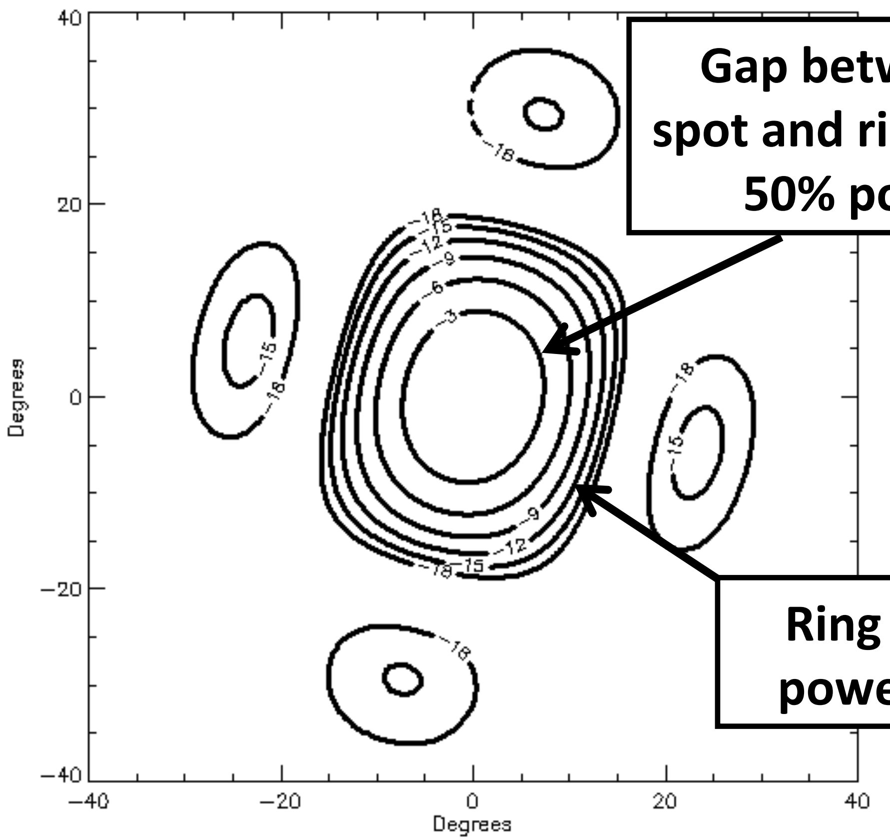
Power Thresholds to Trigger Processes in the Ionosphere

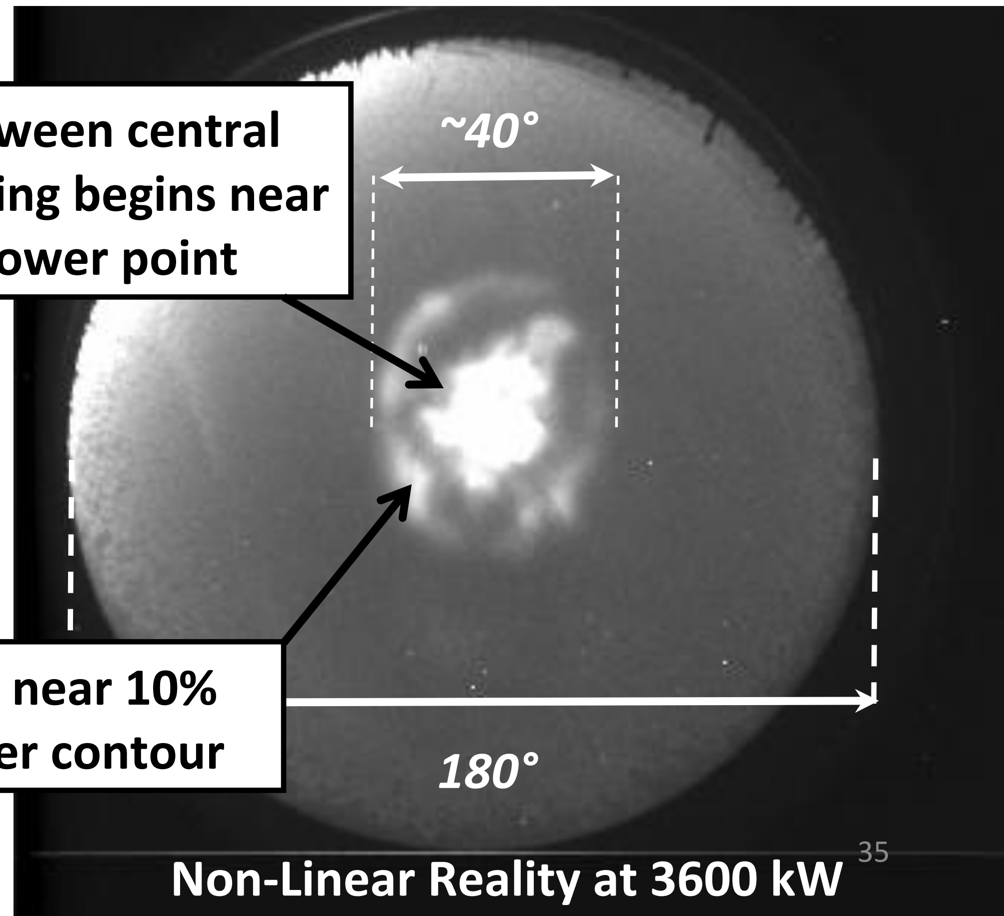


HAARP AT 3.6 MW – NEW THRESHOLD - APL

- 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

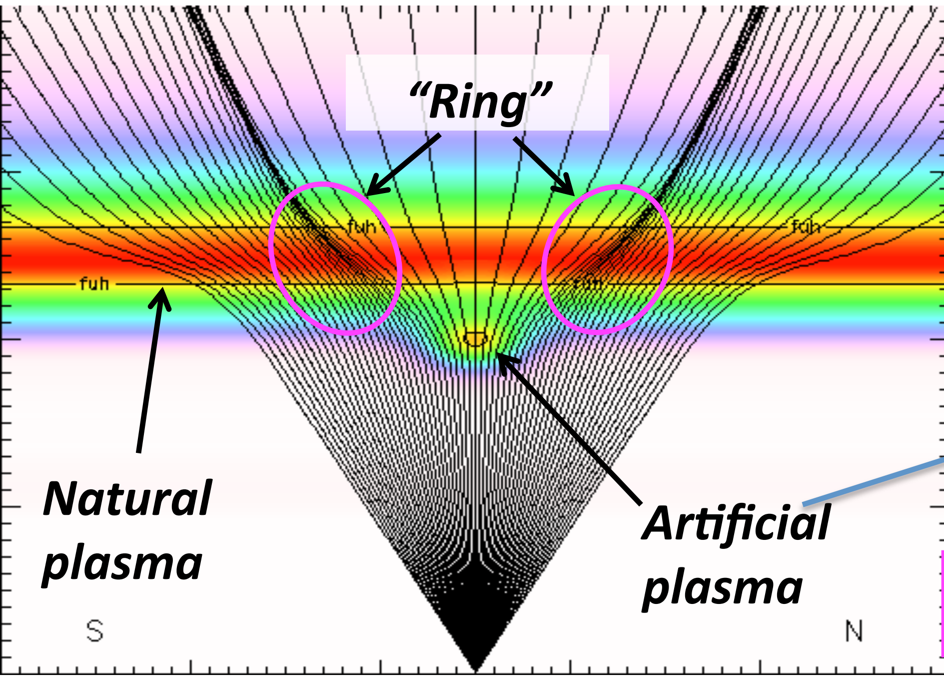
HAARP Transmitter Beam Pattern





HYPOTHESIS – ARTIFICAL PLASMA LAYER

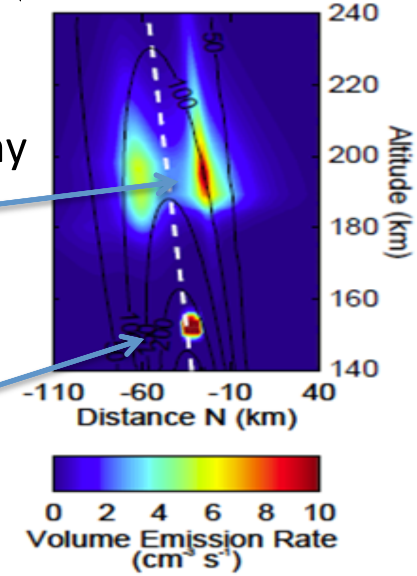
PEDERSEN ET AL, GRL 2009,2010,2011

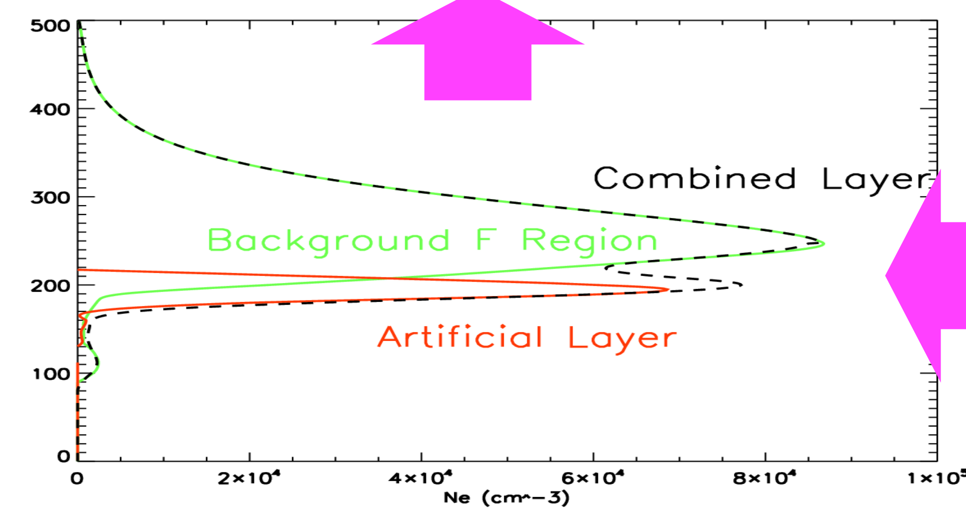


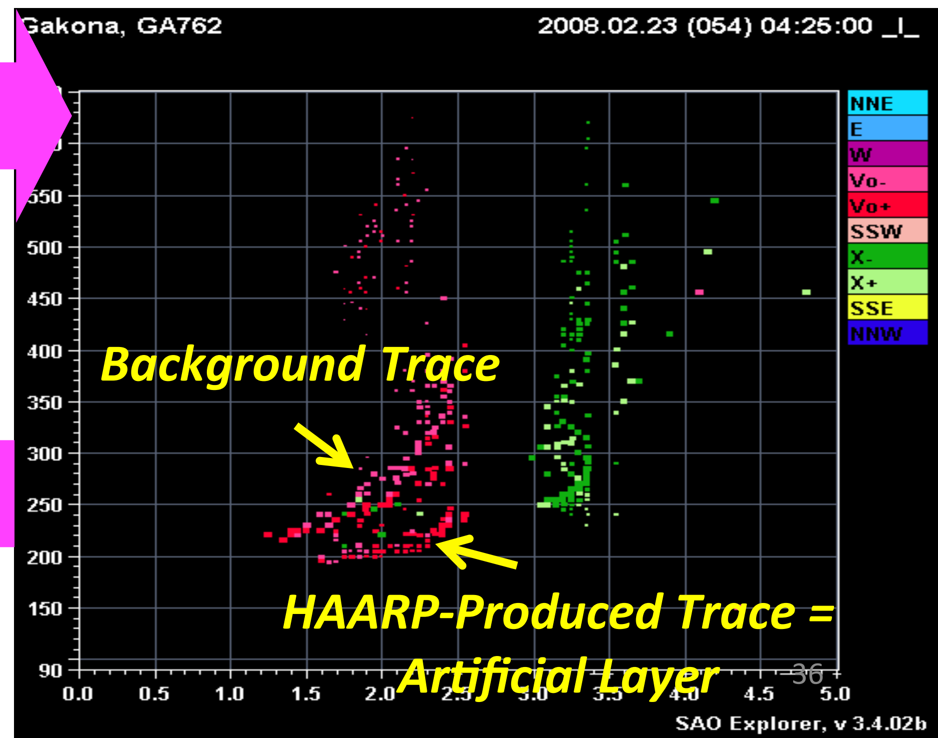
Tomography

Reflection

Cartoon

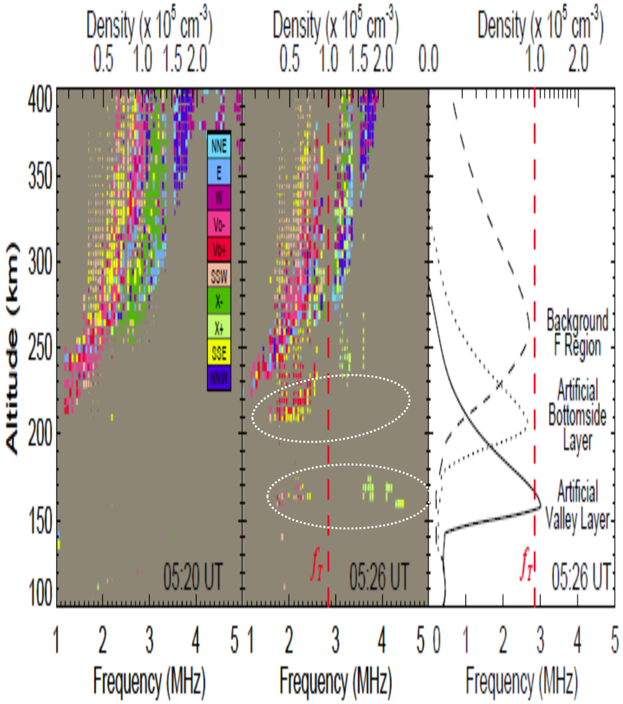


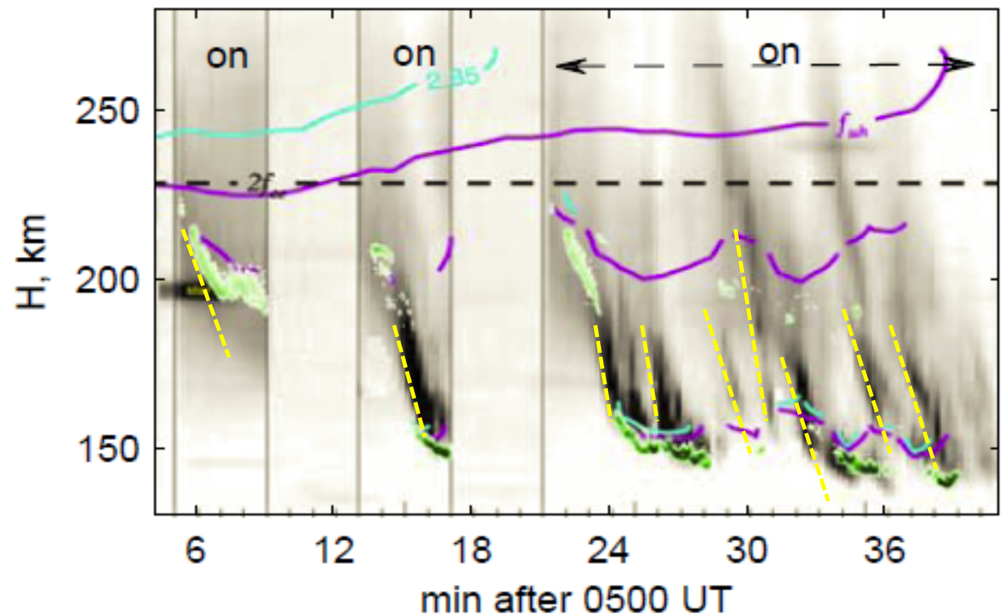




Descending APL

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.

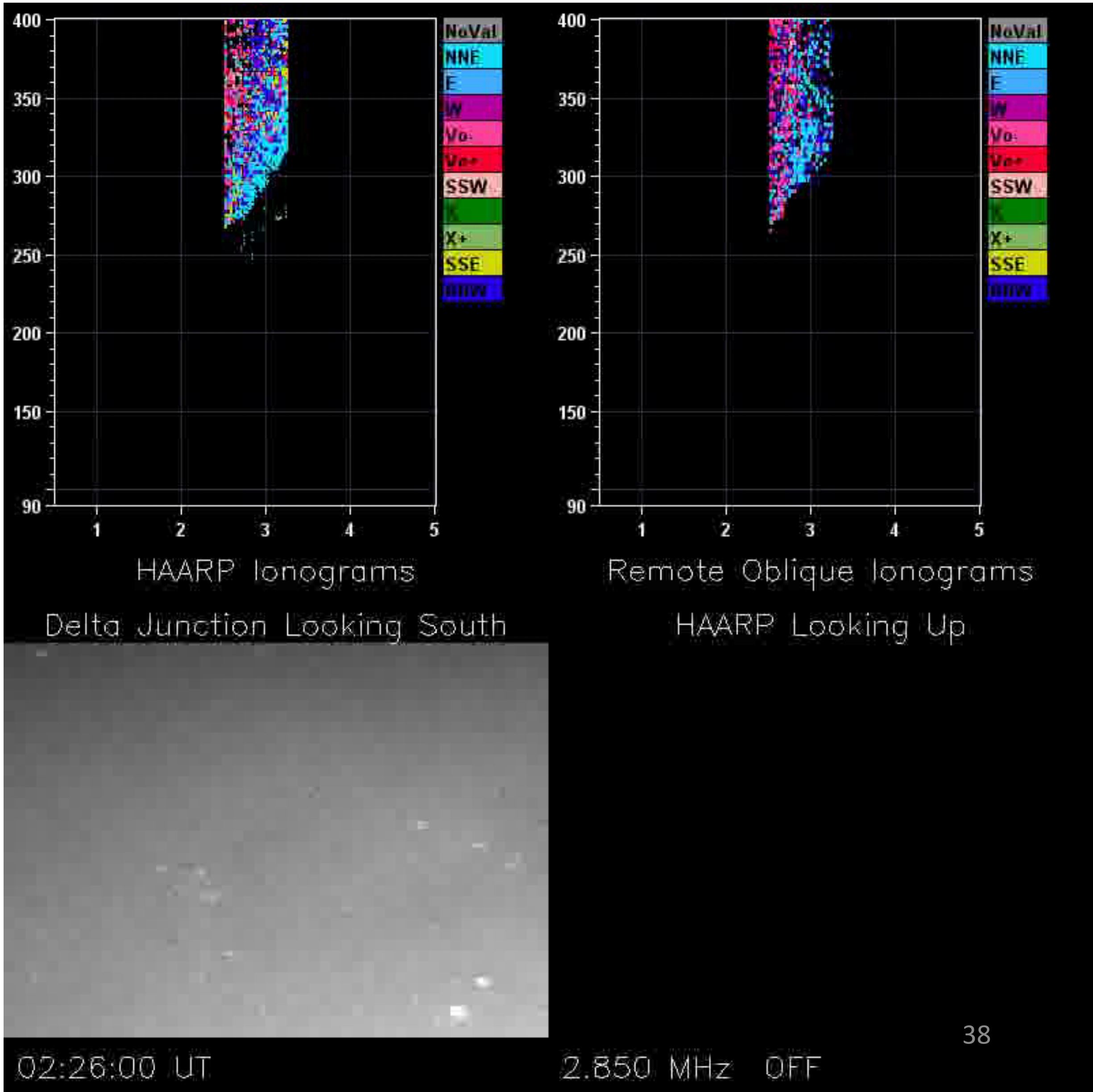
Courtesy of E. Mishin

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



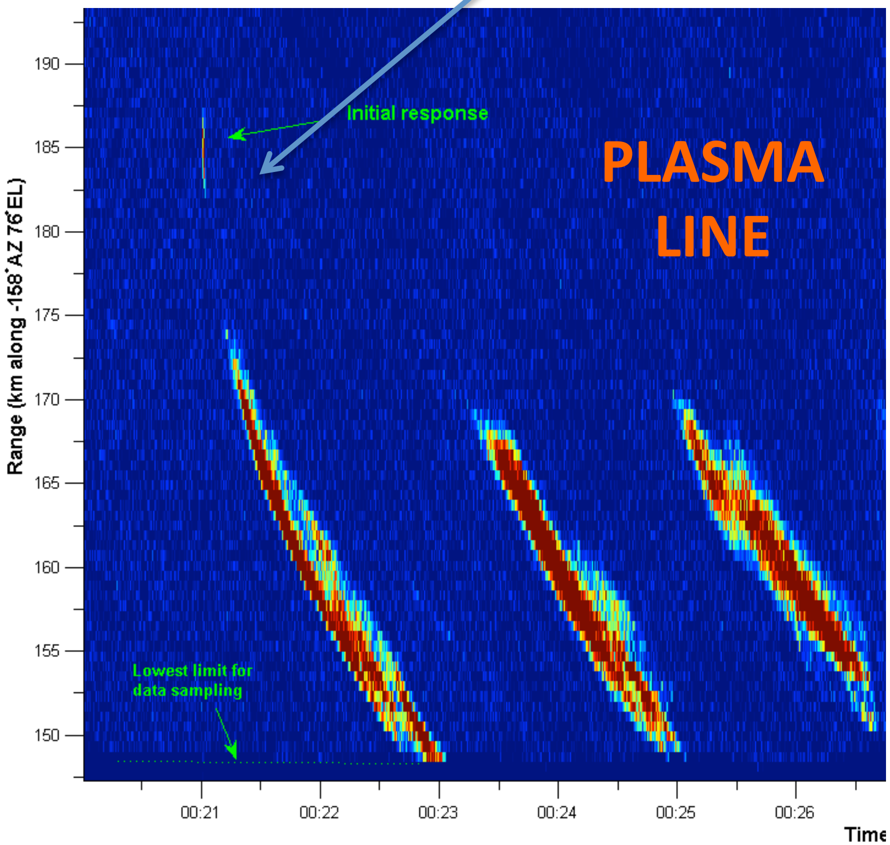
Courtesy of T. Pedersen

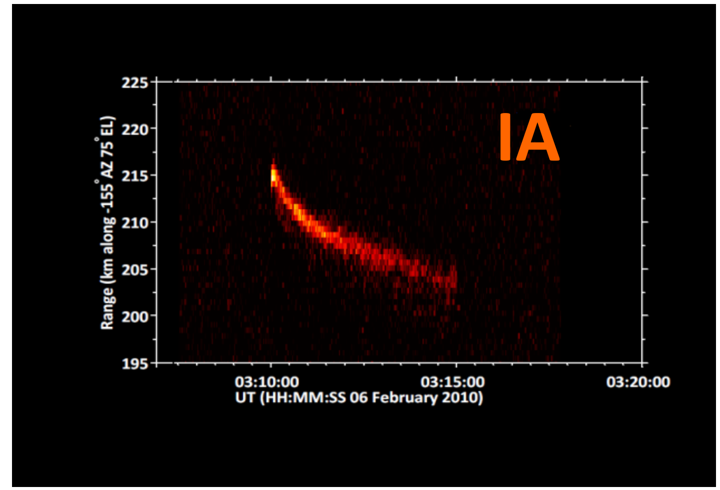
Note similarity with optical emissions descent except for initial response

MUIR DATA - WATKINS

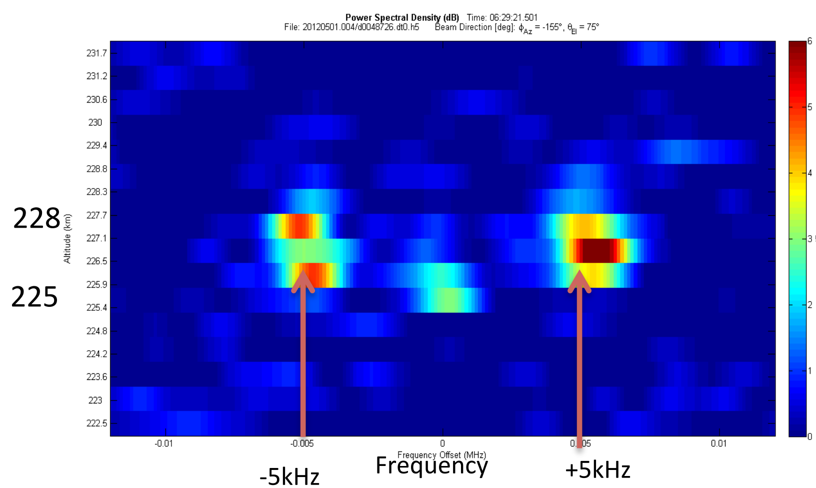
frequency shift from 446 MHz

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.



$$\Delta\omega \approx kC_s = 2k_oC_s$$

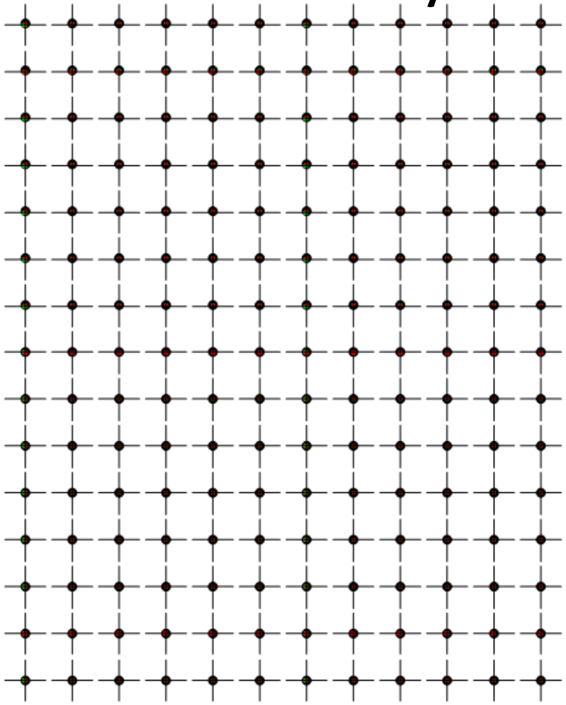
$$C_s = \sqrt{\frac{\gamma T_e}{M}}$$

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

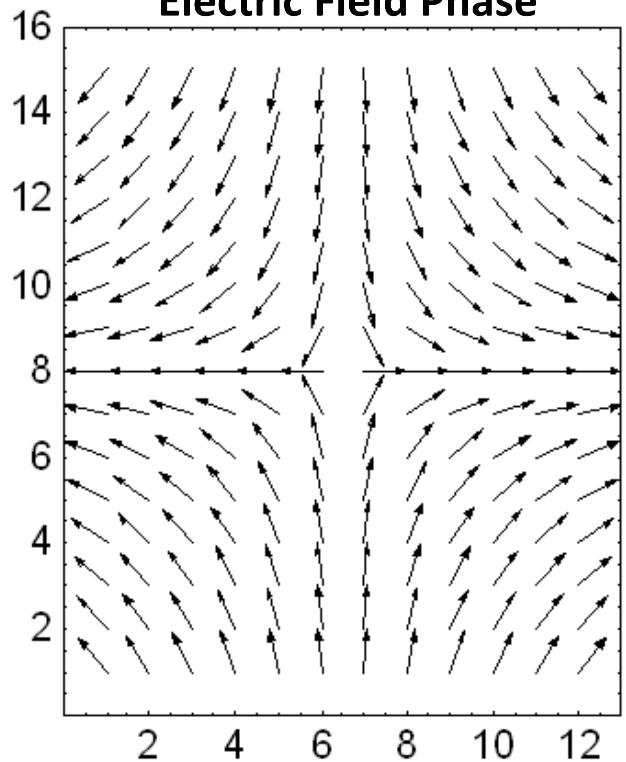
BERNHARDT

L=1 OAM Generation with HAARP

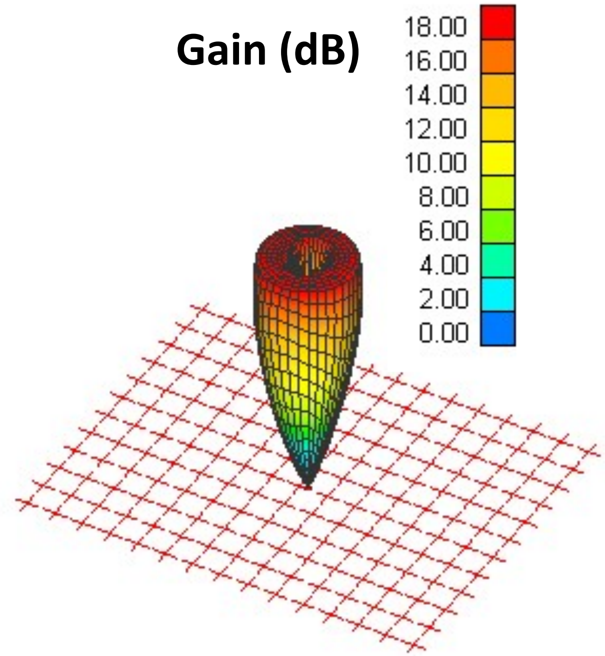
Antenna Array



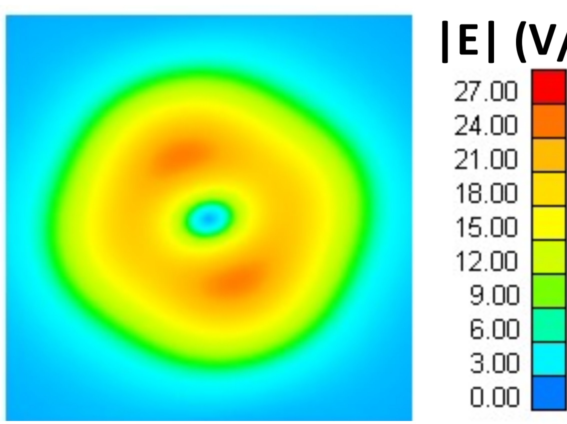
Electric Field Phase



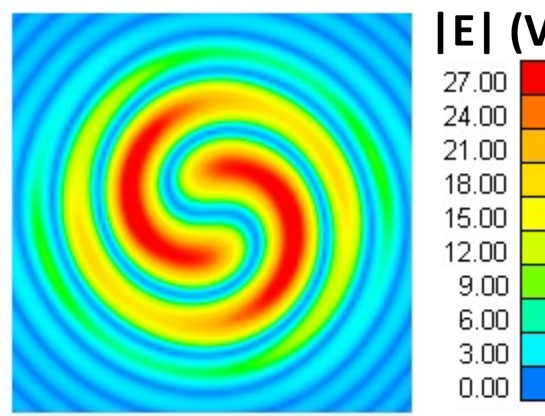
Gain (dB)



Average |E| (V/m)



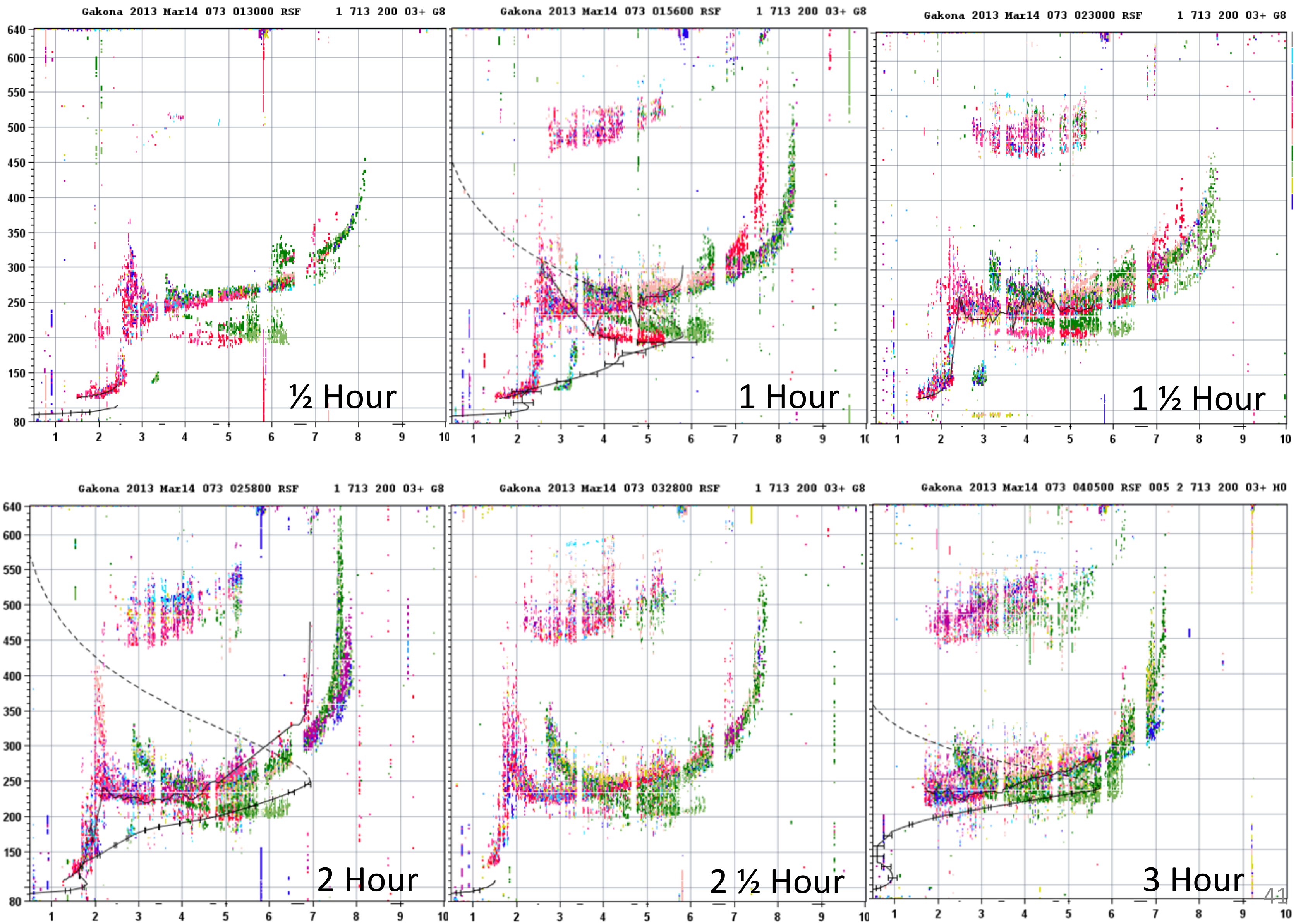
Instant |E| (V/m)



BERNHARDT

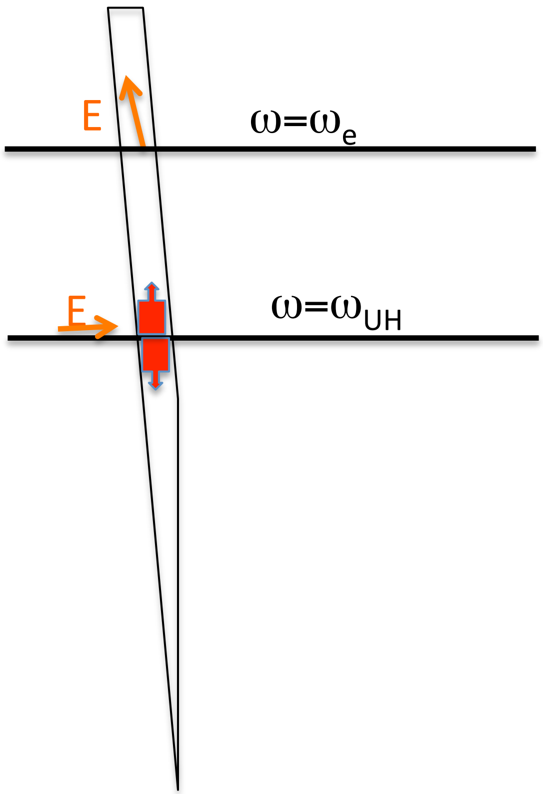
14 March 2013 01:30 to 04:00 GMT

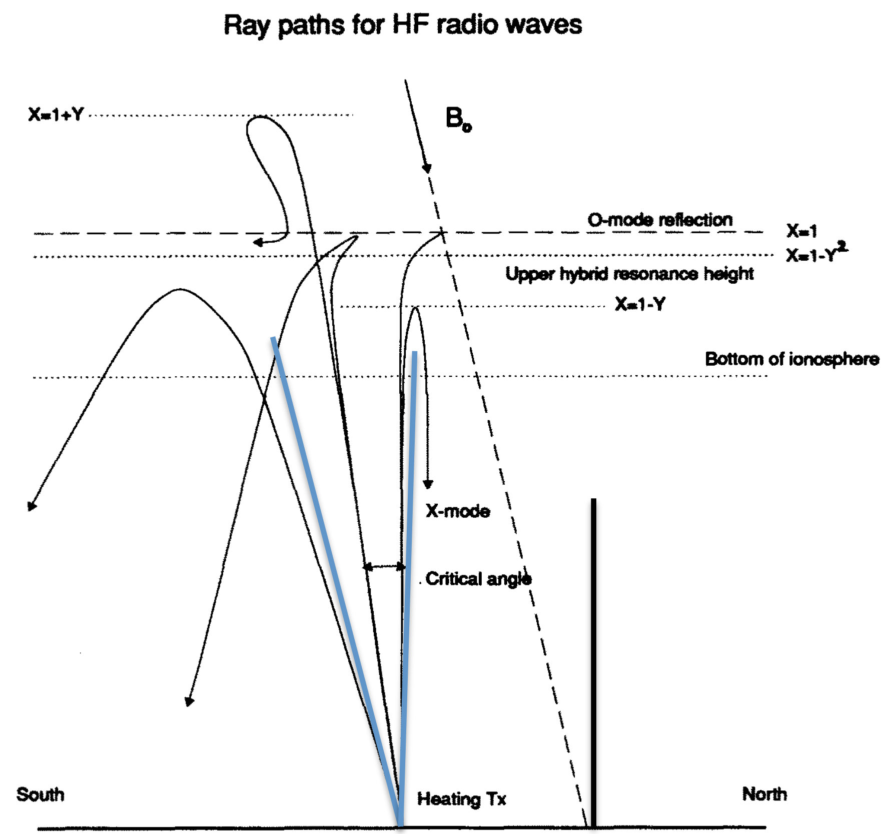
Extended Artificial Ionization with 5.8 MHz Twisted Beam

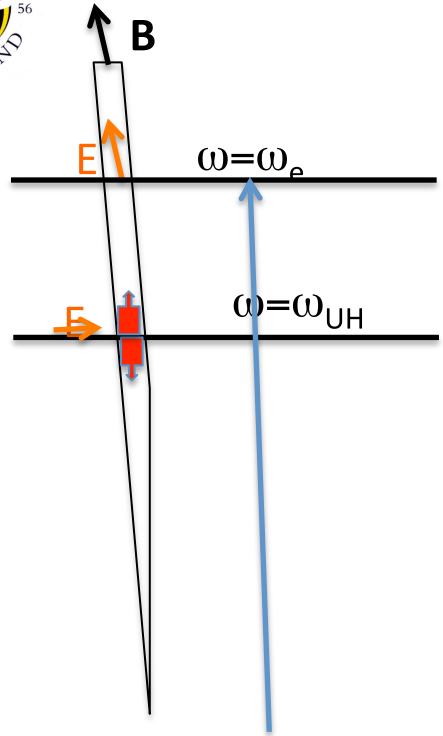


Theory/Modeling - Key Physics Ideas

- 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

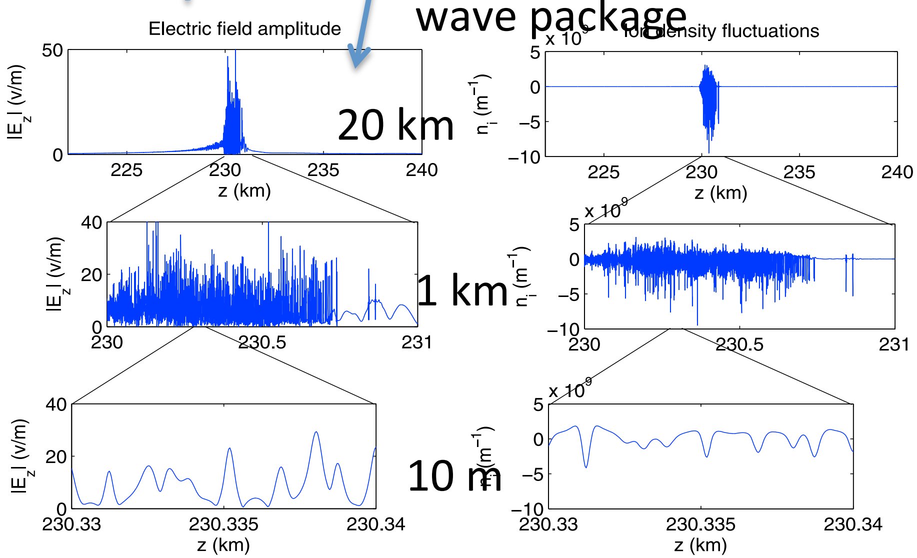
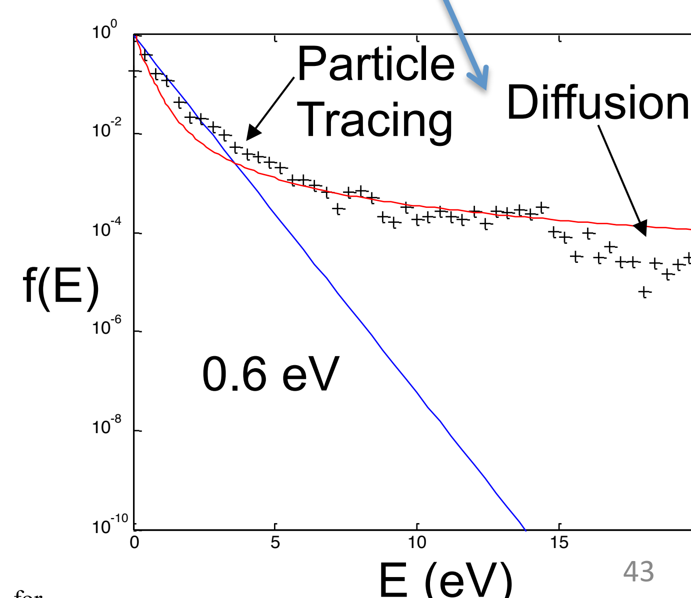
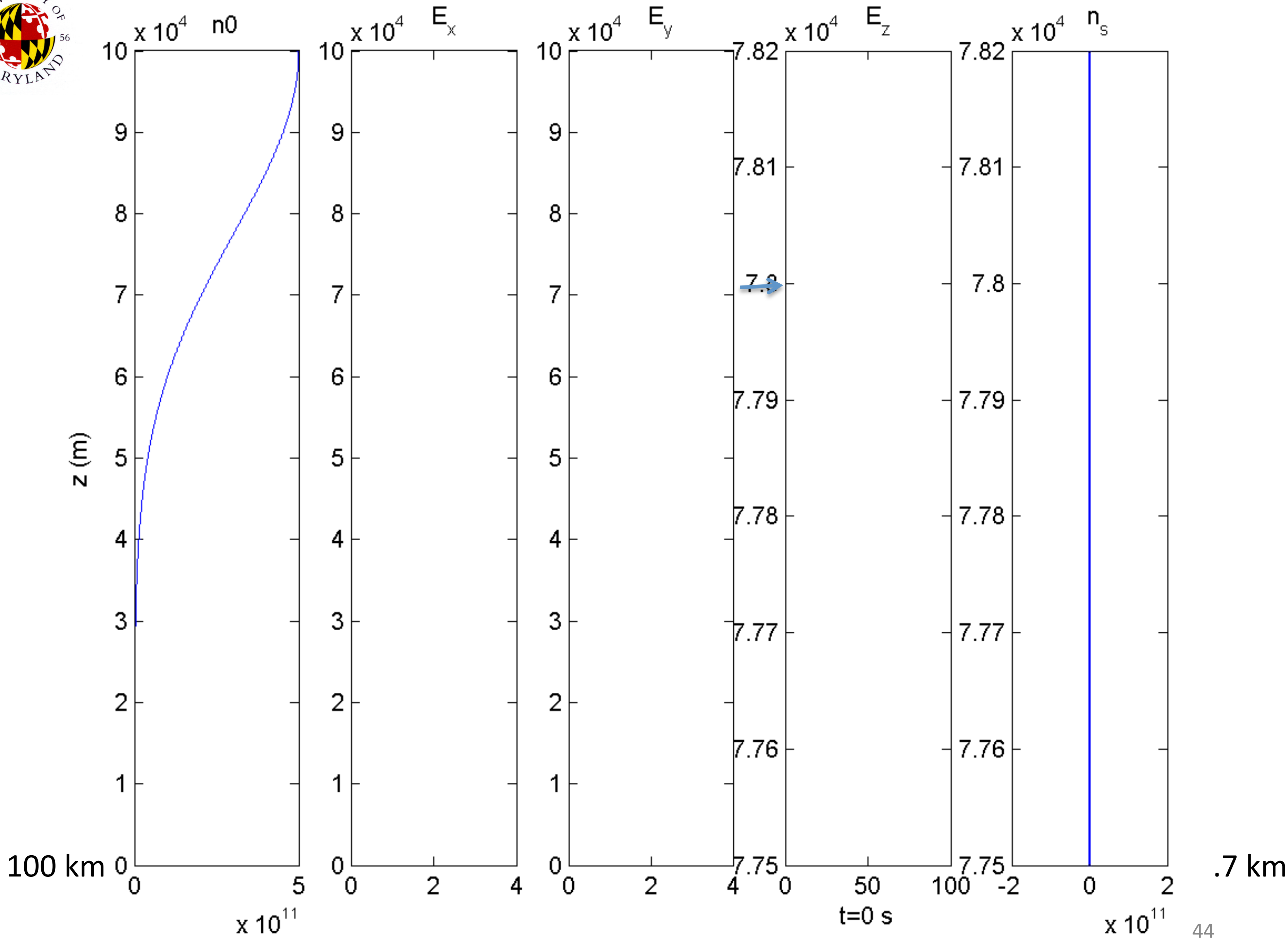
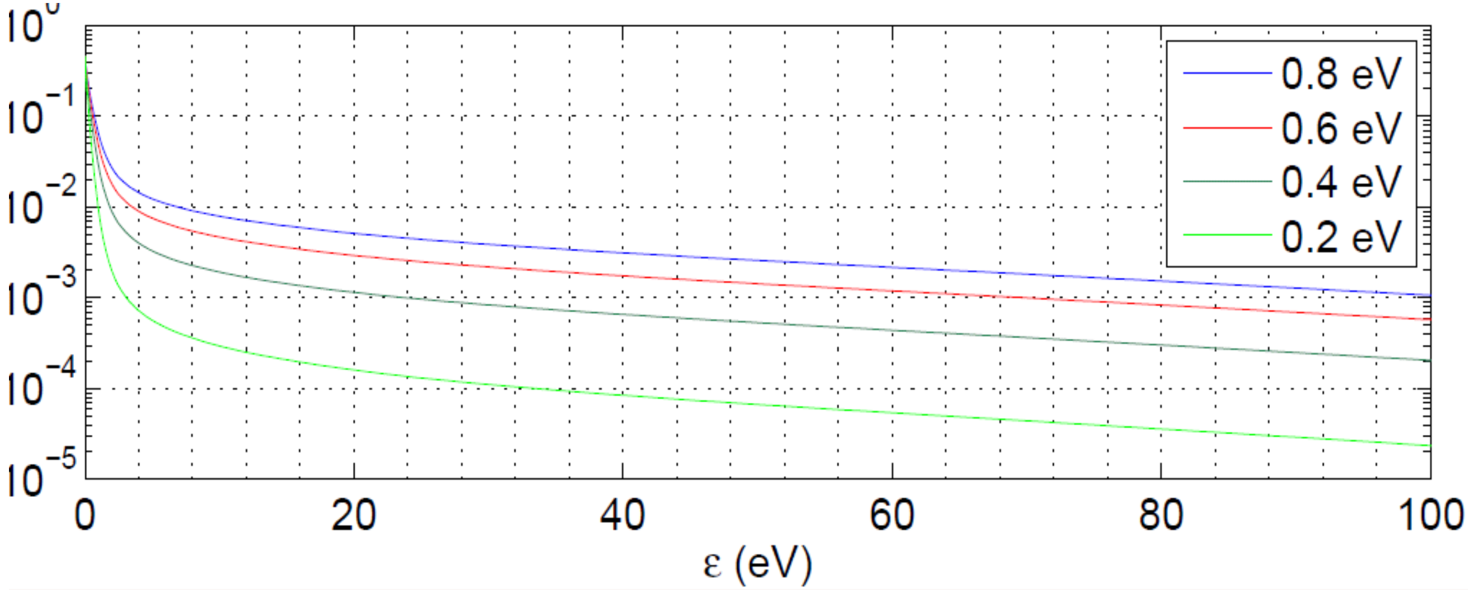


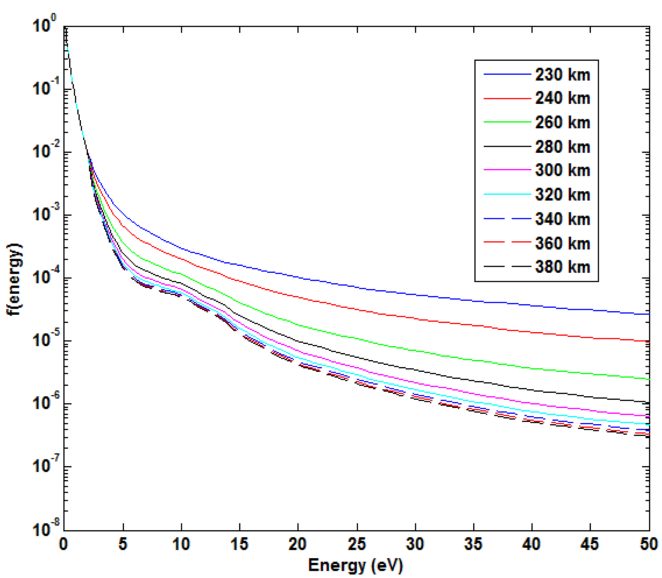
Figure 2. The amplitude of E_z and slowly varying ion density fluctuations n_i at various altitudes, for $E_O = 1.5$V/m.



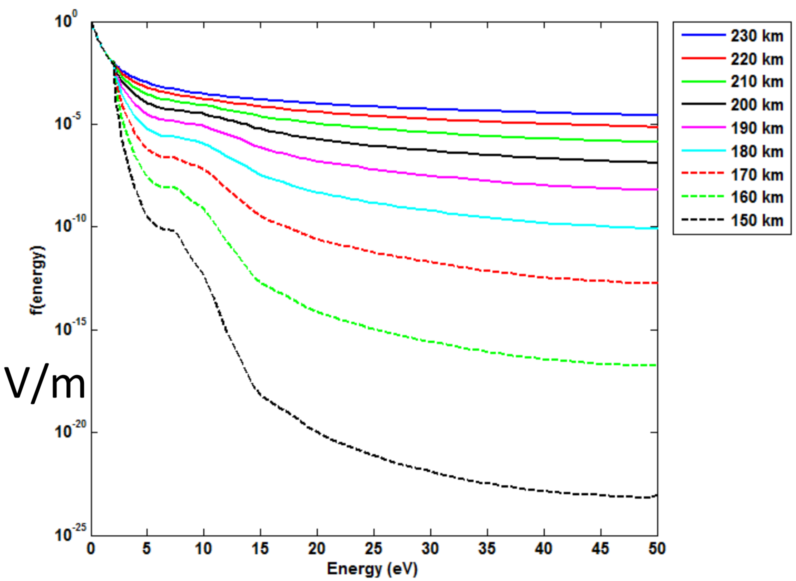

n0
E_x
E_y
E_z
n_s
x 10^4
z (m)
t=0 s
x 10^11
100 km
.7 km

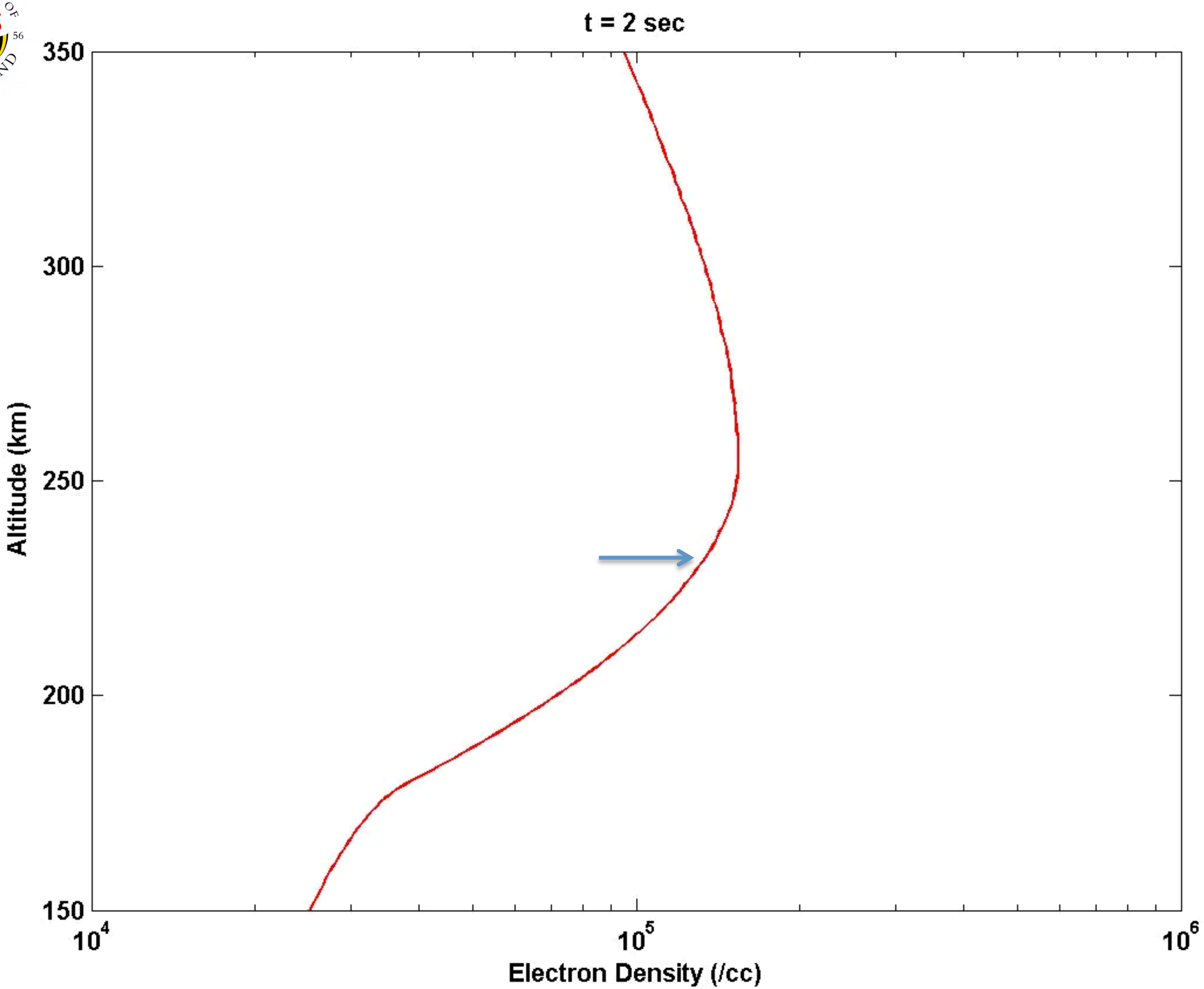
Normalized EDF of supra-thermal electrons for E 1.5 V/m at 100 km



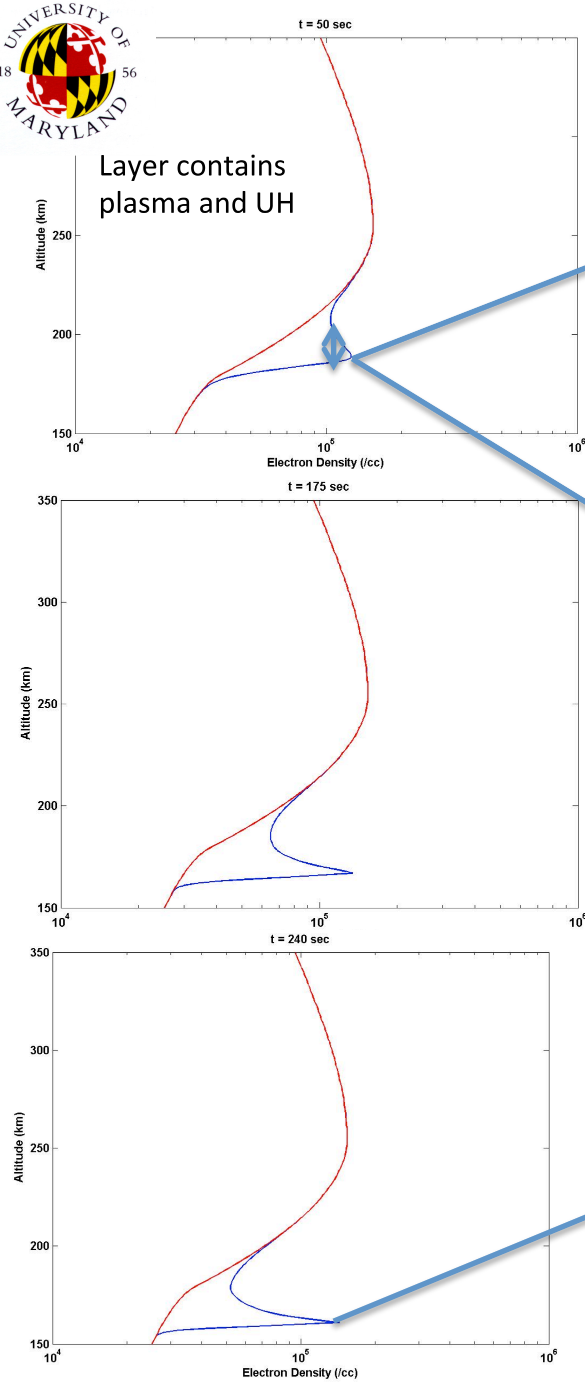


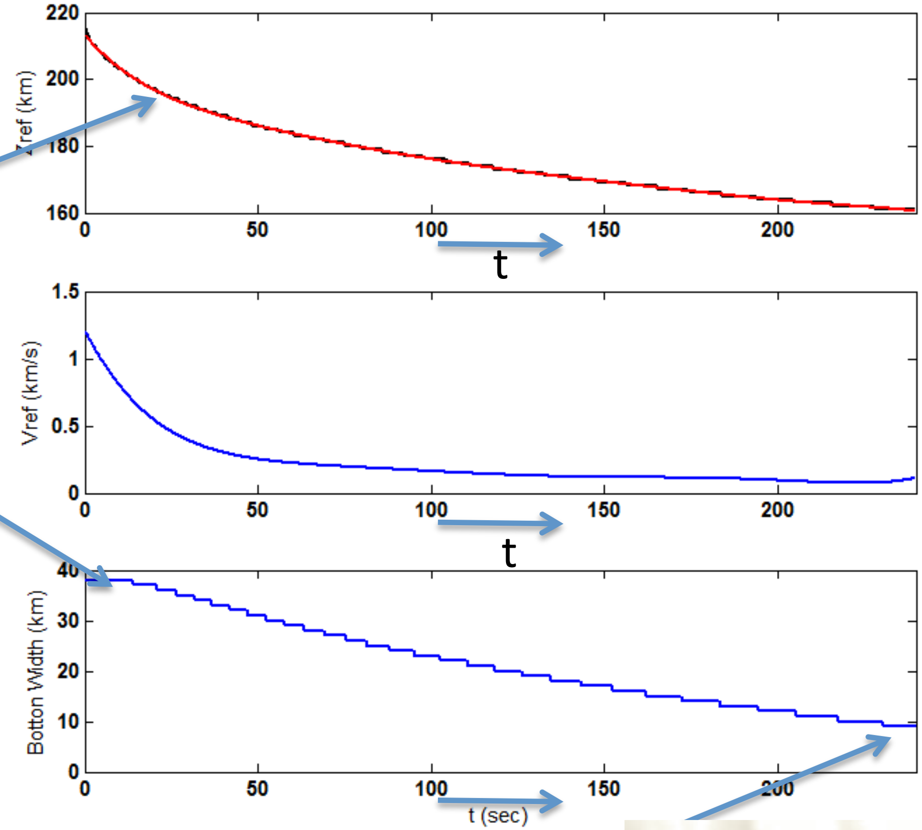
.6 eV, 1.5 V/m




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

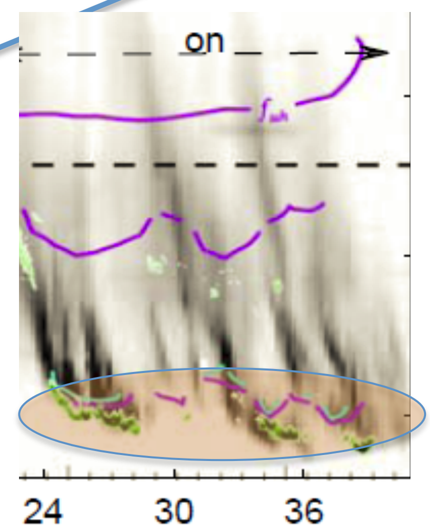
Layer contains plasma and UH





40 km

10 km



Algorithm

Plasma Line

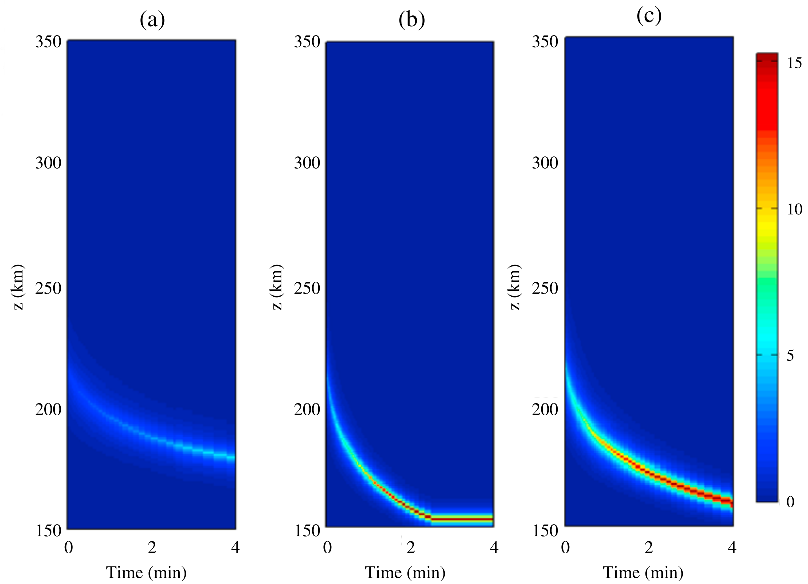
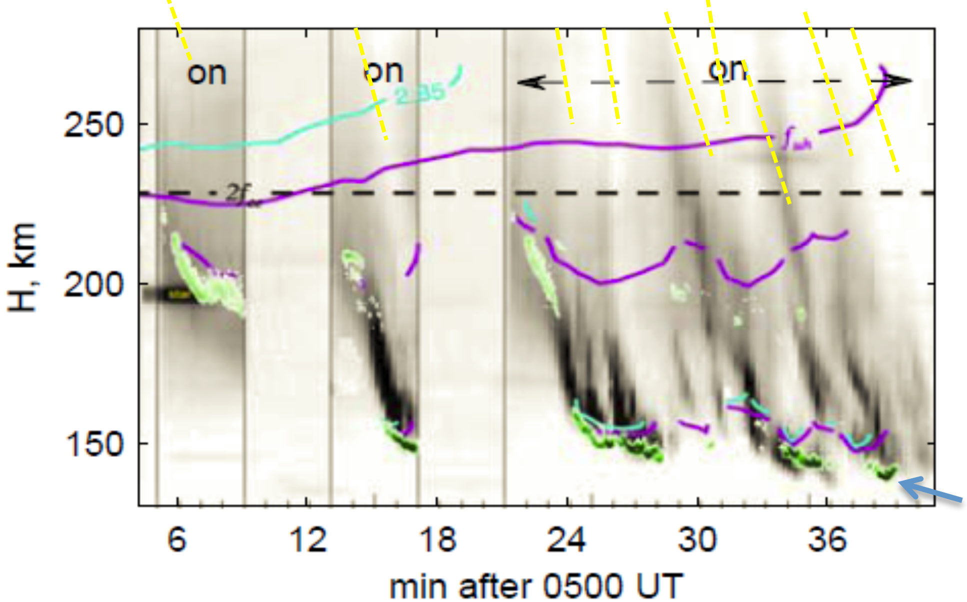


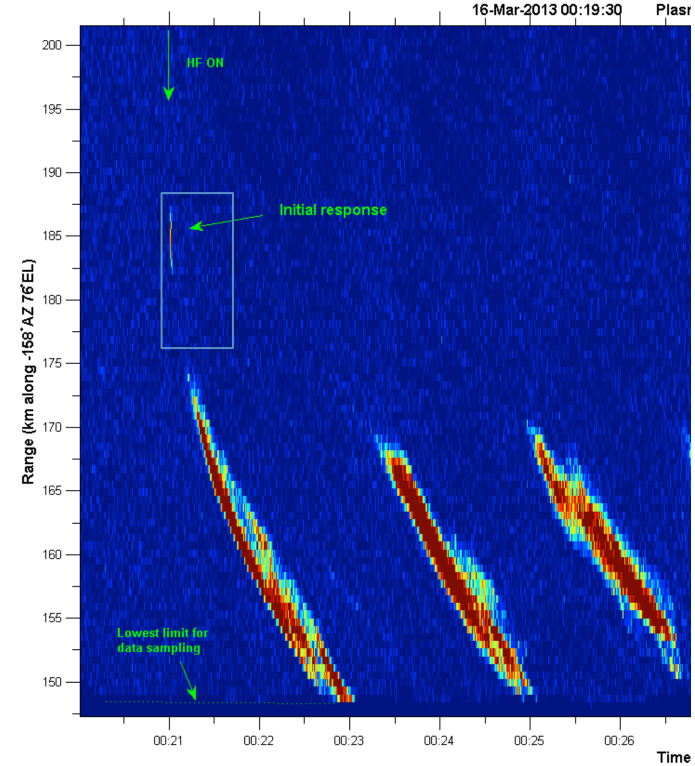
Figure 13. Green line emission as derived from simulation for different input wave amplitude and initial electron thermal energy: (a) $E_0 = 1$ V/m, $T_e = 0.4$ eV, (b) $E_0 = 1.5$ V/m, $T_e = 0.4$ eV, and (c) $E_0 = 1$ V/m, $T_e = 0.6$ eV.



IA

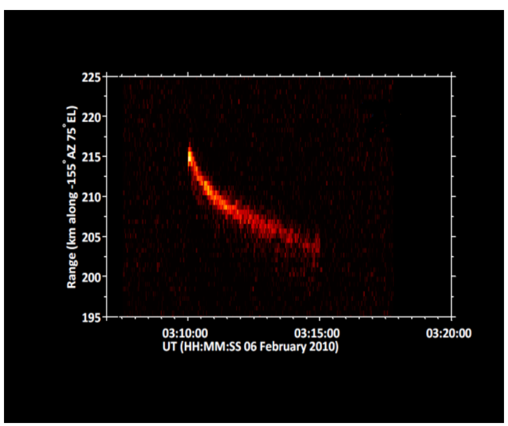
f_p =2.85 MHz (blue), f_{UH} = 2.85 (violet)

Pedersen et al. 2010



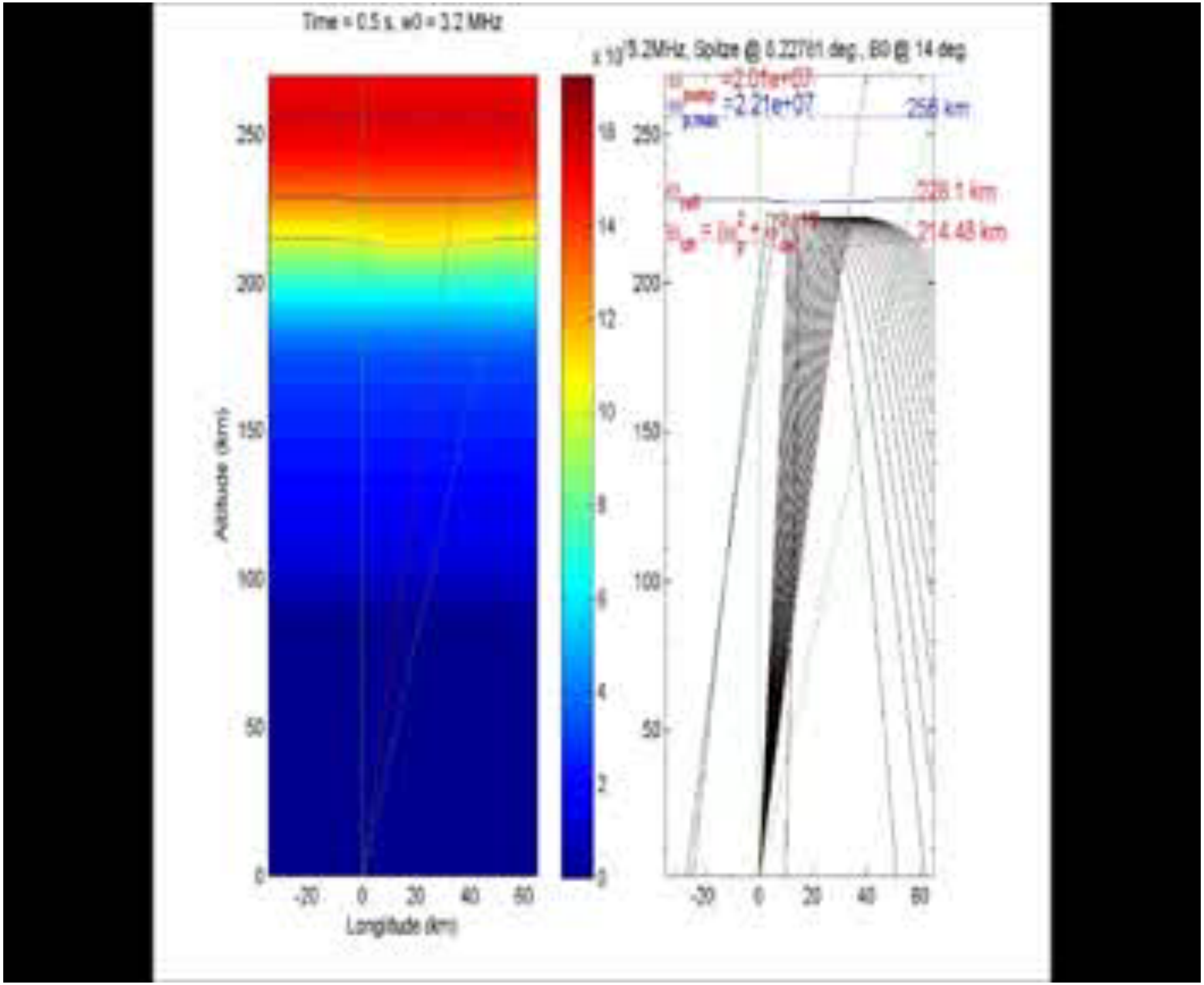
Descending ion-line and plasma line structures observed with UHF radar during heating.

Watkins

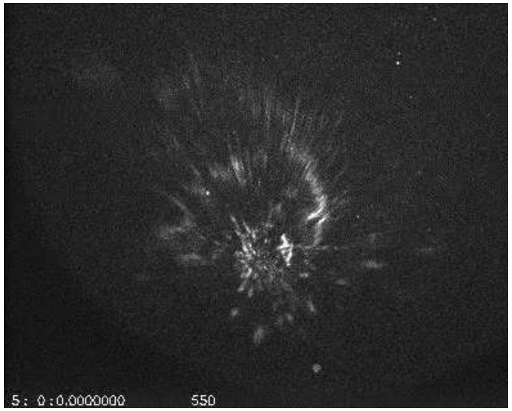


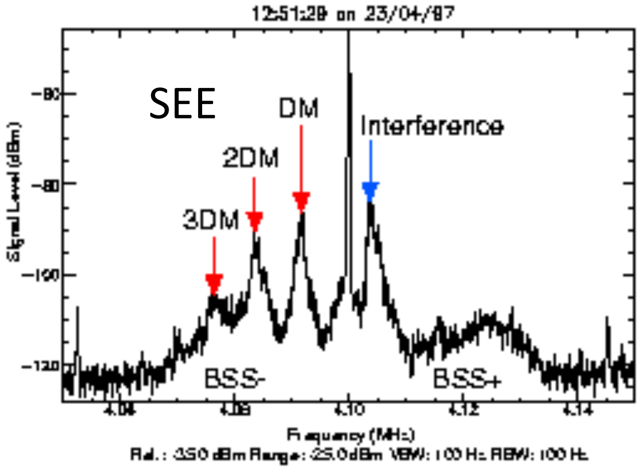
Ion Line

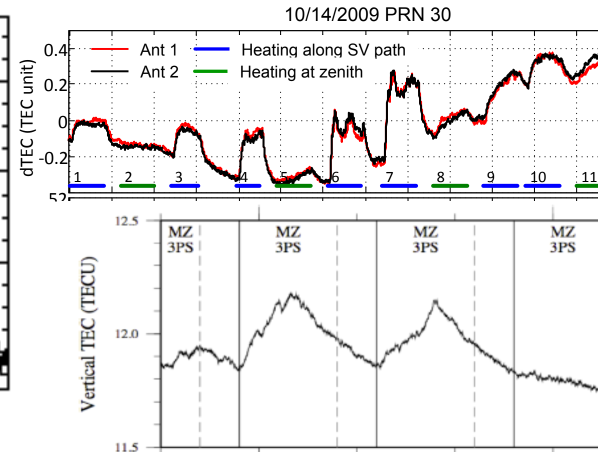
HF TRAPPING ON PLASMA LAYER



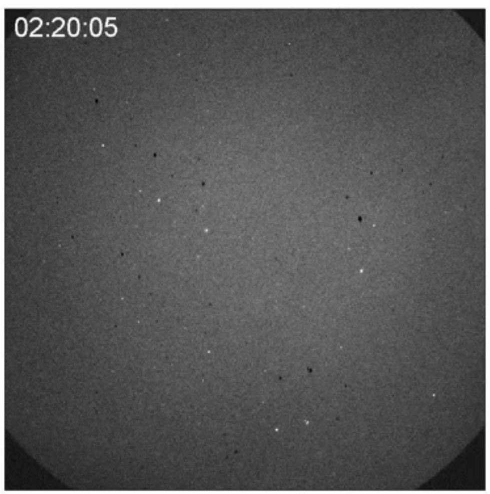
ARTIFICIAL IONOSPHERIC TURBULENCE (AIT)

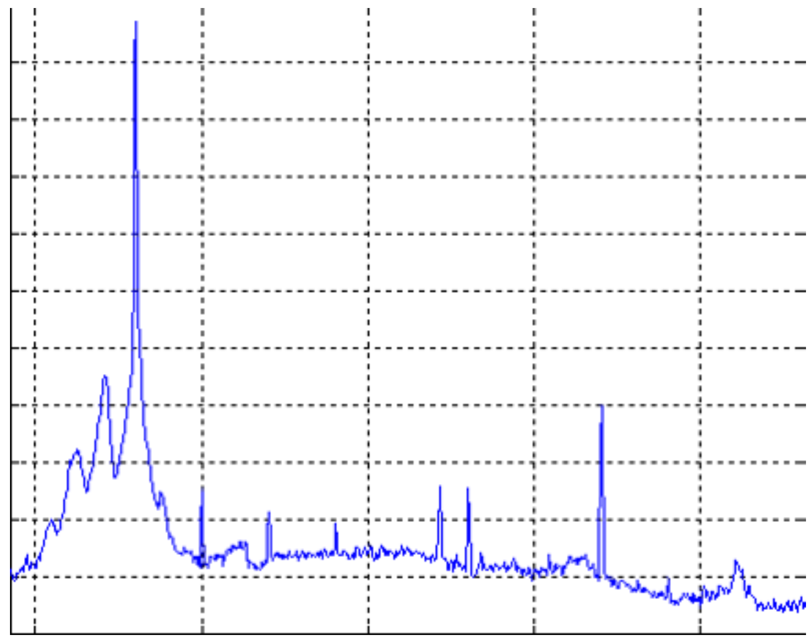




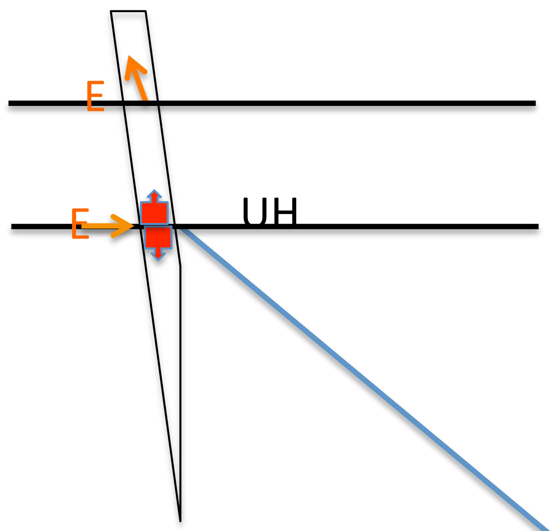


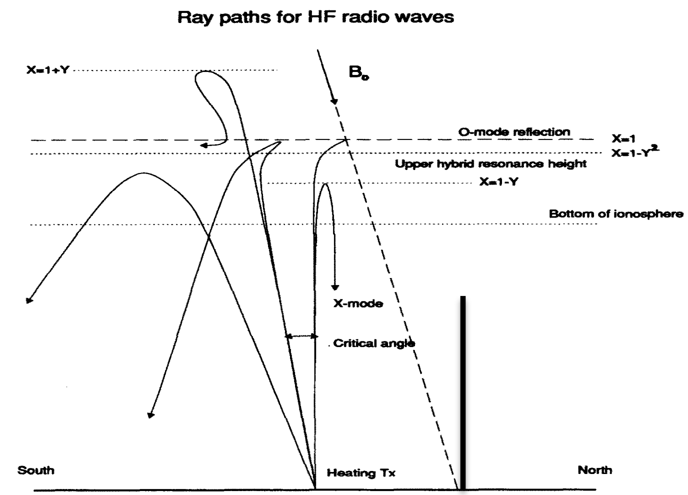
Heater induced GPS scintillations

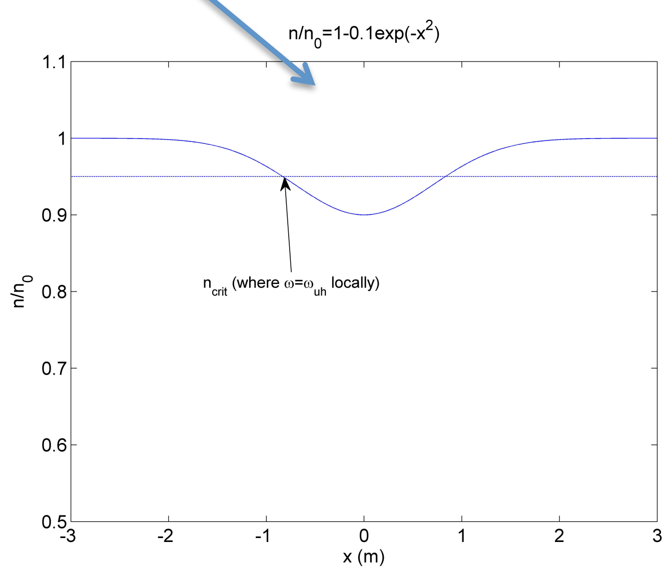


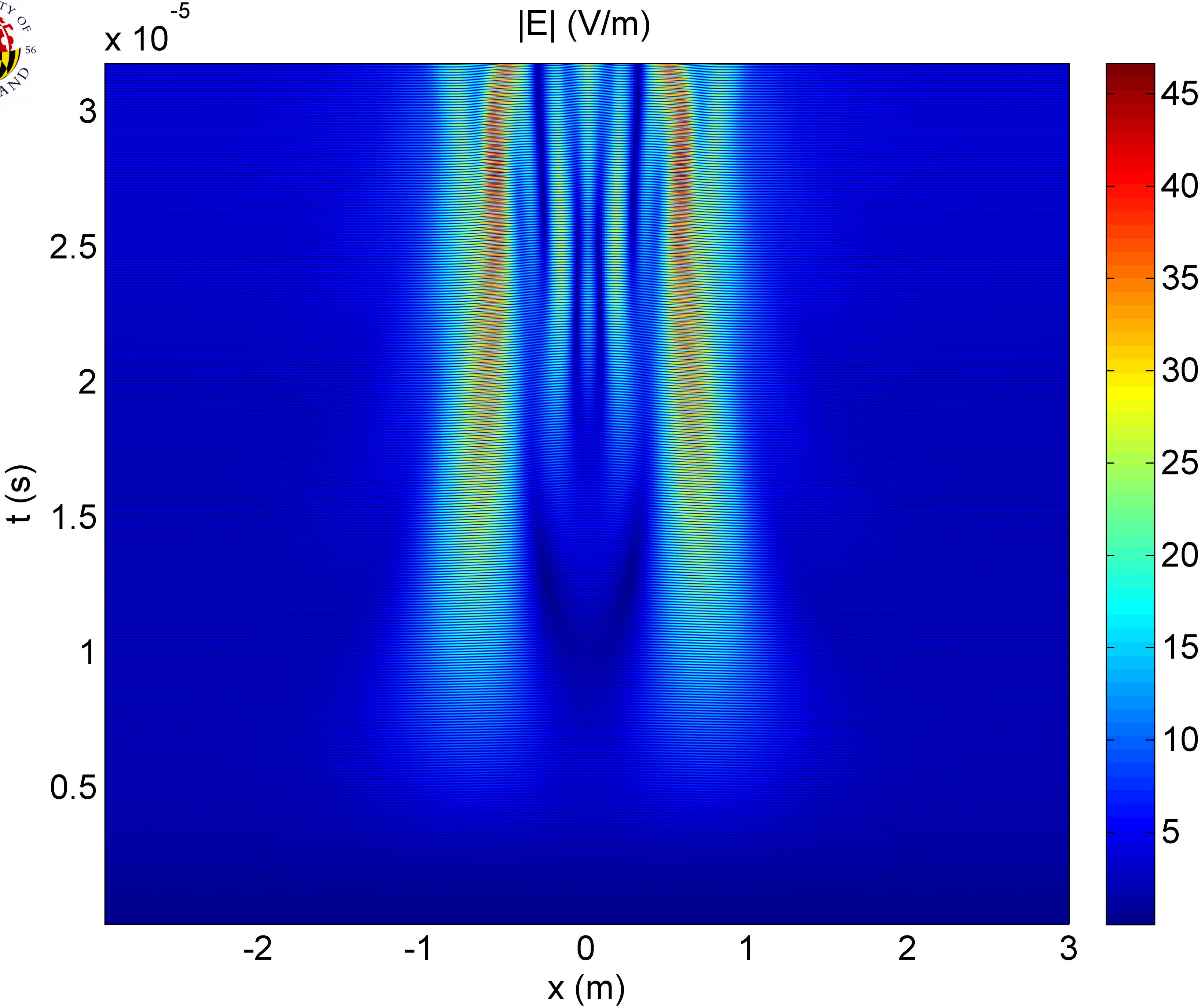


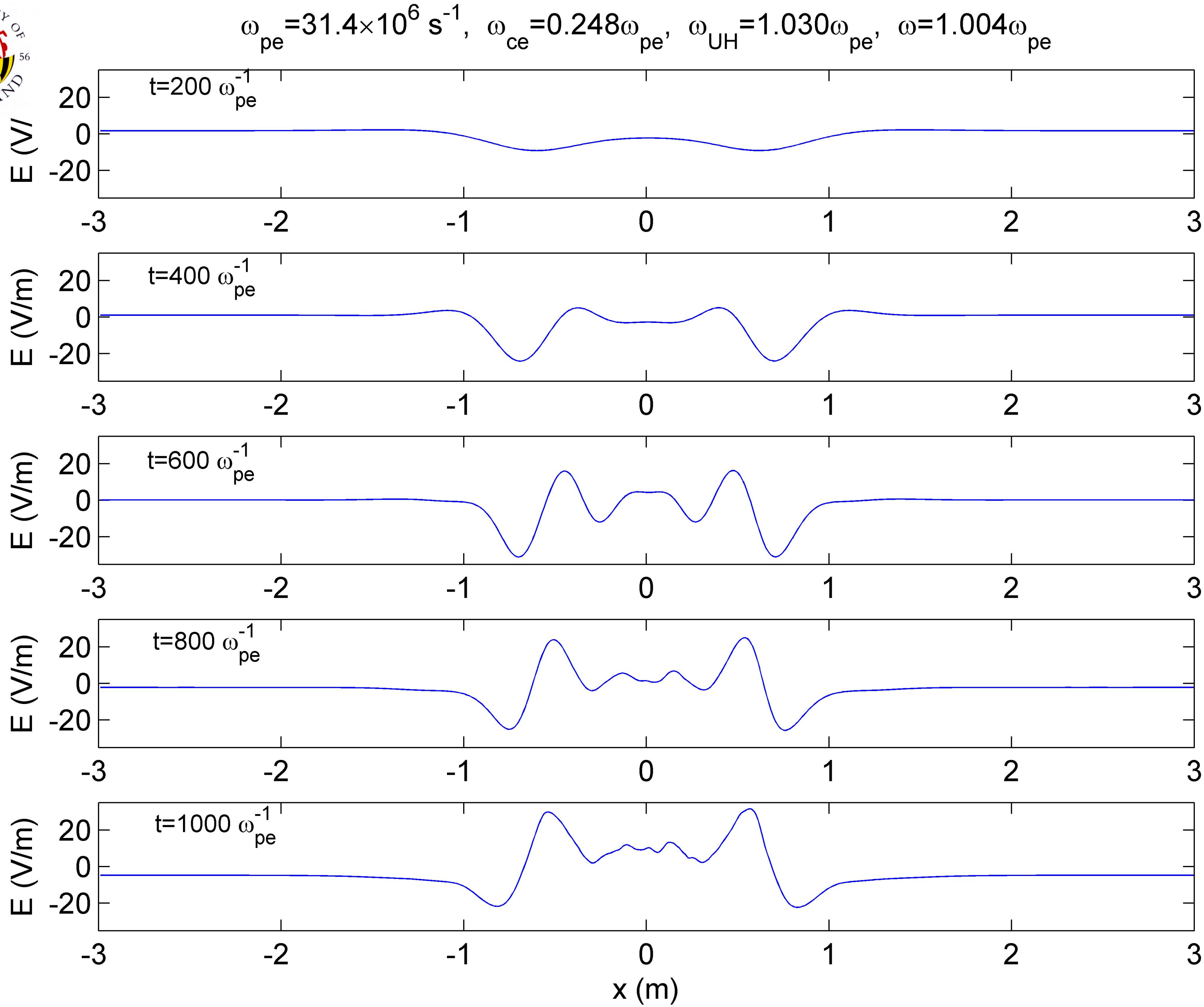
UPPER HYBRID – ELECTRON HEATING – AIT Modeling



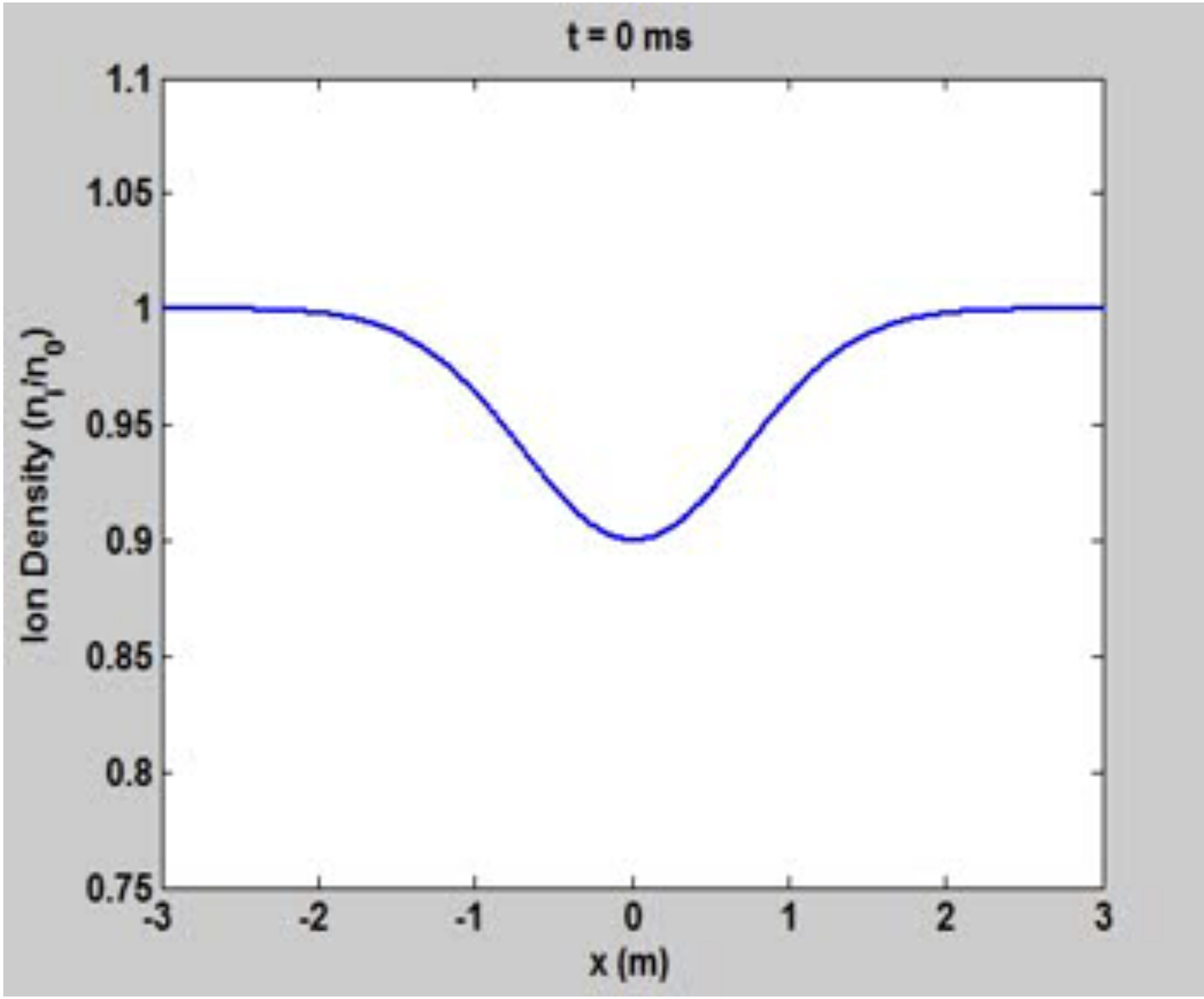


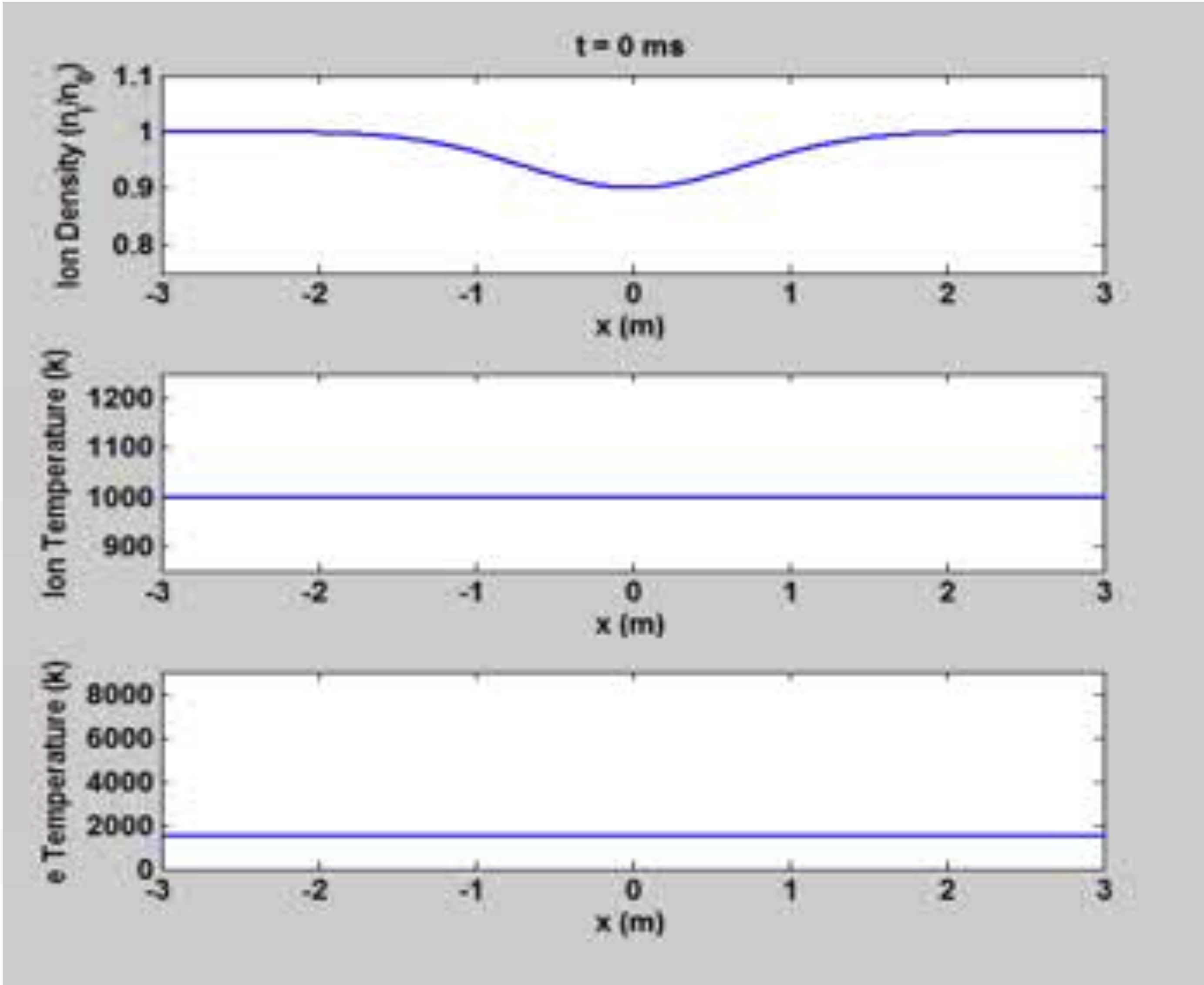



|E| (V/m)
x 10^-5
t (s)
3
2.5
2
1.5
1
0.5
-2
-1
0
1
2
3
x (m)
45
40
35
30
25
20
15
10
5

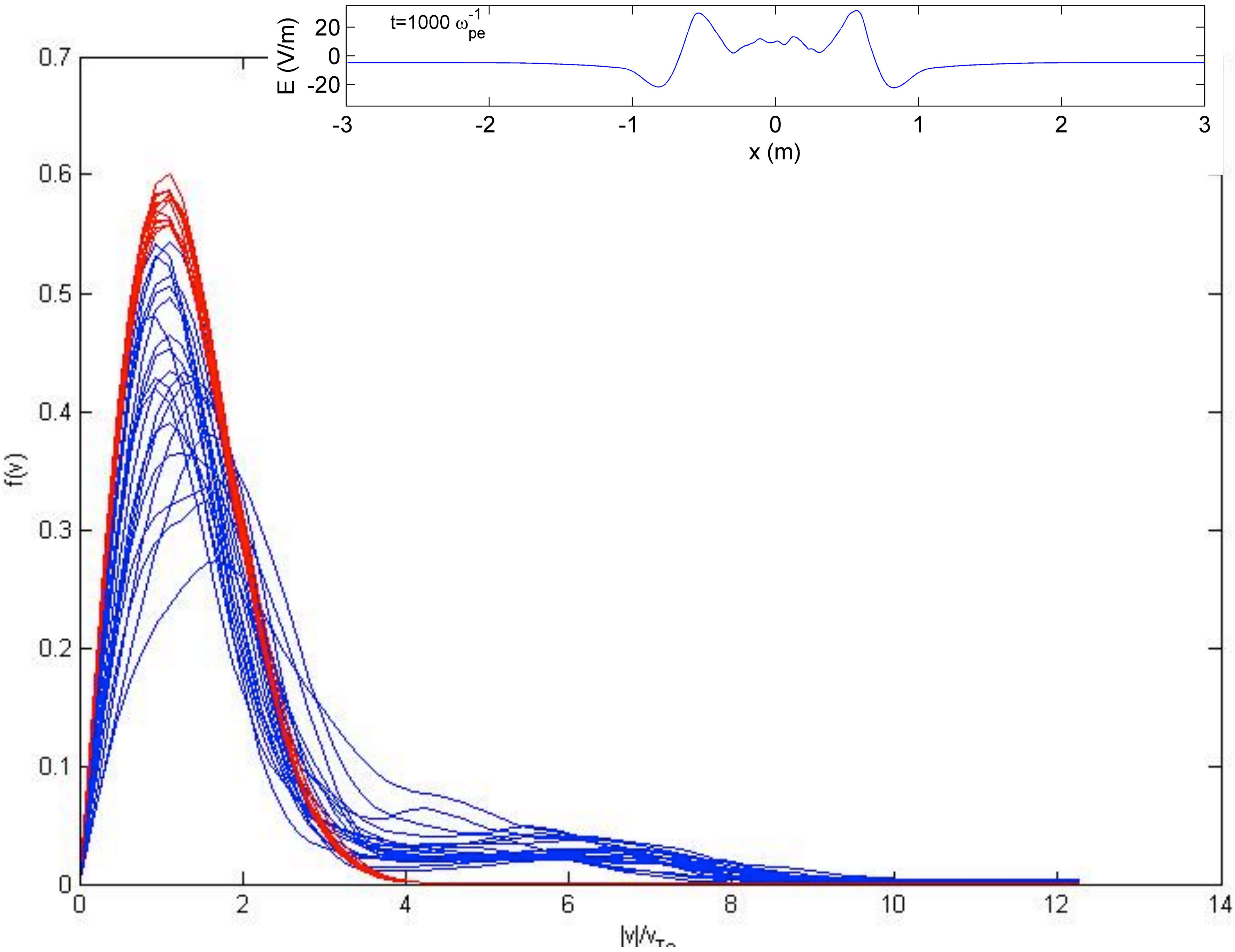


ω_pe=31.4×10^6 s^-1, ω_ce=0.248ω_pe, ω_UH=1.030ω_pe, ω=1.004ω_pe
t=200 ω_pe^-1
t=400 ω_pe^-1
t=600 ω_pe^-1
t=800 ω_pe^-1
t=1000 ω_pe^-1
E (V/m)
x (m)


t = 0 ms
Ion Density (n_i/n_0)
x (m)
1.1
1.05
1
0.95
0.9
0.85
0.8
0.75
-3
-2
-1
0
1
2
3



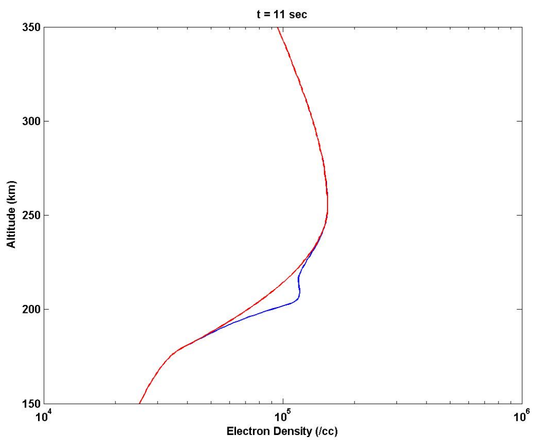
t = 0 ms
Ion Density (n_i/n_0)
1.1
1
0.9
0.8
-3
-2
-1
0
1
2
3
x (m)
Ion Temperature (k)
1200
1100
1000
900
x (m)
e Temperature (k)
8000
6000
4000
2000
0
x (m)

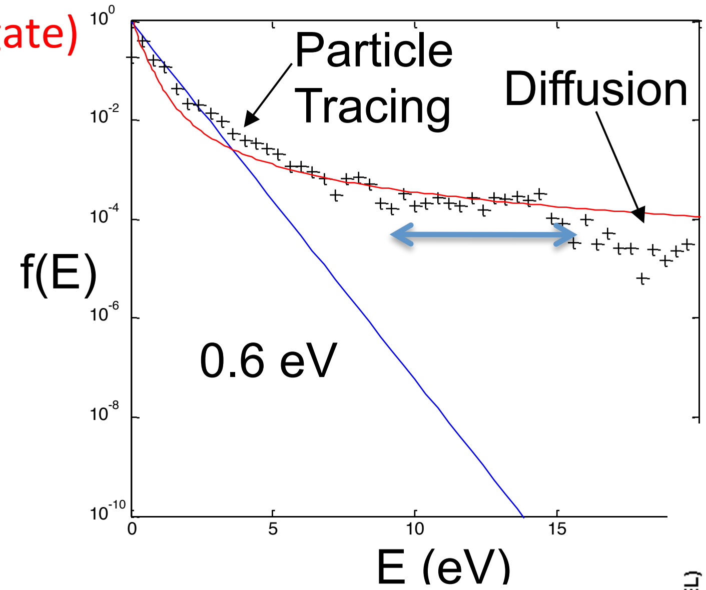


t=1000 ω_{pe}^{-1}
E (V/m)
20
0
-20
-3
-2
-1
0
1
2
3
x (m)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
f(v)
0
2
4
6
8
10
12
14
|v|/v_{Te}

SUPPELEMENTARY SLIDES

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)



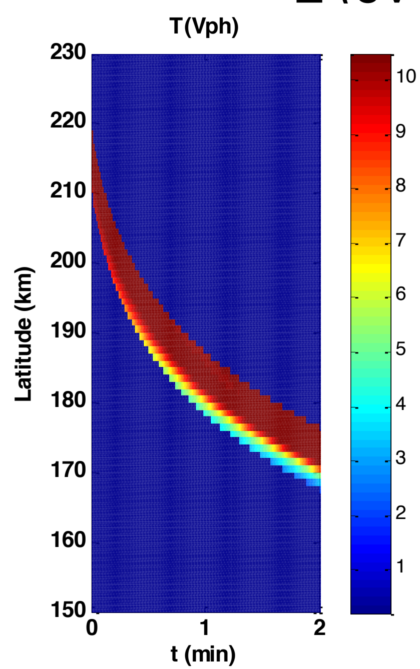


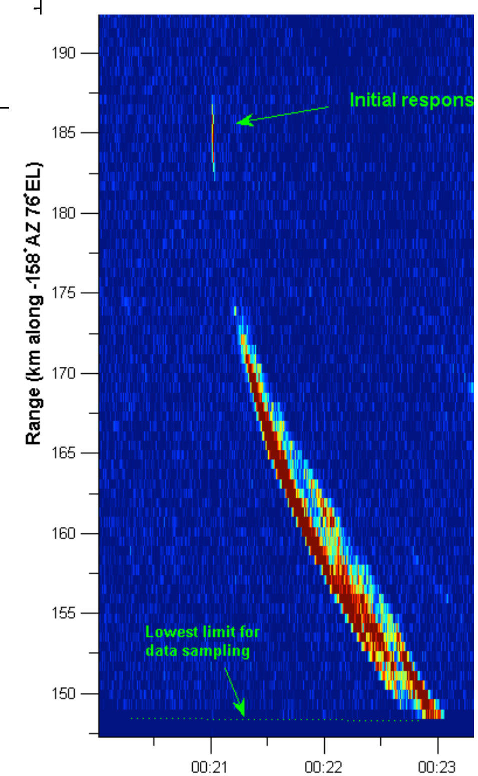
Classic signature of hot plasma with supra-thermal tails

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

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

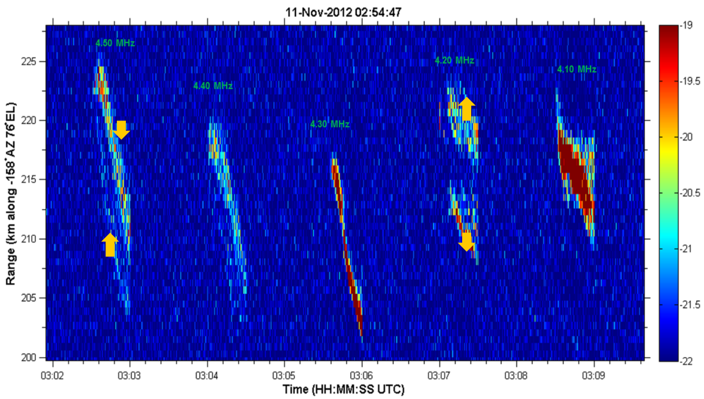
$$\text{if } \nu < \omega_e u_{ph}^2 F'(u_{ph})$$

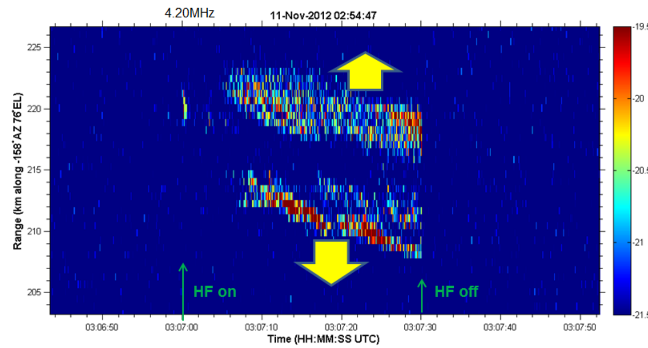


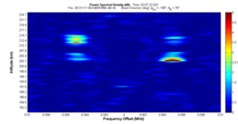


ION LINE PECULIARITIES

B. Watkins

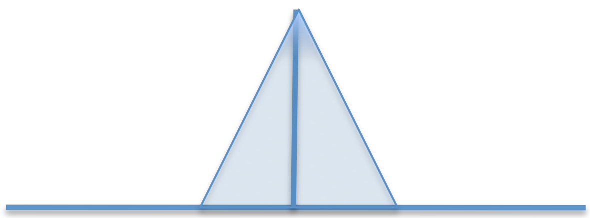




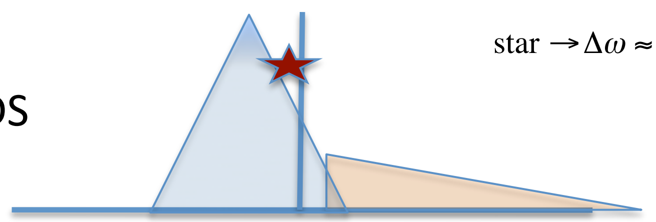


Power-height-time plot of HF-enhanced ion-line signals. Close to 3rd gyro-harmonic signals split into two layers. Doppler spectra (example to left) show strong asymmetries that indicate mainly upward propagating only ion-acoustic waves in the upper layer. The downward layer is associated with primarily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

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.

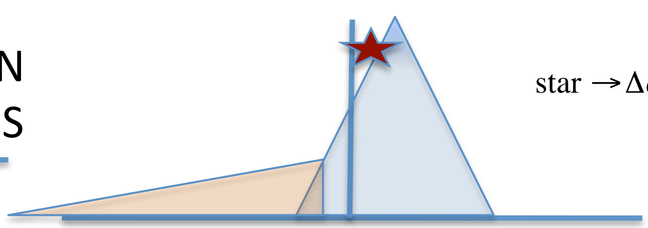


INJECTION DOWNWARDS



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

INJECTION UPWARDS

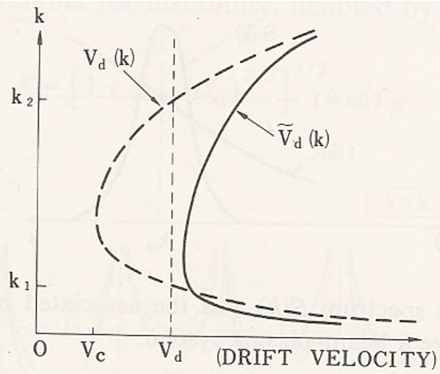


star $\rightarrow \Delta\omega \approx -2k_R c_s$

Plasma with drift γ(k)=0 gives

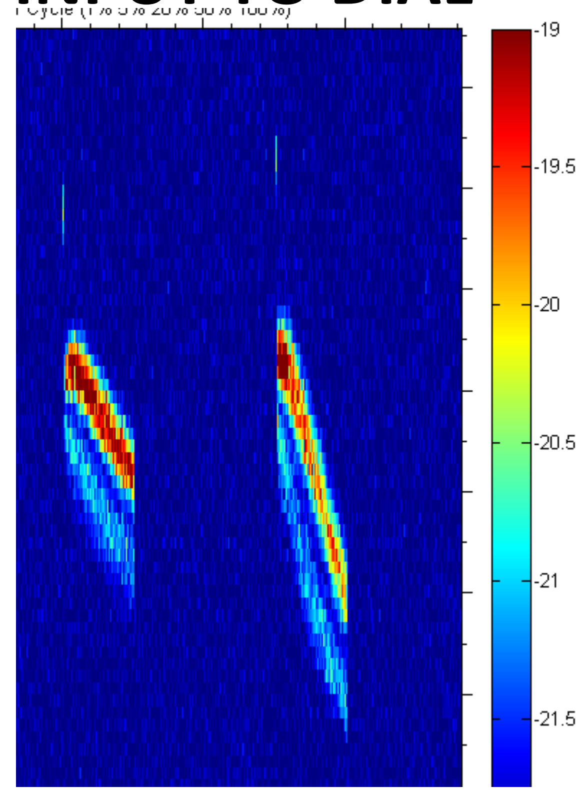
$$V_d(k) = (\omega_k / k) + (ion\ \mathrm{L\ damping})$$

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

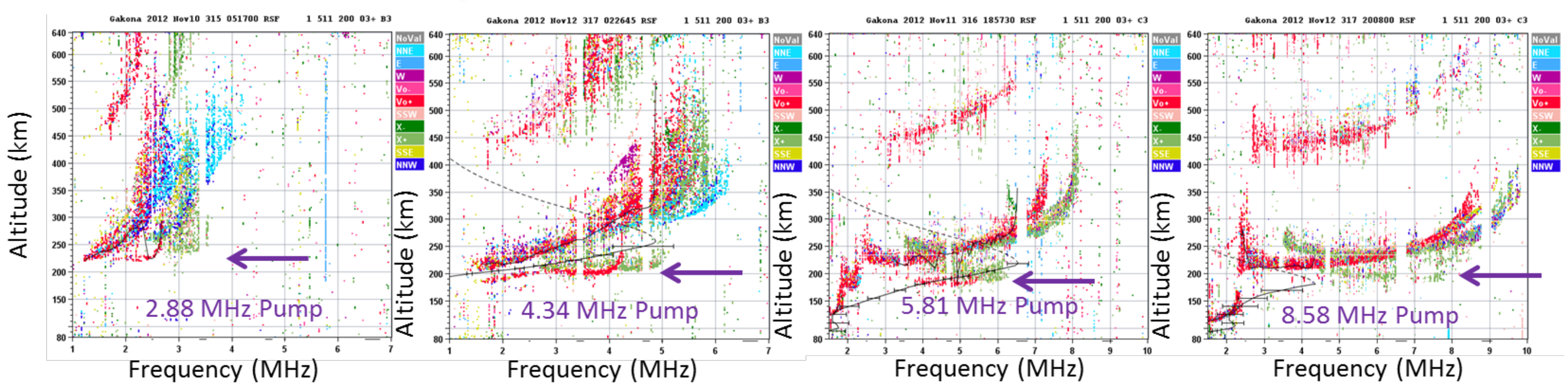


ONGOING PHYSICS STUDIES FOR INPUT TO DIAL MODEL

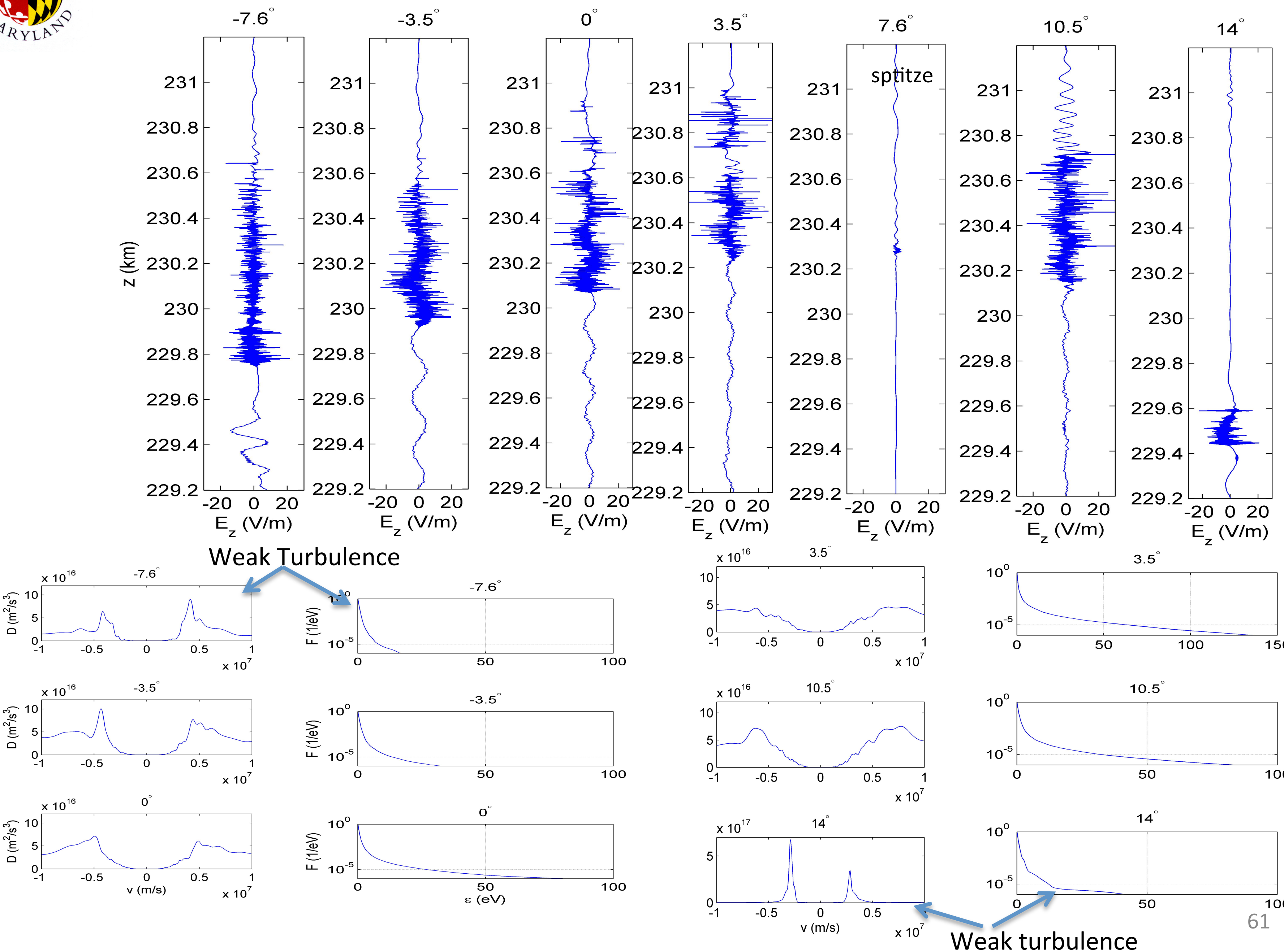
1. MULTI-DIMENSIONAL ISSUES
2. UPPER HYBRID
3. DOUBLE RESONANCE HEATING



P. BERNHARDT

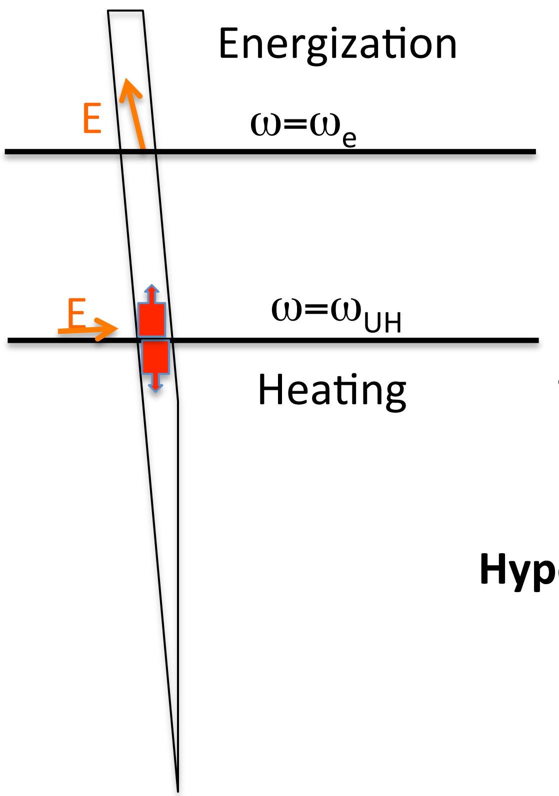


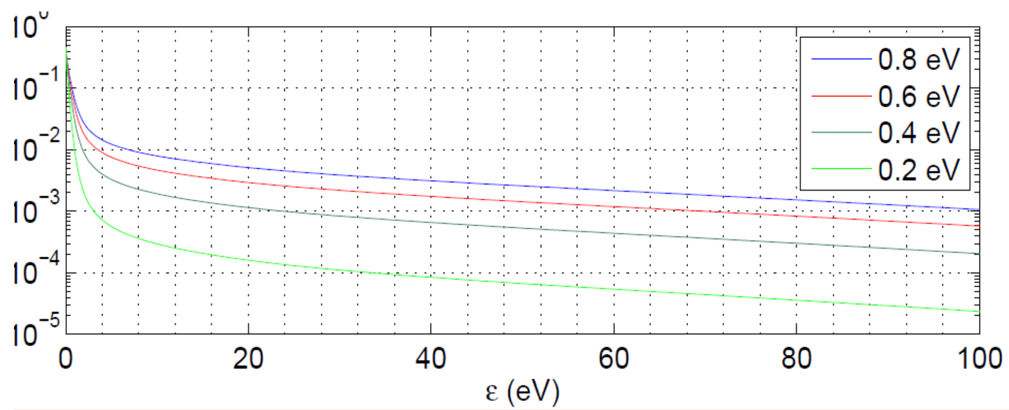
O-mode, 1V/m amplitude, electron temperature 0.4 eV, and different angles of incidence,



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

SEE Spectra

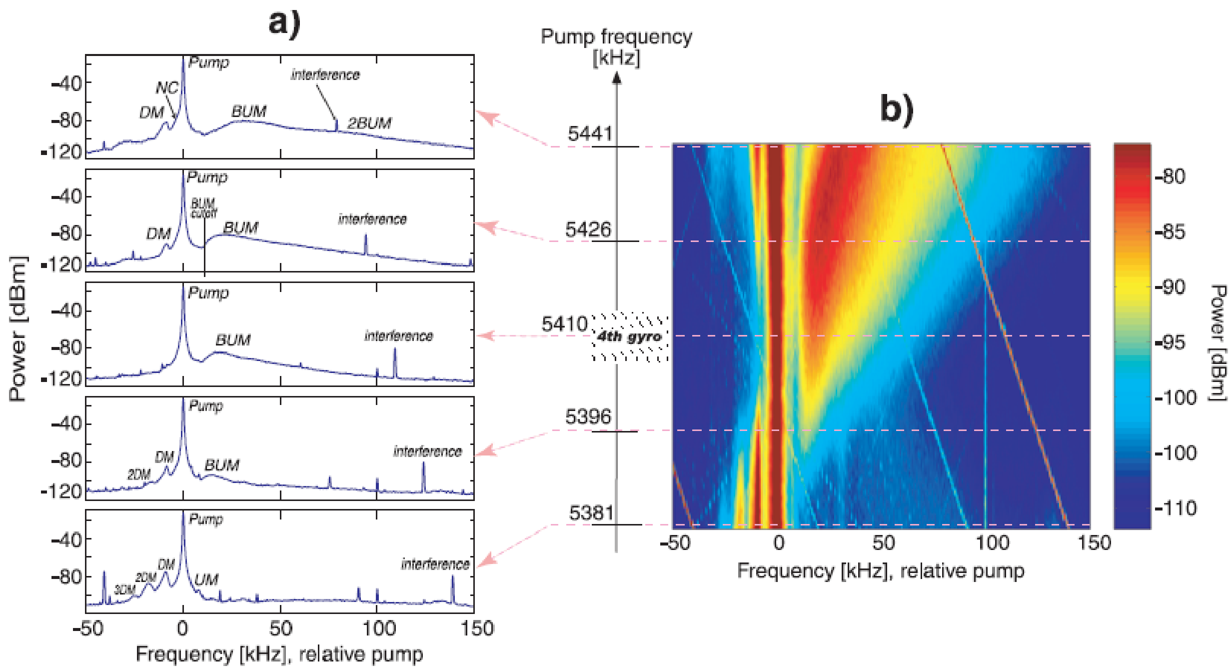
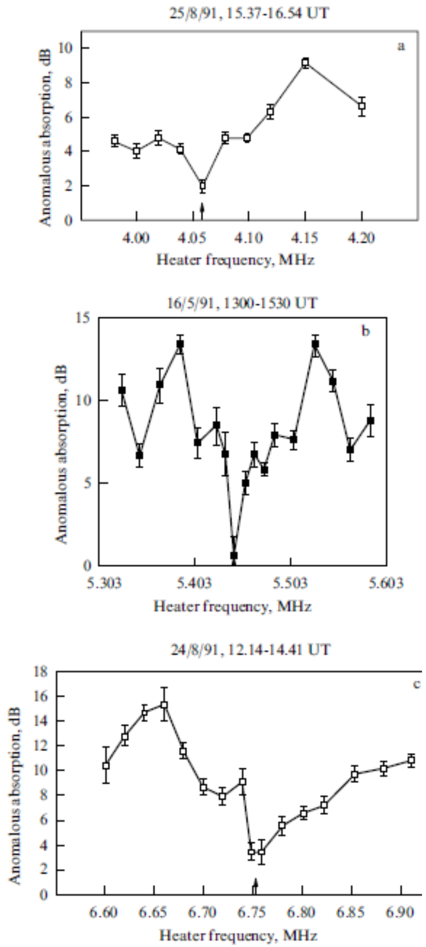


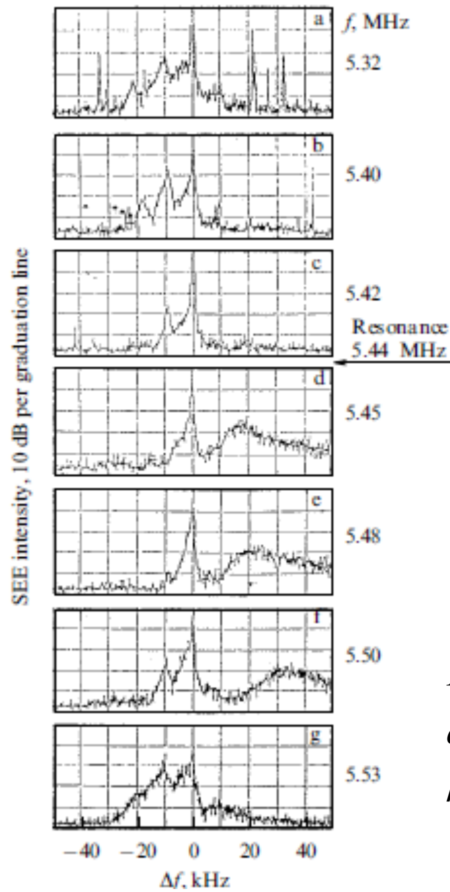
Figure 3. (a) The stack of five plots showing SEE spectra for the five different pump frequencies marked on the vertical axis in the middle of the figure. The standard SEE spectral features and the pump are labeled. These spectra are cross sections of the pump relative spectra versus pump frequency two-dimensional 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.

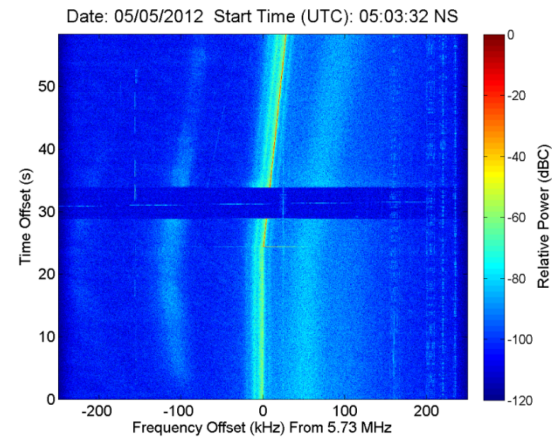
SuPer-Short Striations

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

Gurevich Physics-Uspekhi, 2007







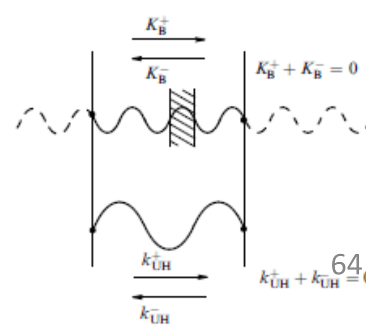
Paul's BUM

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

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

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

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

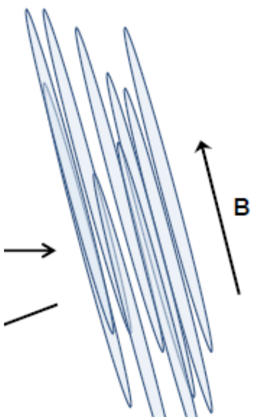


BUM

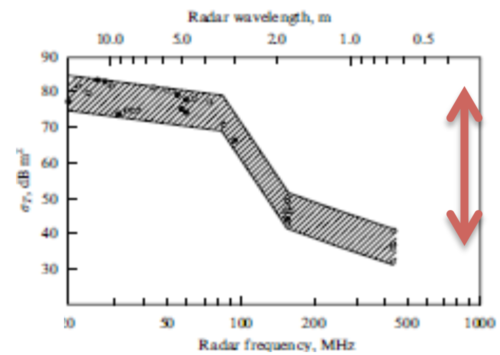
Suppression of anomalous absorption

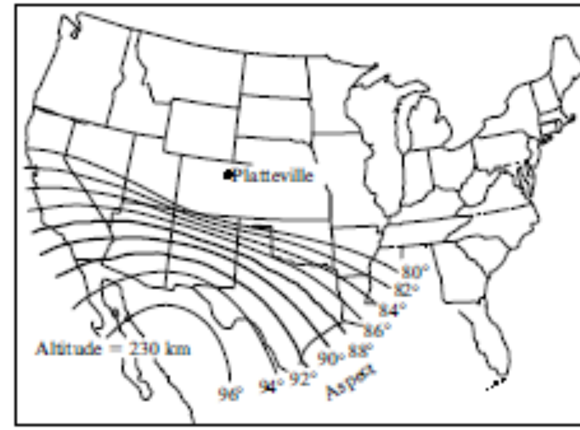
Generation of short scale FAI Super-Short-Striations (SSS)

Raising MUF to GHz



Platteville FAS:





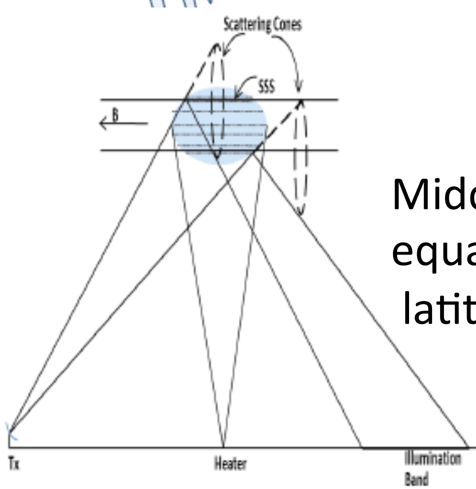


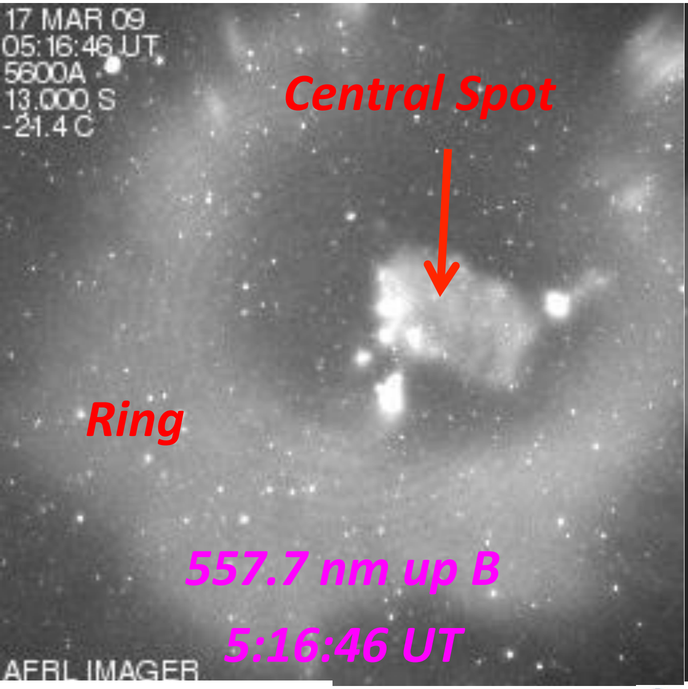
Fig. 1: Schematic of SSS FAS system at GHz.

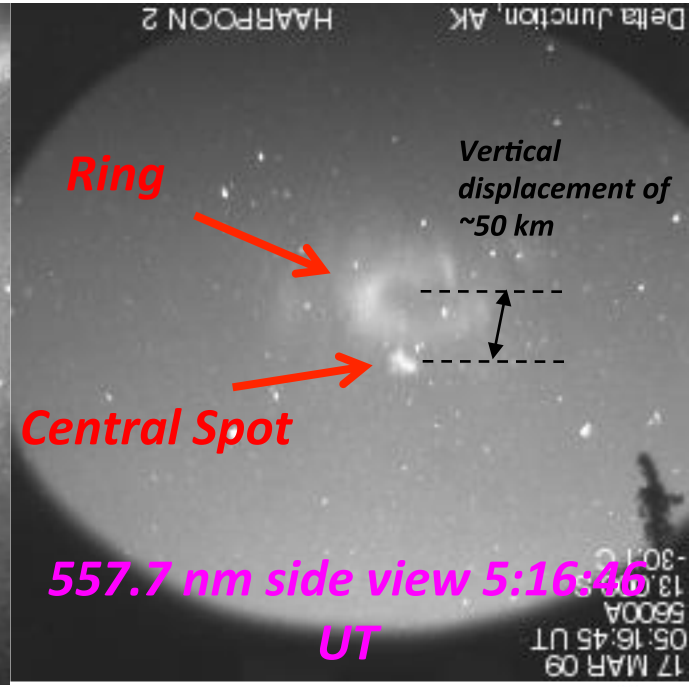
Middle or equatorial latitude

Potential answer from physics of ion cloud formation

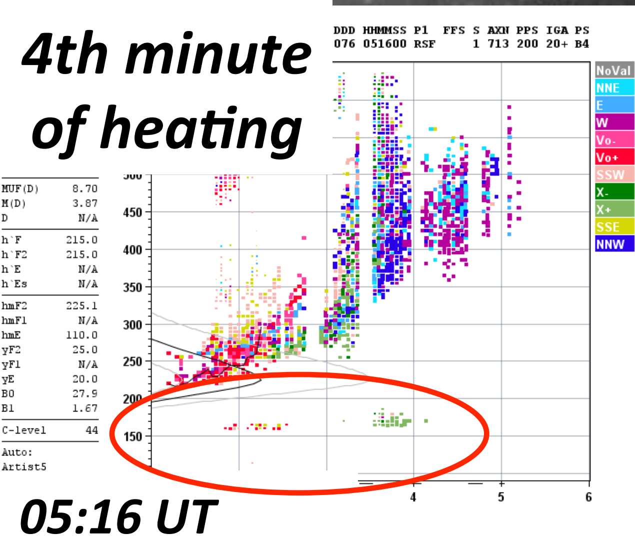
FAS Concept- Aspect scattering. RF transmitted from Tx along the 90^0 line are orthogonal to FAI and will be observed everywhere at the 90^0 line. Tx located in the 92^0 line observed at 88^0 and vice versa

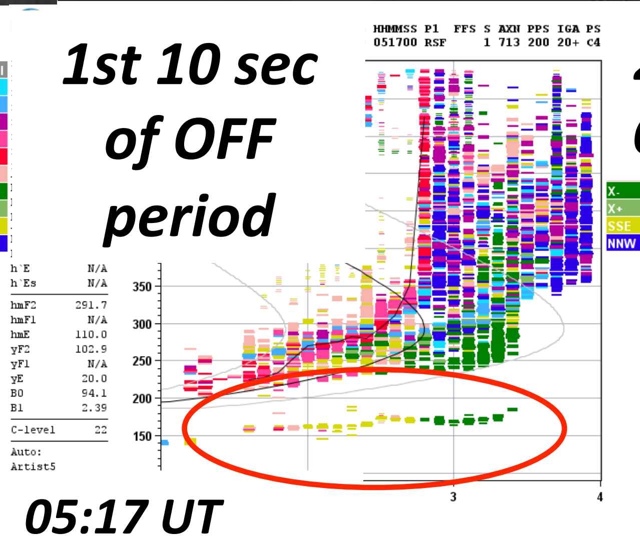
Mystery Solved by Multi-Site Optical Observations: March 2009

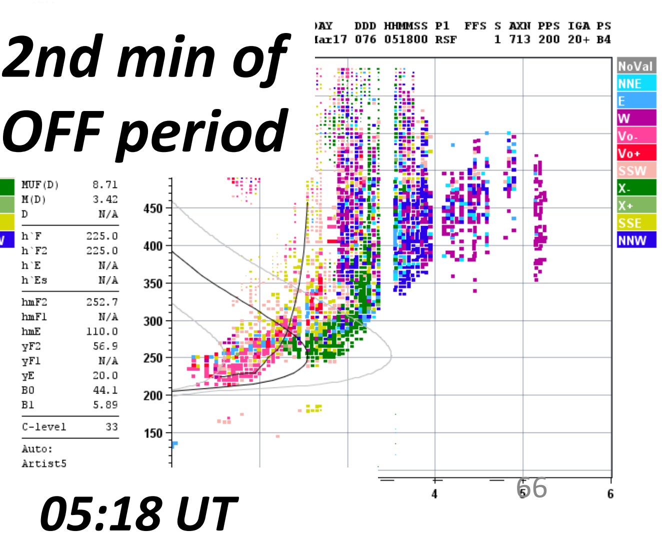




- Combined data sets indicate presence of artificial plasma sufficient to interact with heater beam
- At altitudes with no significant natural plasma!







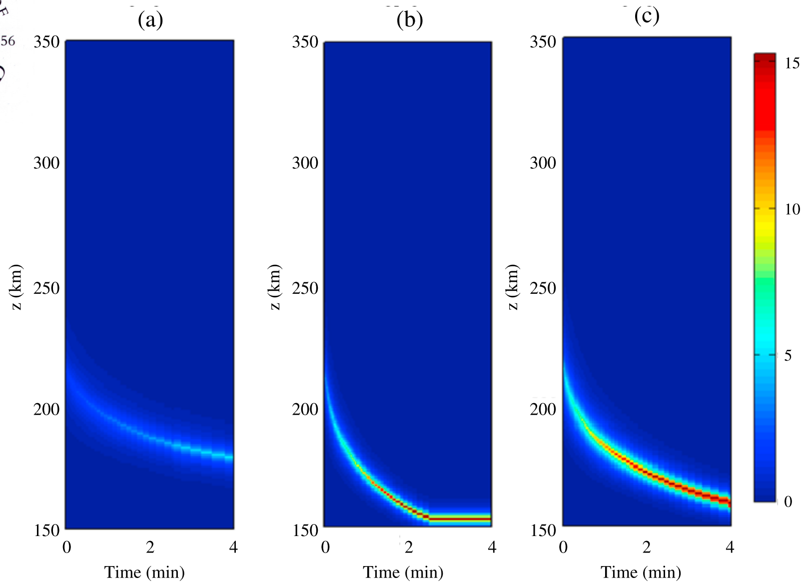
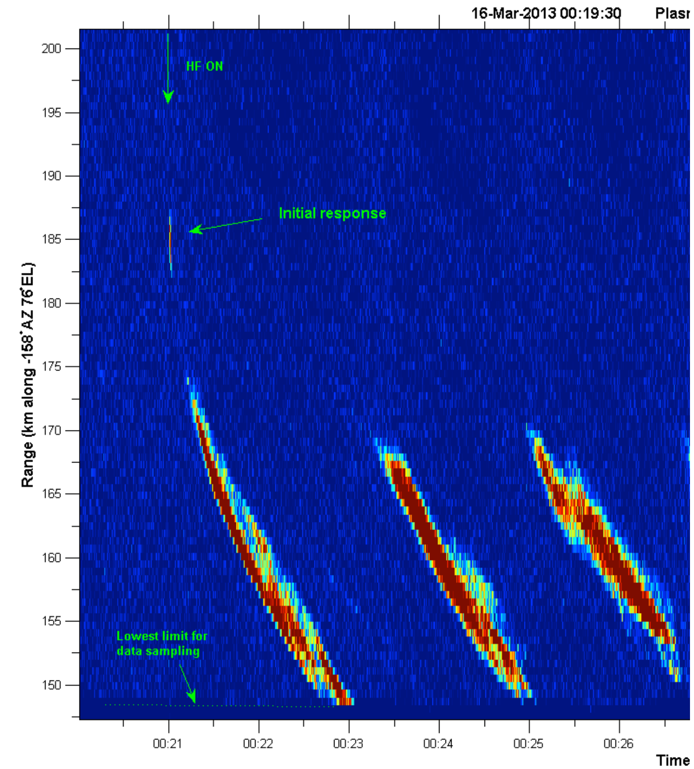
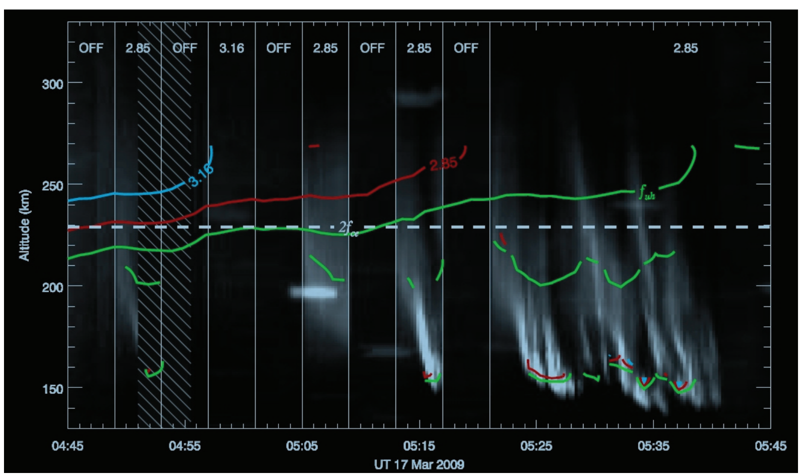


Figure 13. Green line emission as derived from simulation for different input wave amplitude and initial electron thermal energy: (a) $E_0 = 1$ V/m, $T_e = 0.4$ eV, (b) $E_0 = 1.5$ V/m, $T_e = 0.4$ eV, and (c) $E_0 = 1$ V/m, $T_e = 0.6$ eV.

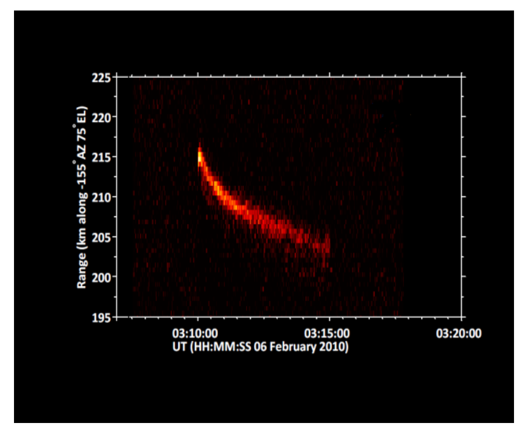
Plasma Line





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

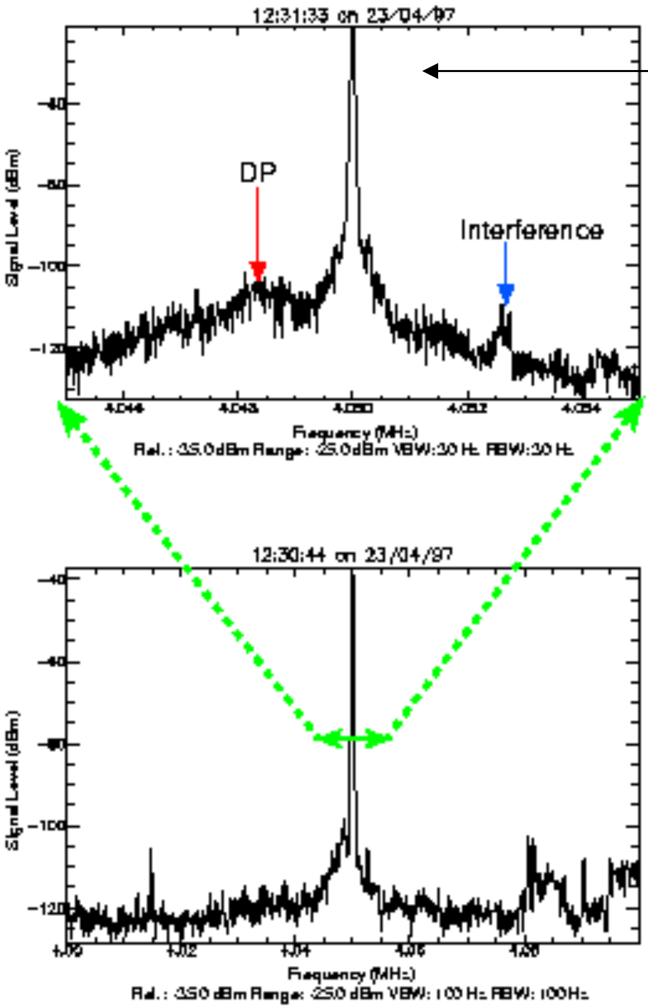
Watkins



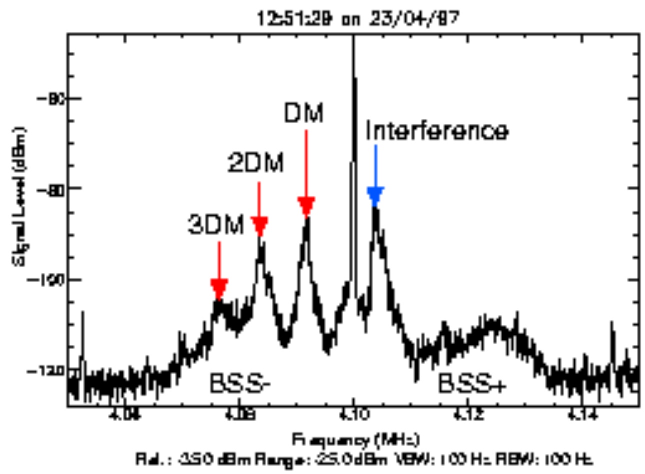
T. Pedersen et al. 2010

Ion Line

Stimulated Electromagnetic Emissions (SEE)



HF transmit frequency



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

Above Gyroharmonic

Gyroharmonic ≈ 1.38 MHz in F-layer

3rd Electron Gyroharmonic

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

SEE Spectra

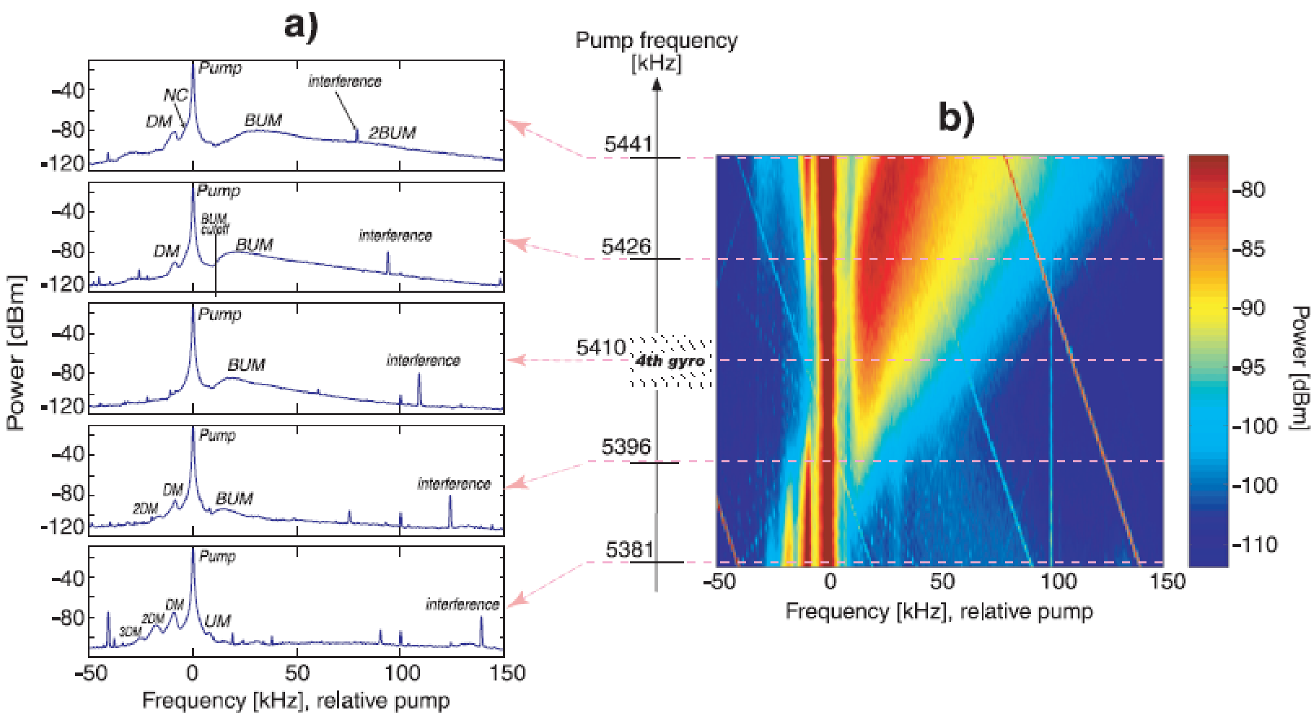
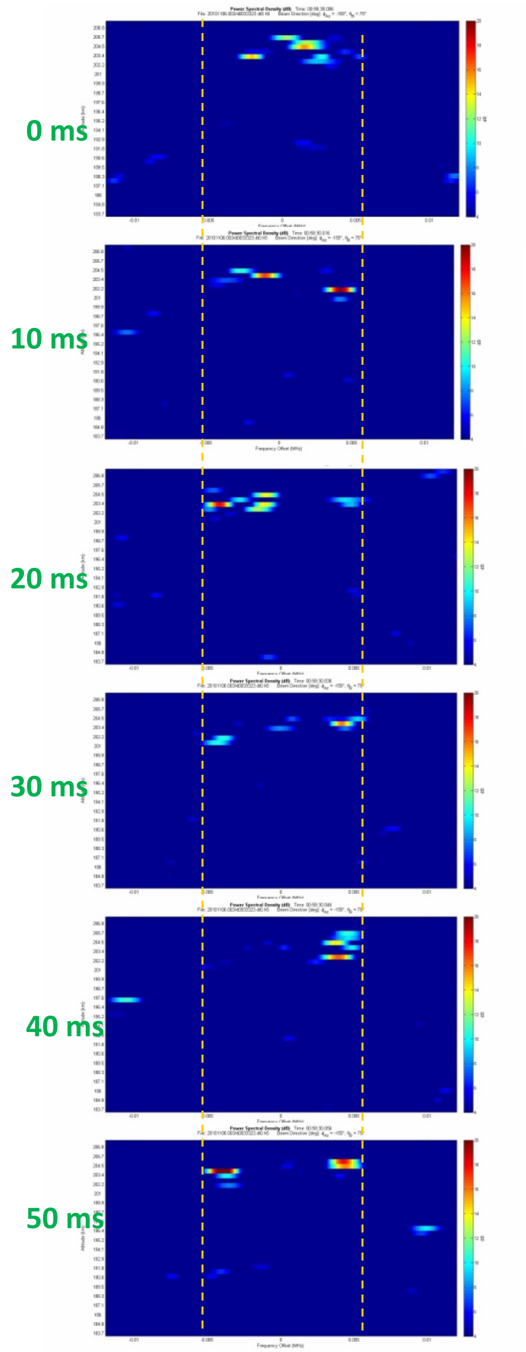
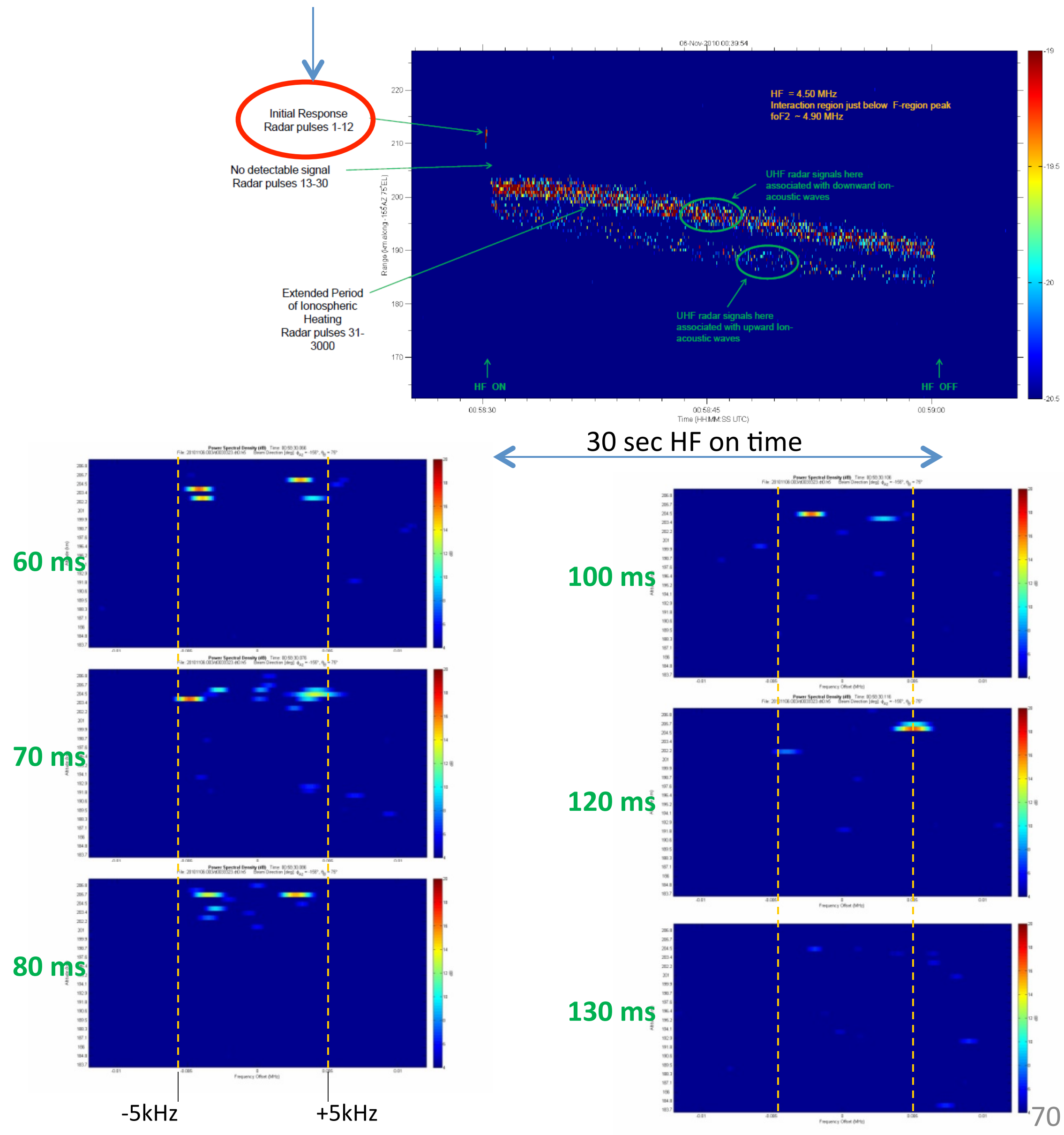


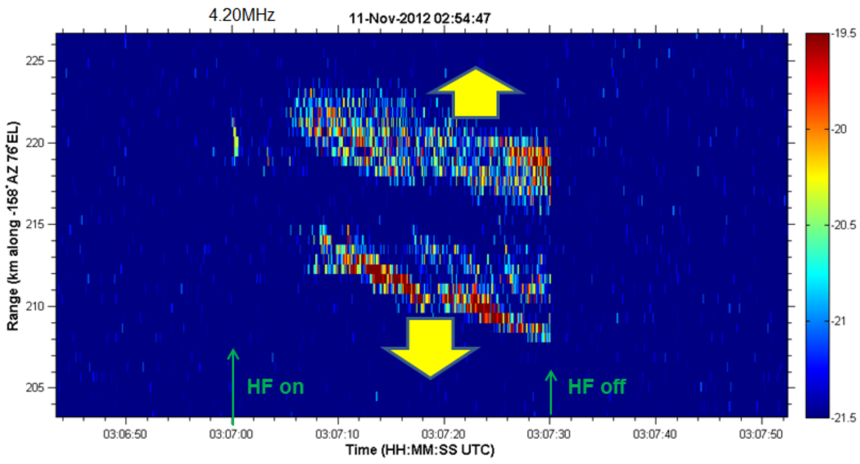
Figure 3. (a) The stack of five plots showing SEE spectra for the five different pump frequencies marked on the vertical axis in the middle of the figure. The standard SEE spectral features and the pump are labeled. These spectra are cross sections of the pump relative spectra versus pump frequency two-dimensional 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

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
225
220
215
210
205
Range (km along -158°AZ 76°EL)
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

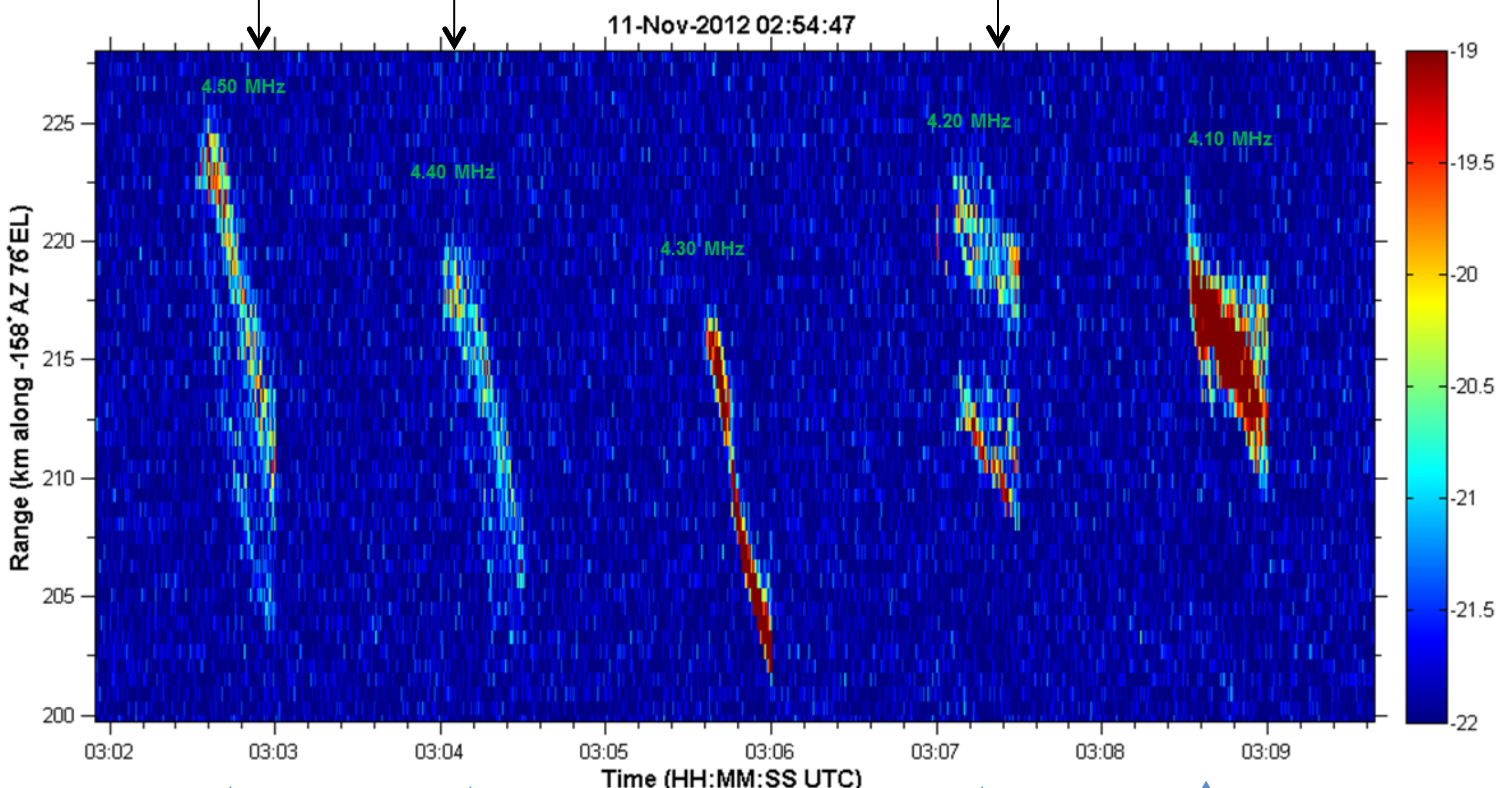
Experimental results that suggest:

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



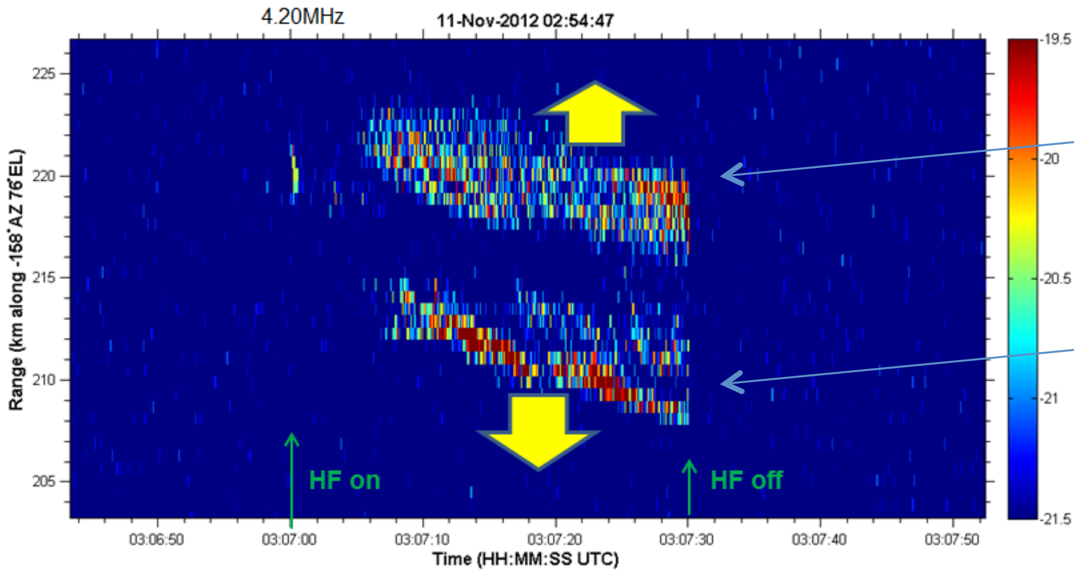
Drops ~20 km ~700 m/s

Drops 10 km ~330 m/s

Topic 4: *UHF Radar Doppler Power Spectra Observations*

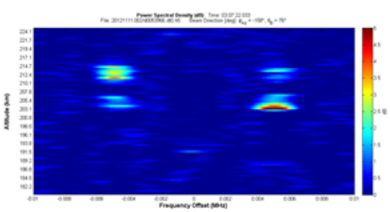
Enhanced Ion-Line Doppler Spectra for 4.20MHz (close to 3rd Gyro-Harmonic)

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



Upward ion-acoustic waves

Downward ion-acoustic waves



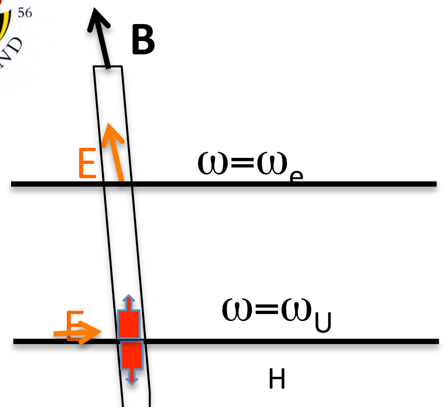
Power-height-time plot of HF-enhanced ion-line signals. Close to 3rd gyro-harmonic signals split into two layers. Doppler spectra (example to left) show strong asymmetries that indicate mainly upward propagating only ion-acoustic waves in the upper layer. The downward layer is associated with primarily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

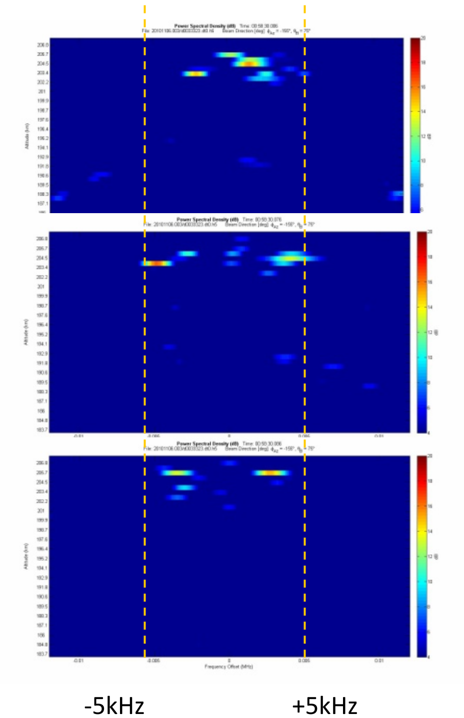
HF Power Cycle

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

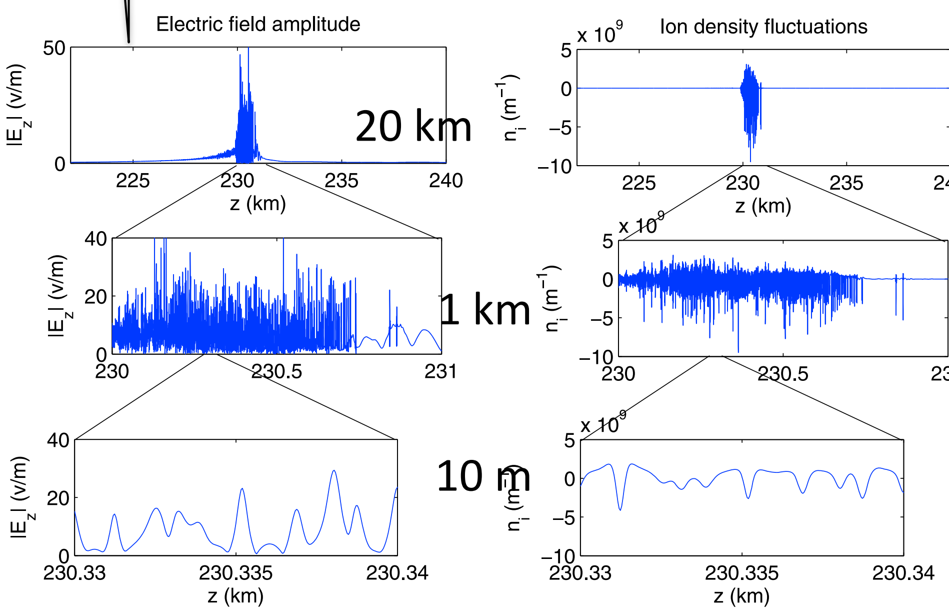
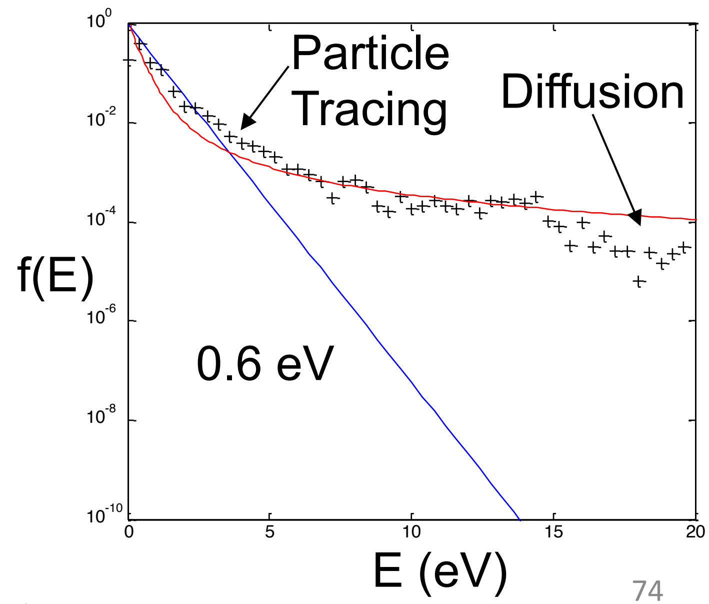
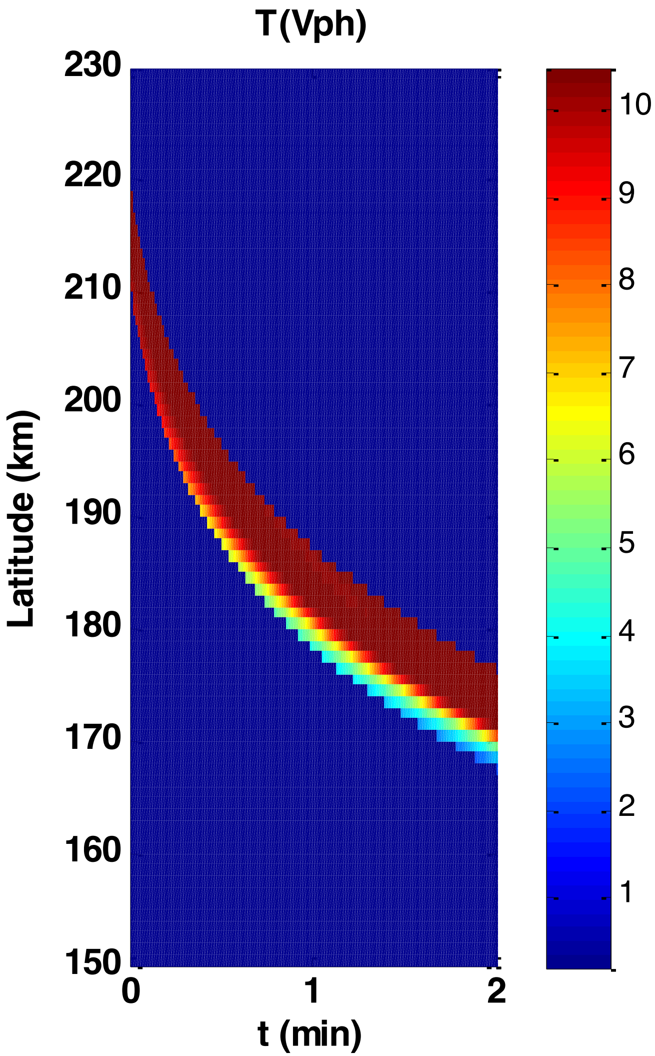
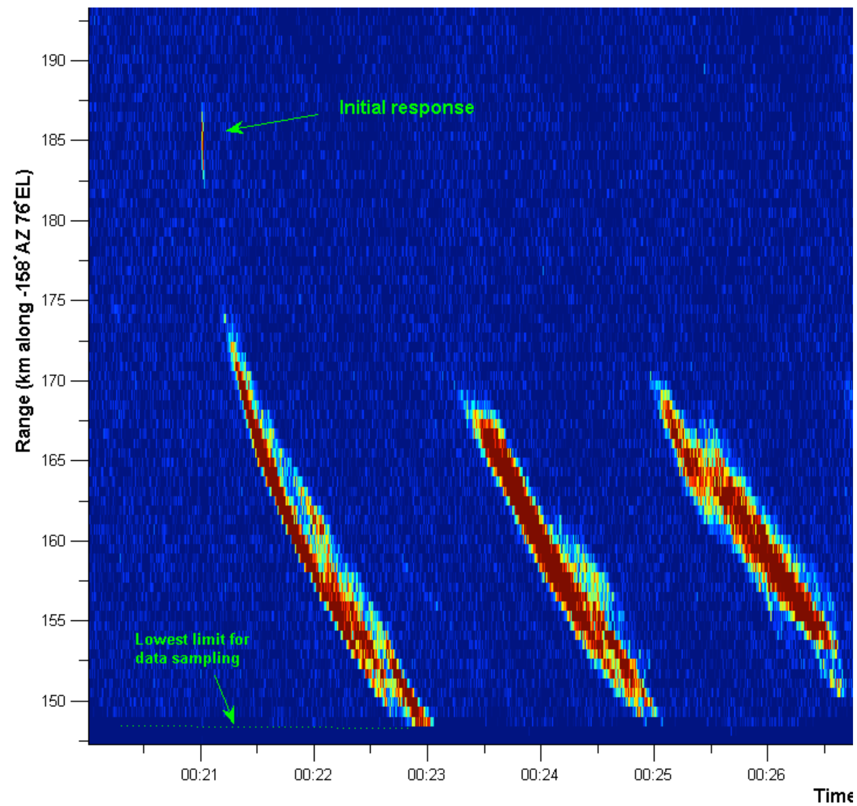


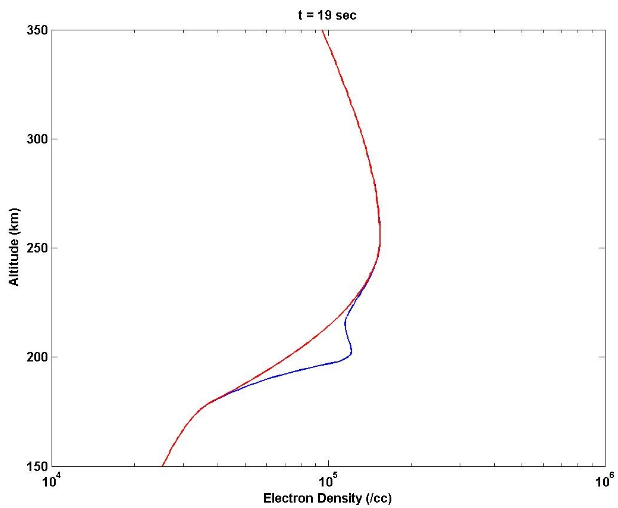
Figure 2. The amplitude of E_z and slowly varying ion density fluctuations n_i at various altitudes, for $E_O = 1.5$V/m.

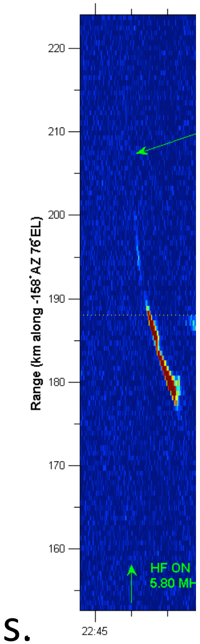


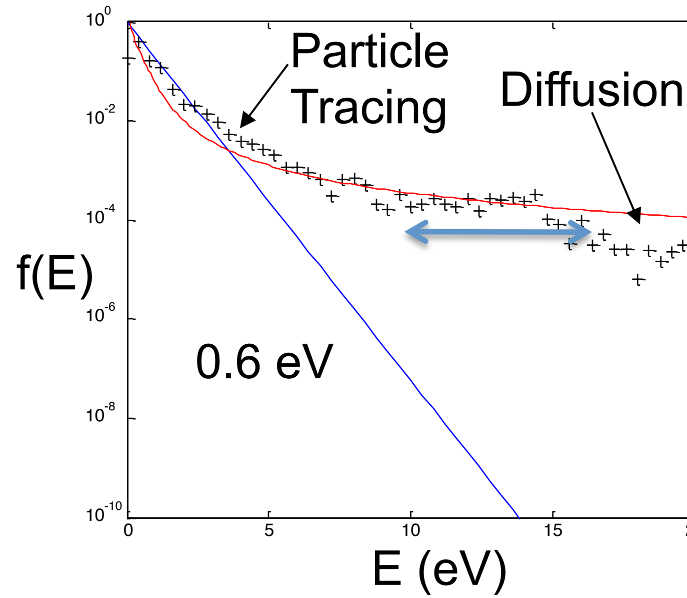

T(Vph)
230
220
210
200
190
180
170
160
150
Latitude (km)
0
1
2
t (min)
10
9
8
7
6
5
4
3
2
1


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







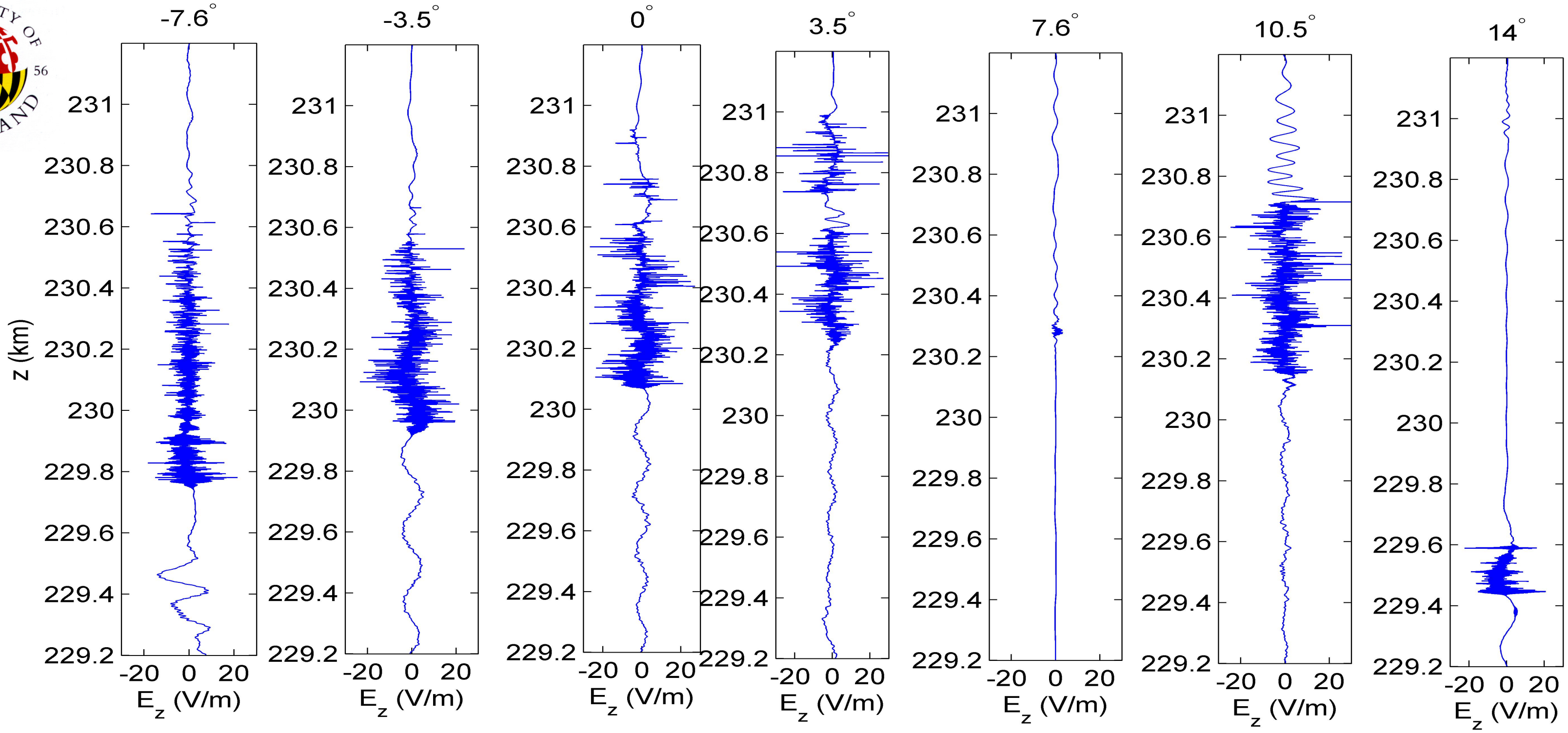
Enhancement due supra-thermal tails. Similar to Arecibo enhancement by photoelectrons but much stronger. The ionizing wave includes large T_e/T_i plasma and hot electron tails. Enhancement stops at low altitude when collisional damping dominates over Landau.

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

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

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

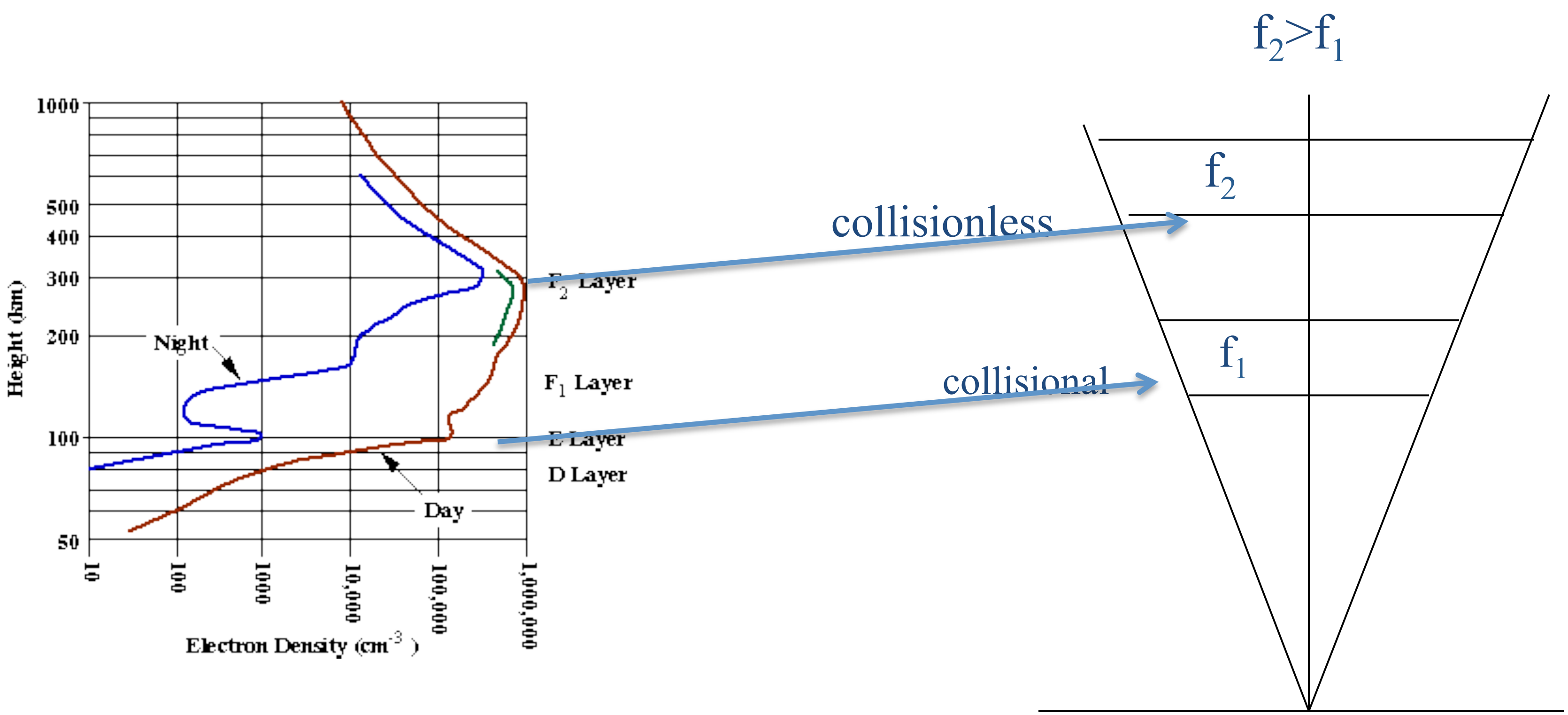
$$\text{if } \nu < \omega_e u_{ph}^2 F'(u_{ph})$$



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).

Ionospheric Heater – What it is and what it does

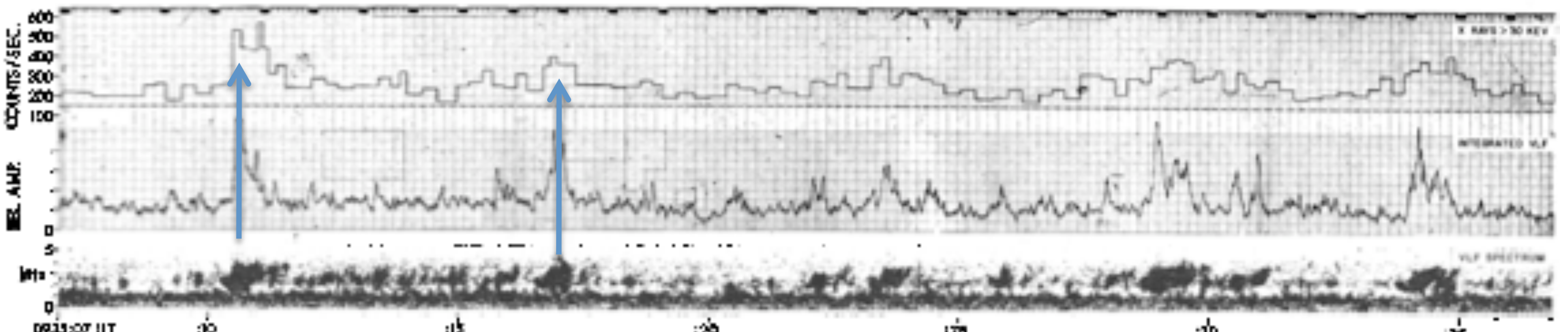


High power RF transmitters between 2.5-10 MHz that deposit energy into the electrons at altitudes 70-100 km (D/E region) or 200-300 km (F-region) in a controlled fashion.

What function of Ionospheric Heaters is relevant to Magnetosphere/RB Research ?

Puzzle: Coupled Whistler-driven Precipitation spikes with ULF (SAW) waves

Rosenberg et al. JGR 76, 8445, 1971; Lanzerotti 6 sec micropulsations



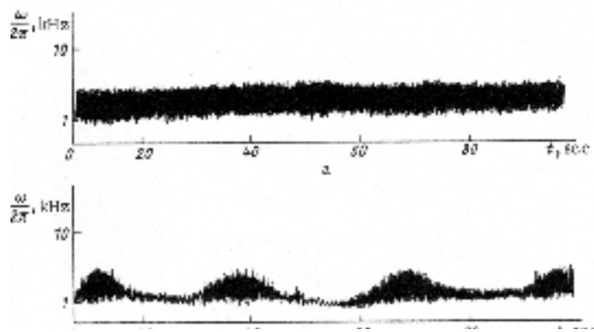
>30 keV

X-rays

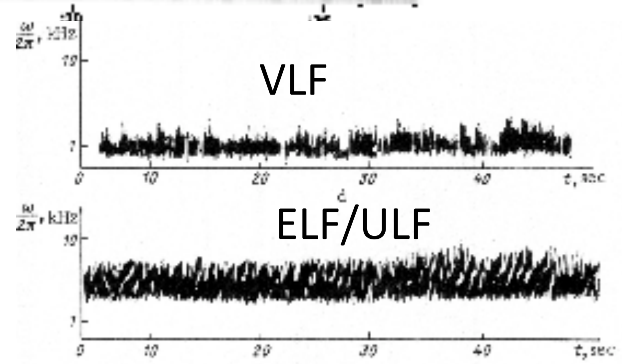
.5-5 kHz

6 sec mod

Ground



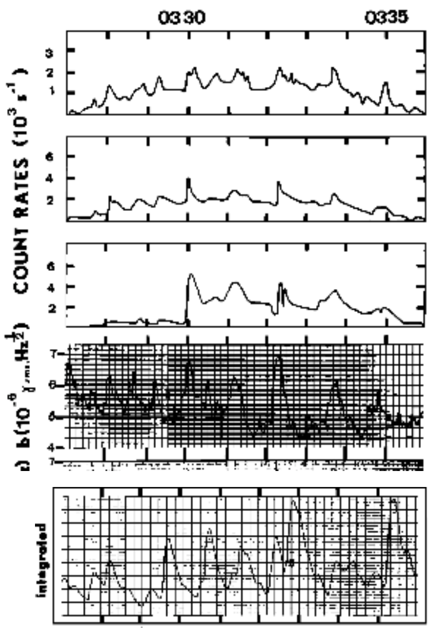
Hiss and q-periodic hiss



Chorus – Coherent hiss

Increase whistler energy density ->increase precipitation –RBR-> Inject whistlers (Helliwell 70's; DSX-Inan et al., 2002) Alternative: Is it possible to inject SAW and use them to amplify whistlers or convert them to EMIC?

Speculation: SAW can lead to amplified whistler spikes



>210 keV

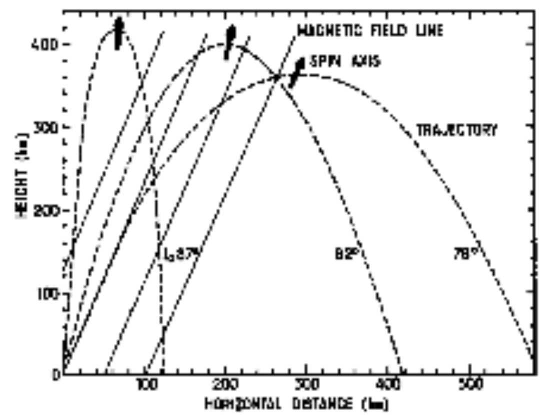
210>E>110 keV

110>E>55keV

VLF

ULF

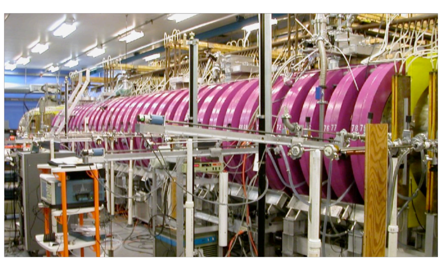
Gedrin et al. JGR, 1970



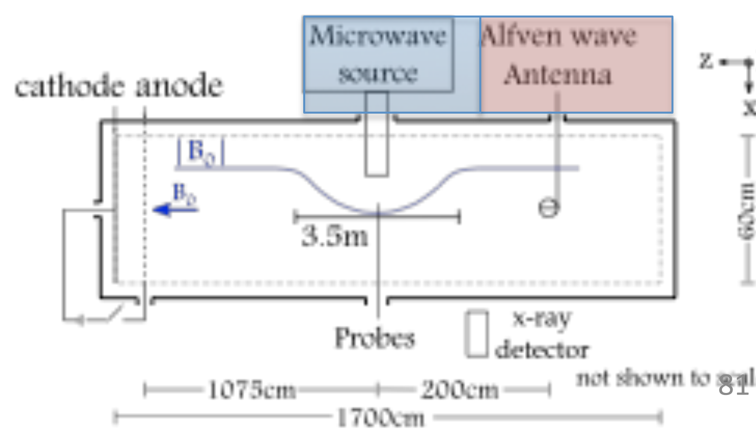
Periodic & quasi-periodic emissions: 100's of papers: Bespalov & Trakhtengerts Rev. Plasma Physics Vol. 10, 1986

CAN SAW CAUSE
MeV Electron Precipitation

Lab experiment UCLA Wang et al. PRL, April 2012



17 m,
10 sections control B
450 diagnostic ports

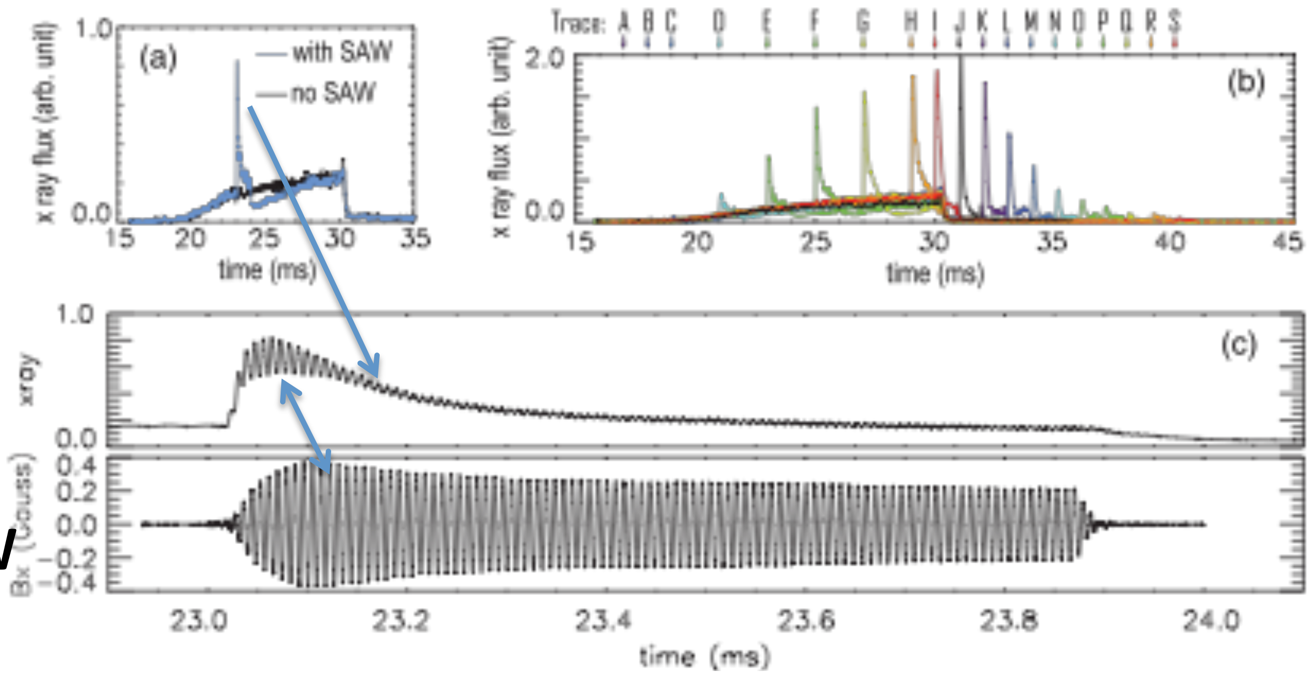


LAPD Experiment

SAW cannot break μ

Single pulse X-rays

Injected SAW 100 cycles



Physics hypothesis: Loss cone drives whistlers leading to steady state loss (KP)- Injection of SAW couples (?) to whistlers giving enhanced spiky loss

$$\frac{dN}{dt} = -\alpha \varepsilon_w N + J(t)$$

$$\frac{d\varepsilon_w}{dt} = \beta N \varepsilon_w - \nu \varepsilon_w + G_w(t) + \eta \varepsilon_w G_{SAW}$$

$$\nu \equiv \frac{2}{\tau_g} |\ln R|$$

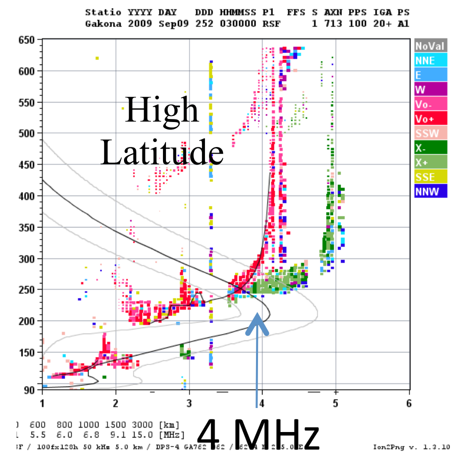
$$\varepsilon_w = (\beta / \alpha \nu) J$$

$$N = \nu / \beta$$

Analogy with Maser. First noted by Trakhtengerts

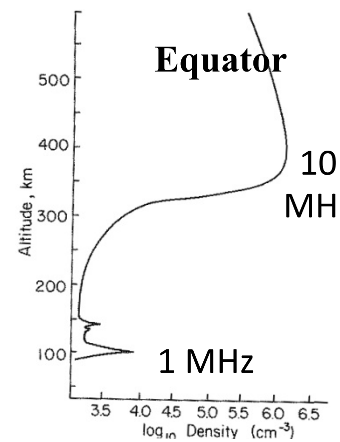
Implications - Barge or Shipboard Option

Combination of low HF power and high HF frequency requirements allow for mobile option



Strawman HF Array

- HF frequency 8-10 MHz
- Linear polarization
- Twenty 25-kW solid state transmitters
- Ship provided power



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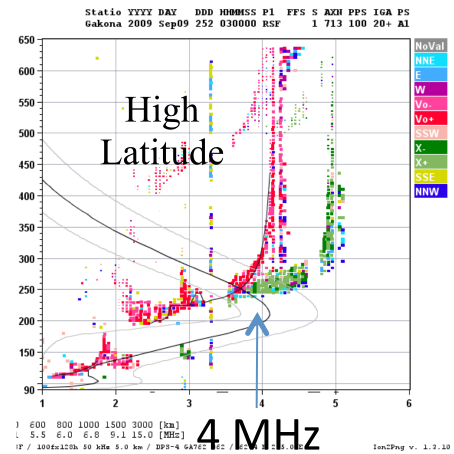

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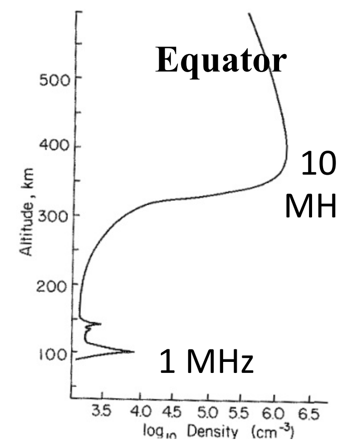
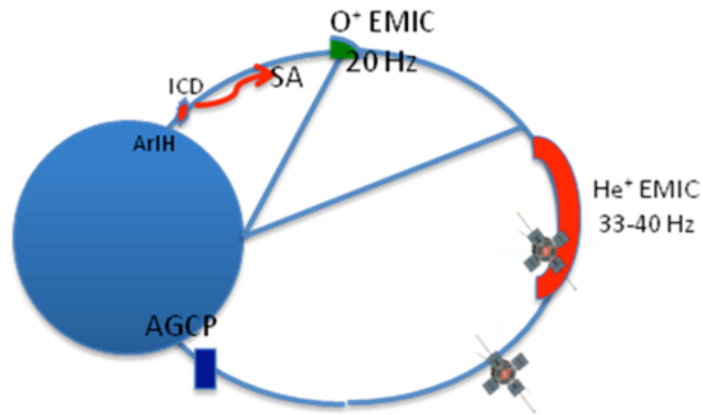
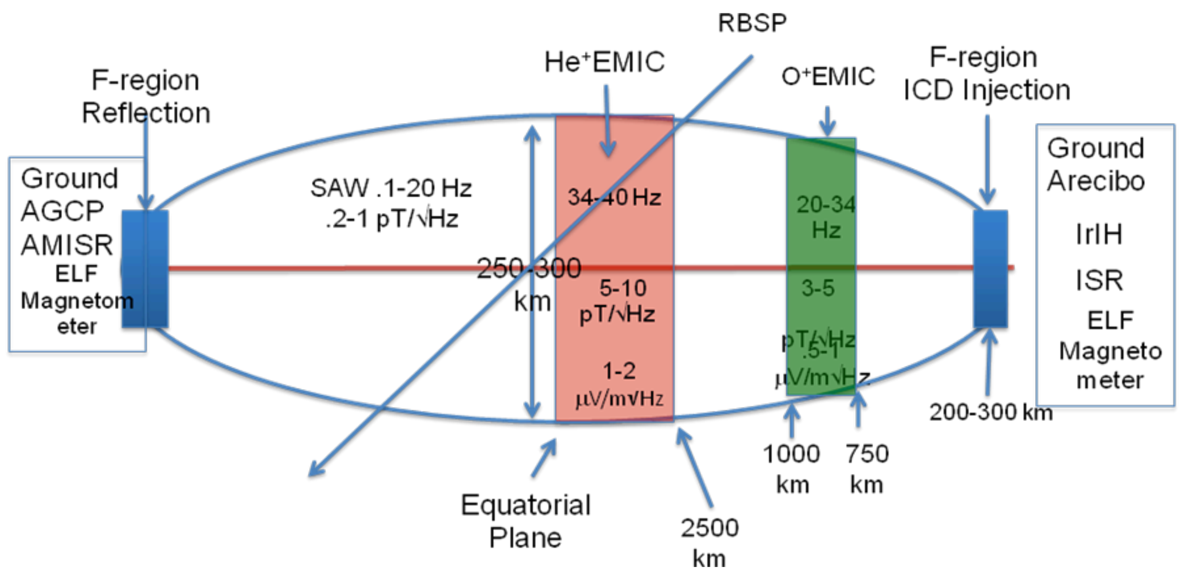


Objective – The goal of this effort is to bring together physicists and engineers from the space science, ionospheric modification, plasma modeling, and high power microwave source communities to examine anew the question of coupling electromagnetic energy to the ionosphere.

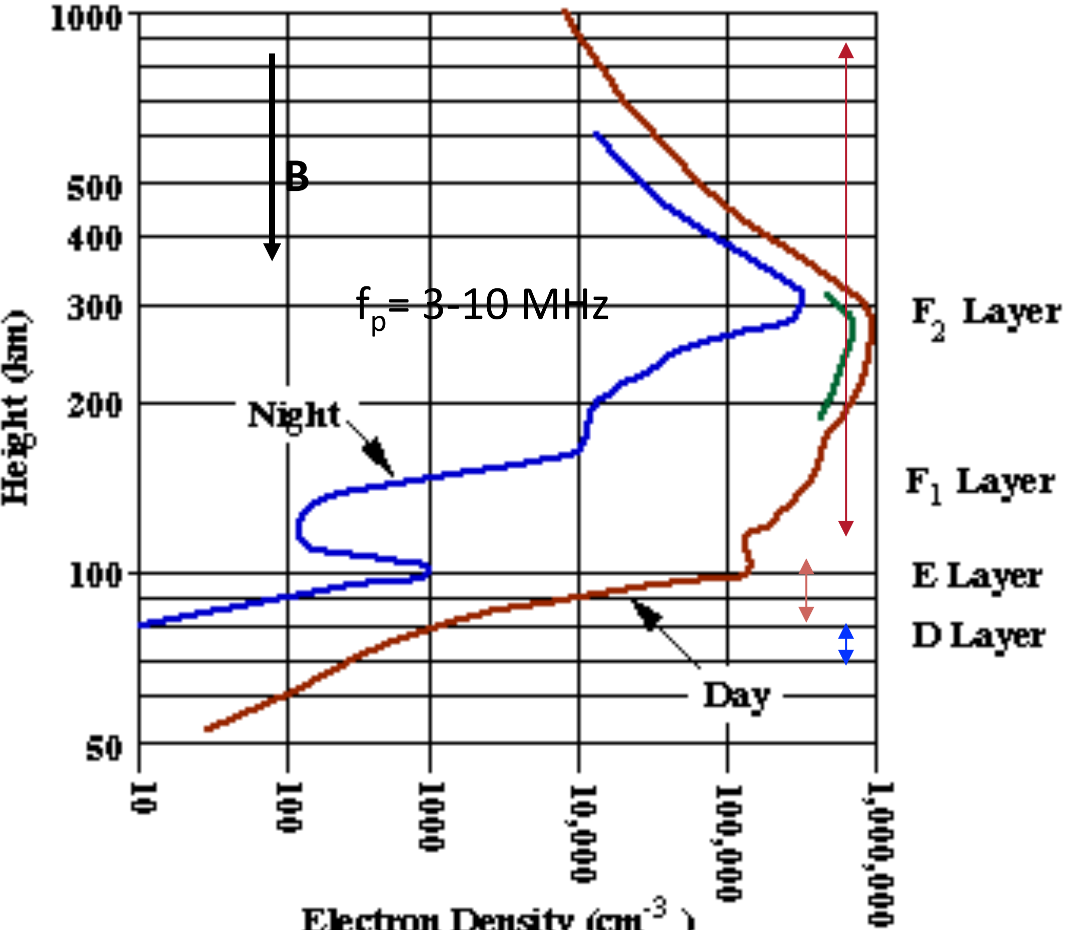
Define, and design modern, efficient, powerful, and adaptive/tunable EM sources for ionospheric modification, and provide hardware testing under laboratory conditions typical at University high power microwave facilities (vacuum loads and/or anechoic chamber);

Example of study of MHD Wave Propagation in the Inner Belt Using Arecibo and Van Allen Probes

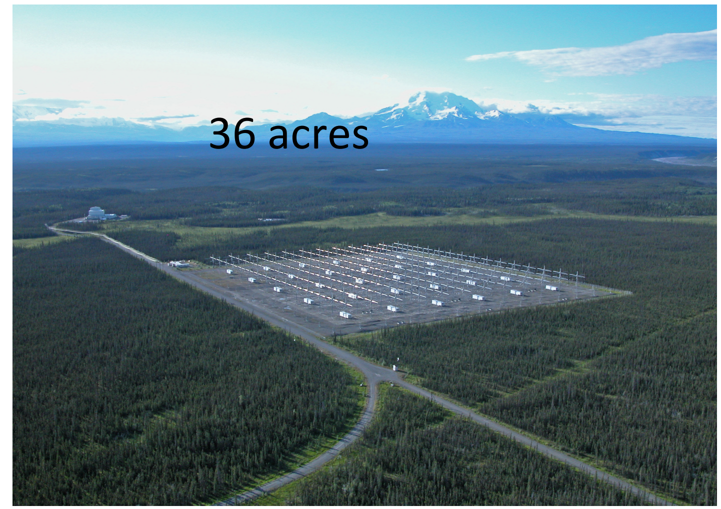




IONOSPHERIC HEATING AND HEATERS



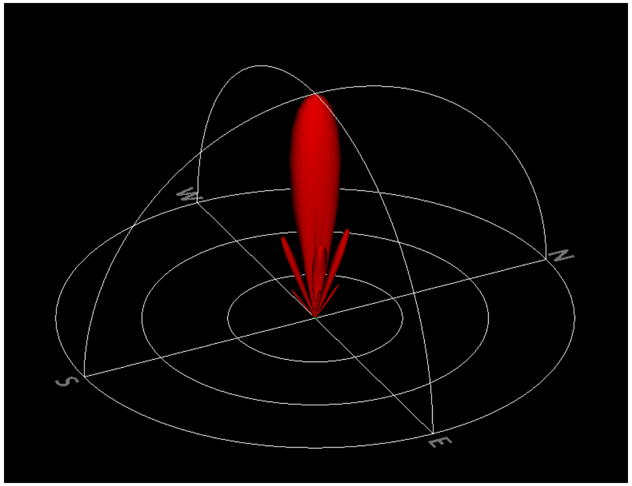
HAARP heater – Phase Array -360 el
2.8-10 MHz, ERP .6-5 GW



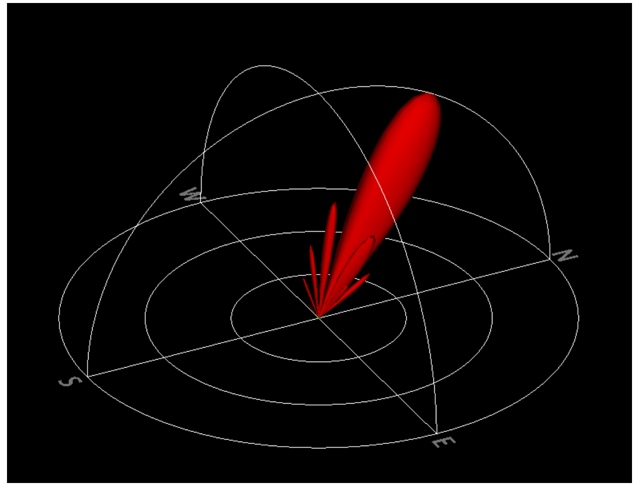
E≈1-1.5 V/m at 150 km, 5 MHz

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

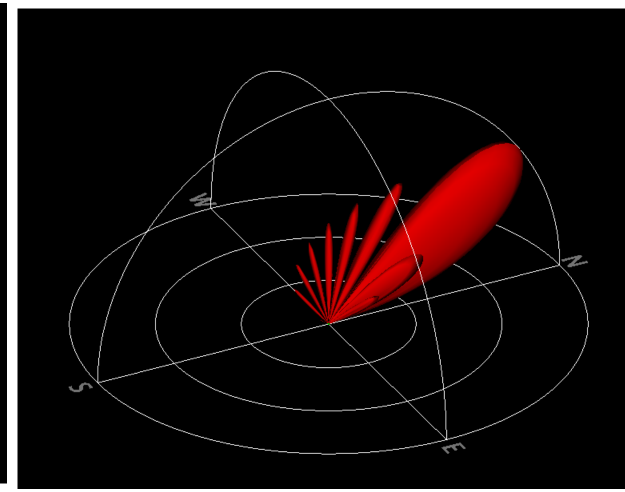
4.5 MHz, Azimuth=0



Zenith =0

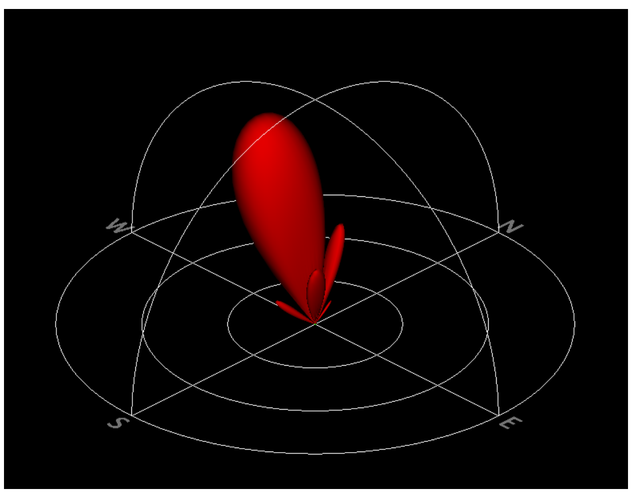


Zenith=45

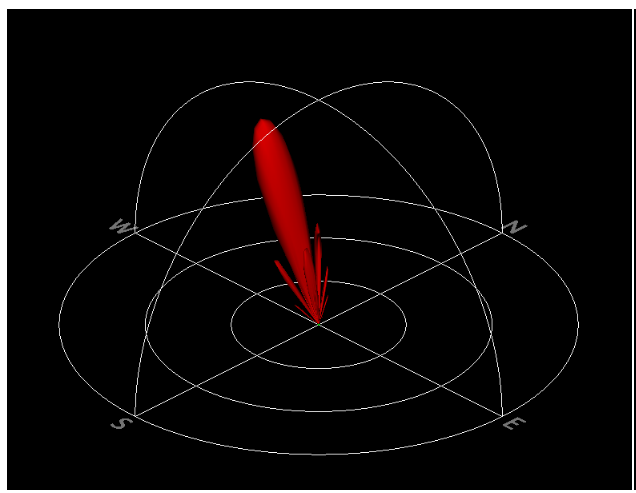


Zenith=60

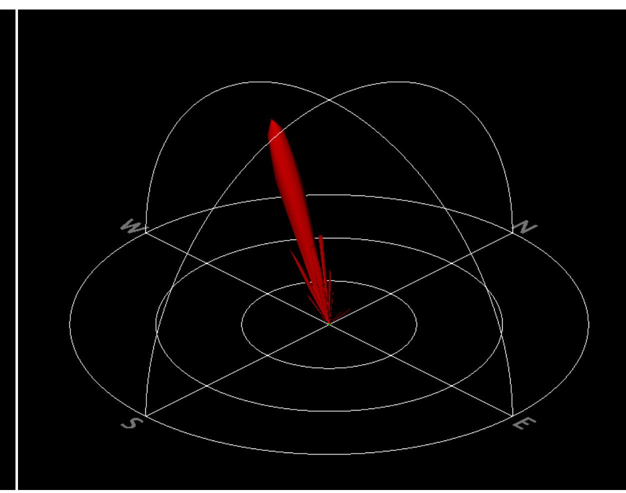
Magnetic Zenith



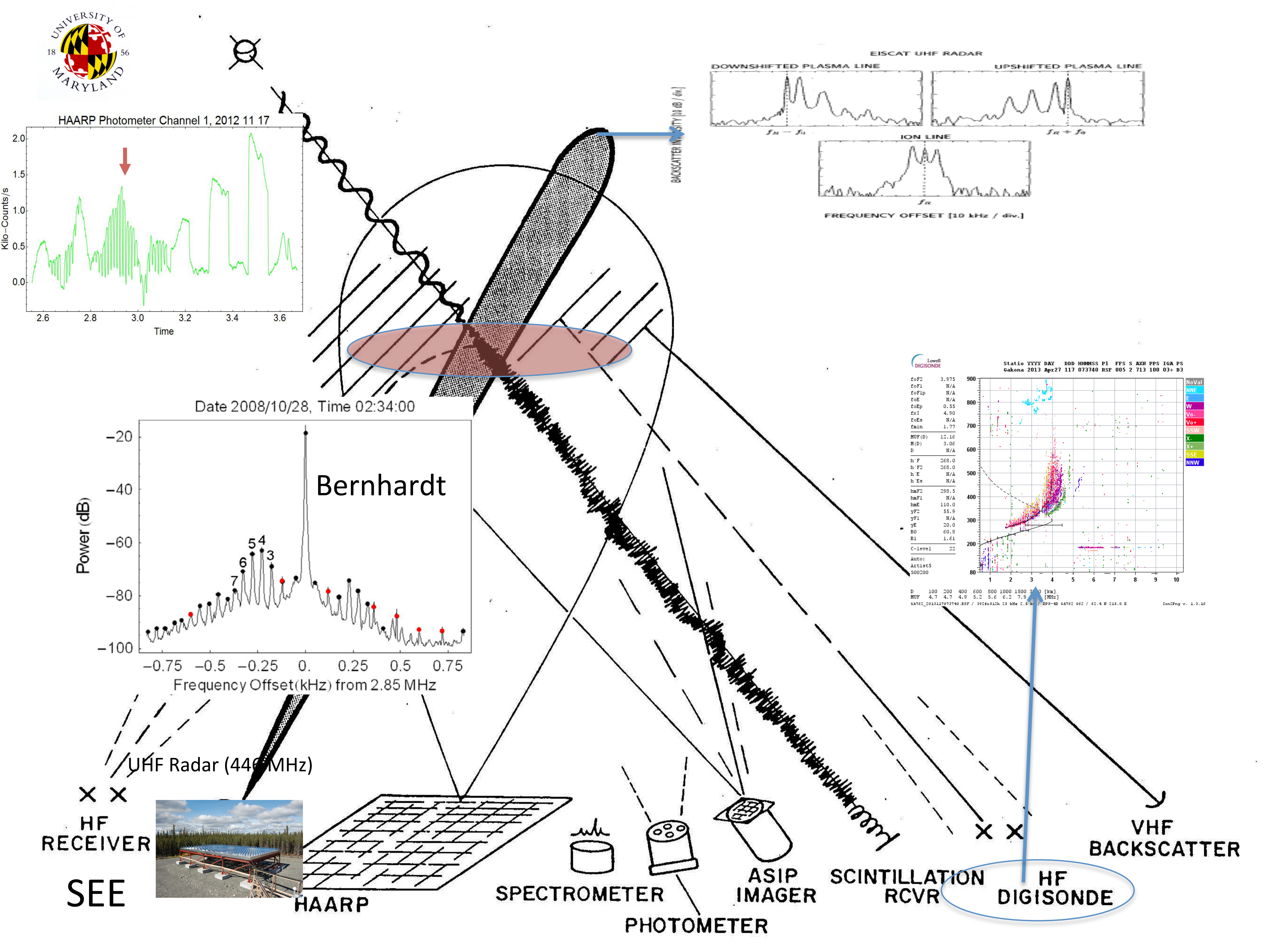
2.70 MHz



5.95 MHz



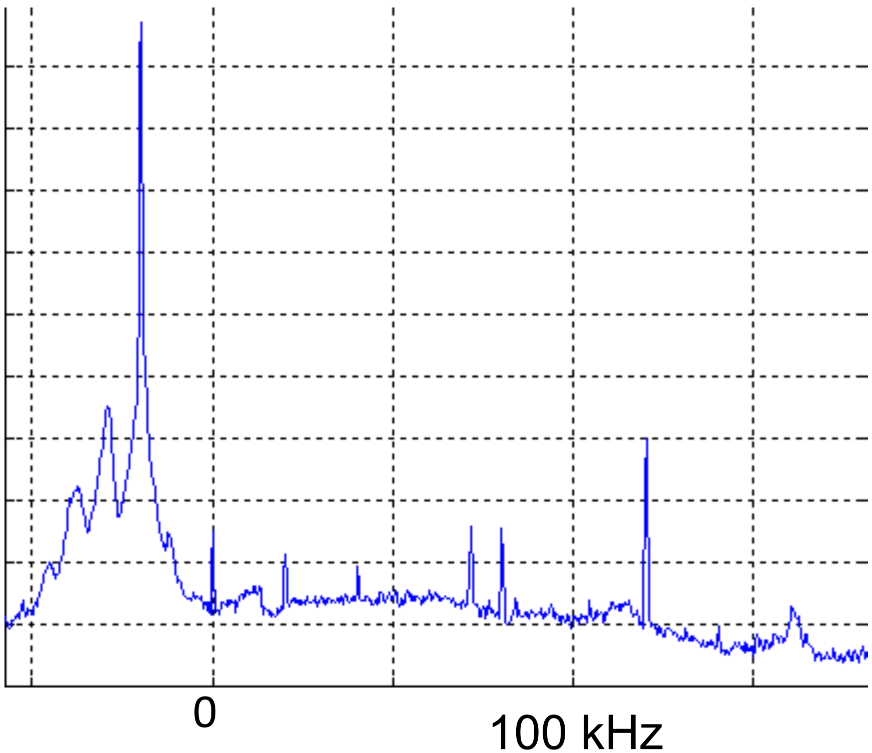
9.2 MHz


UNIVERSITY OF MARYLAND
1856
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
Lowell DIGISONDE
UHF Radar (446 MHz)
HF RECEIVER
SEE
HAARP
SPECTROMETER
PHOTOMETER
ASIP IMAGER
SCINTILLATION RCVR
HF DIGISONDE
VHF BACKSCATTER

SEE Gyro-Harmonics

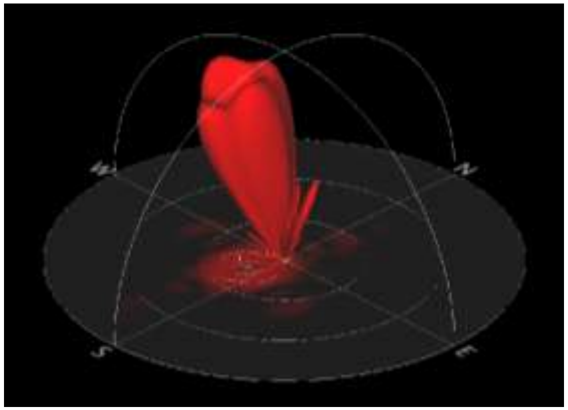
Sub-threshold Power

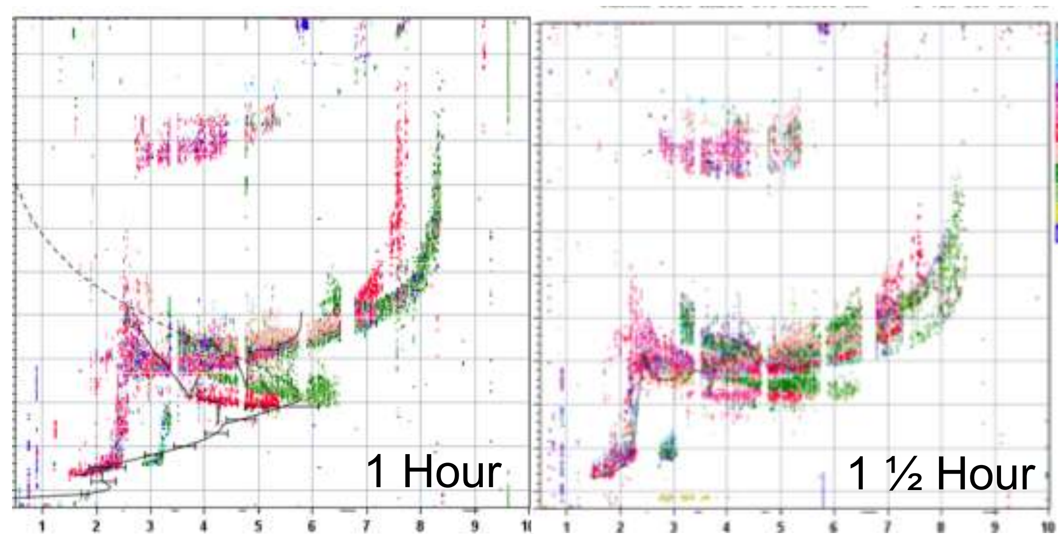
Double resonance near 4th cyclotron harmonic- HF frequency at zero shift 5.4 MHz

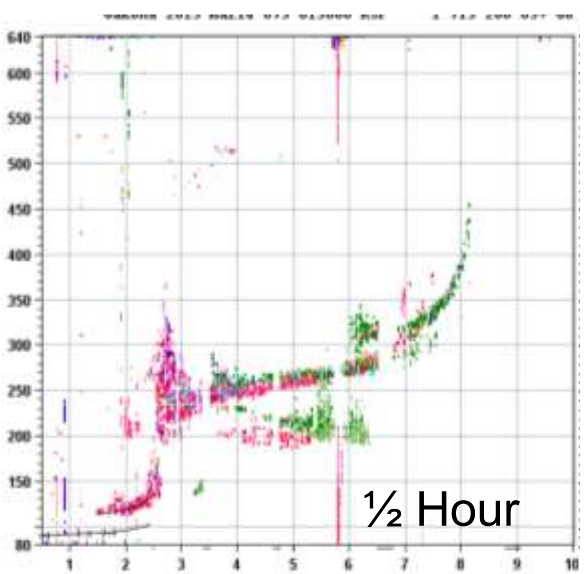


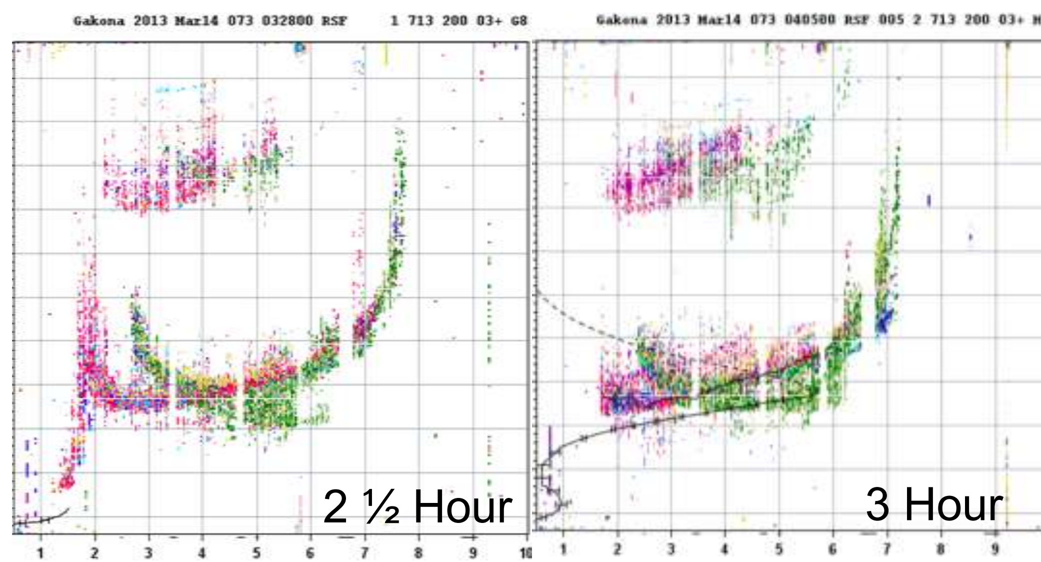
SURA Facility SEE Carozzi et al.JGR 2002

Twisted Beam Experiments
P. Bernhardt


HF Twisted Beam

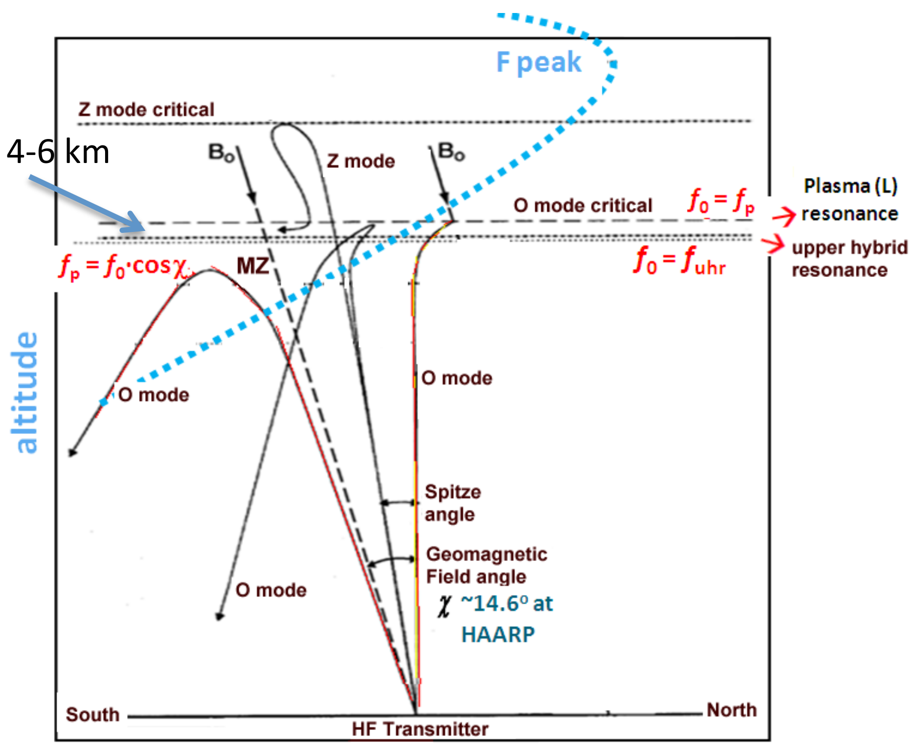


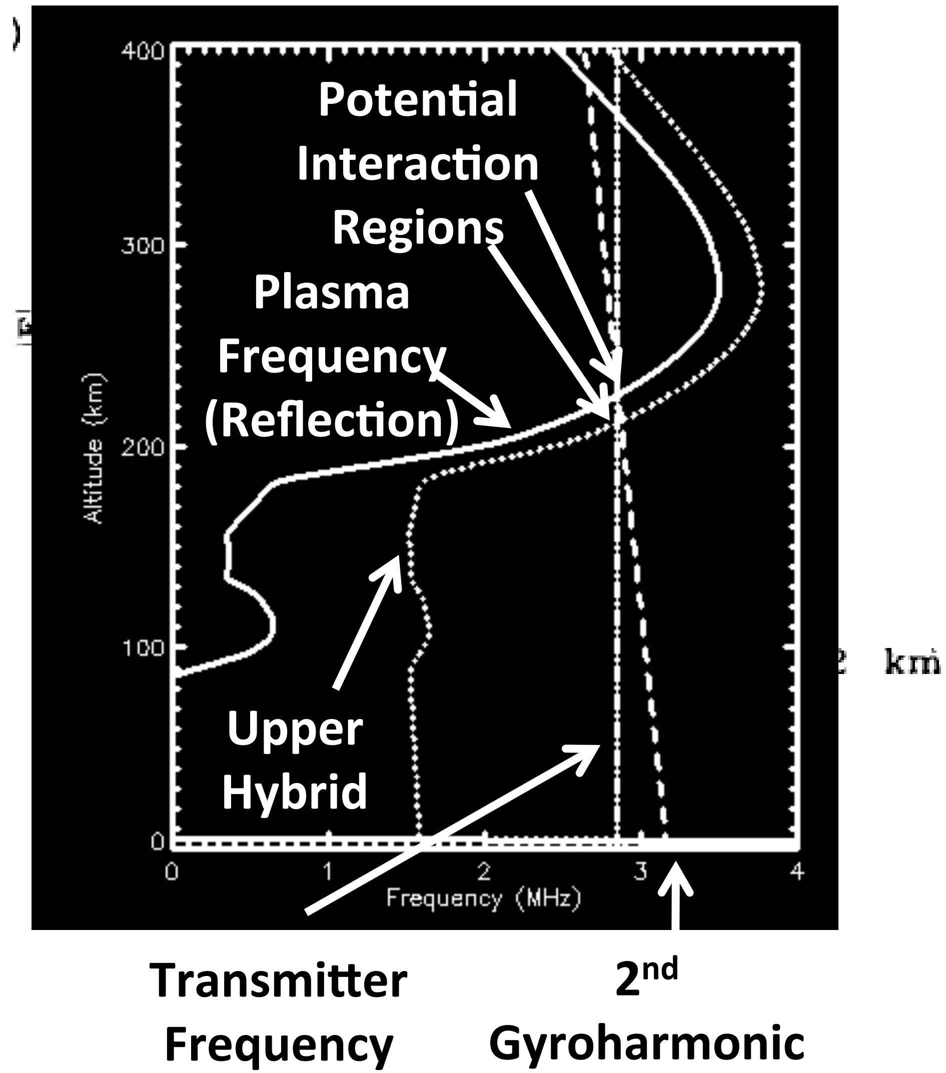




HF PATHS – RESONANCE FREQUENCIES

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





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

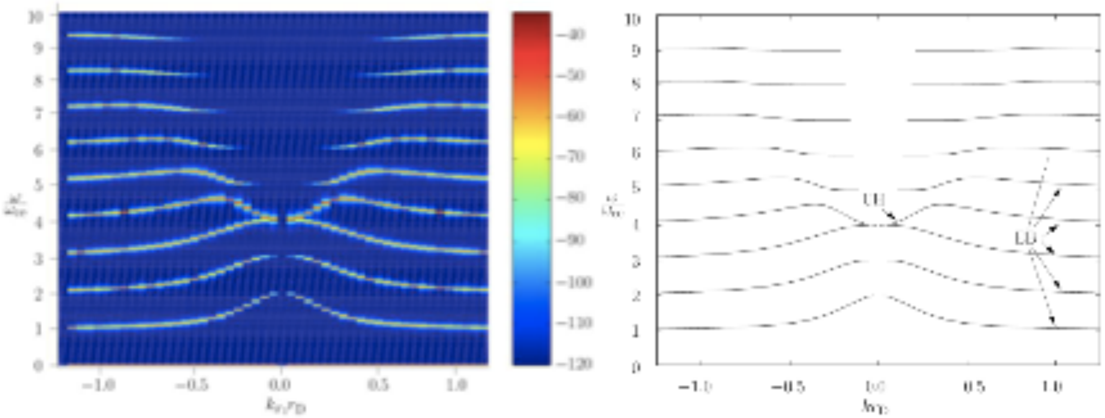


Figure 2: Power spectrum obtained from a Vlasov simulation (left) and theoretical dispersion diagram (right) showing the upper hybrid (UH) branch and several electron-Bernstein (EB) modes at the electron cyclotron harmonics for $\omega_{UH} = 4\omega_{ce}$. The wave energy is concentrated to the eigenmodes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

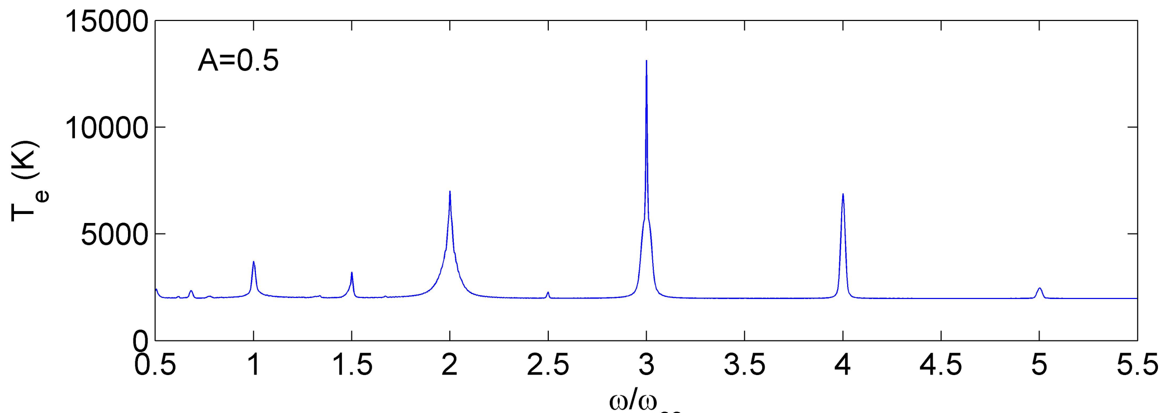
Stochasticity analysis 10^4 particles

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

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

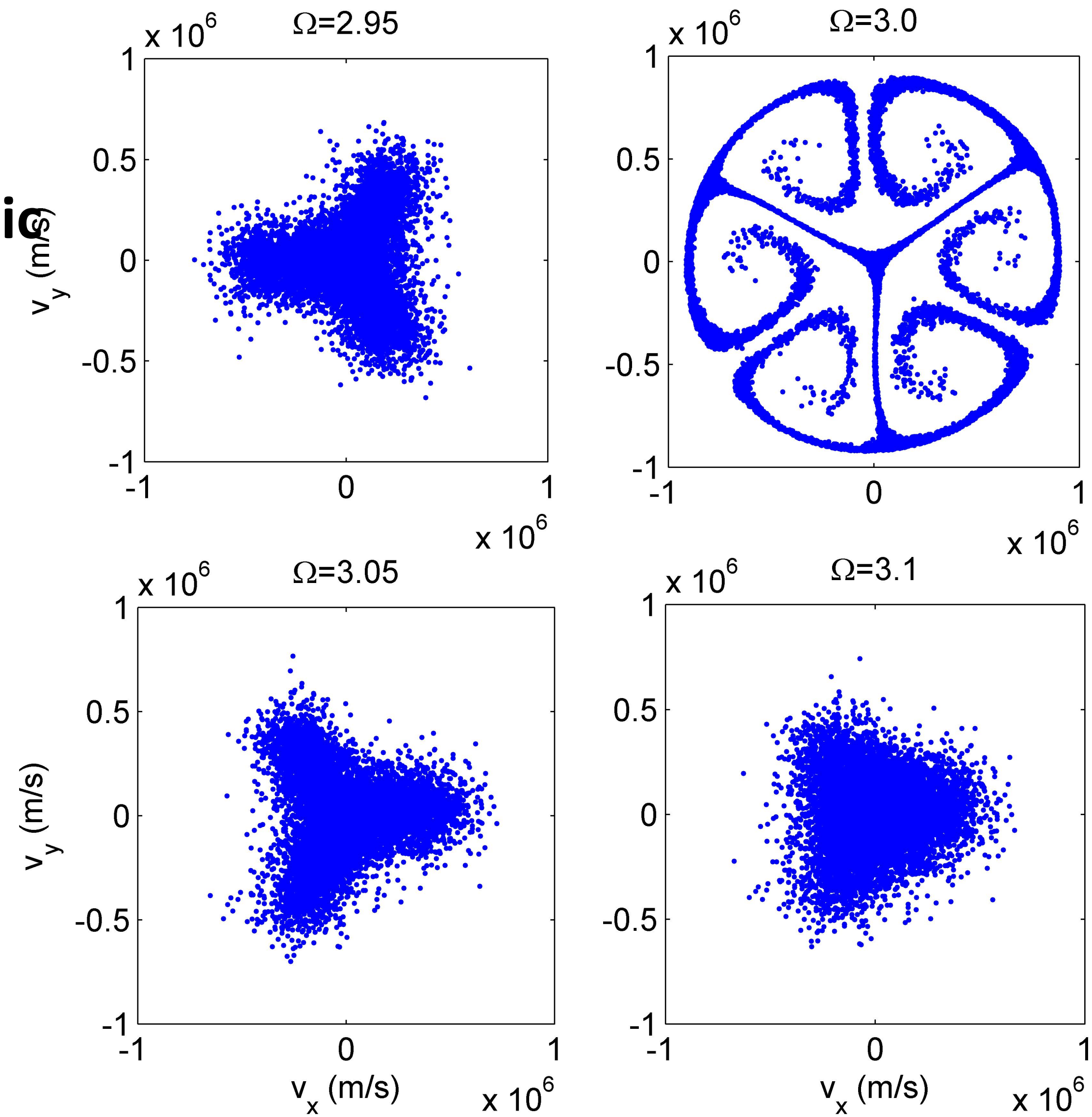
$$\boxed{\frac{du_x^j}{dt} = -A\sin(u_y^j - \Omega t) - u_y^j \qquad \frac{du_y^j}{dt} = u_x^j}$$

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

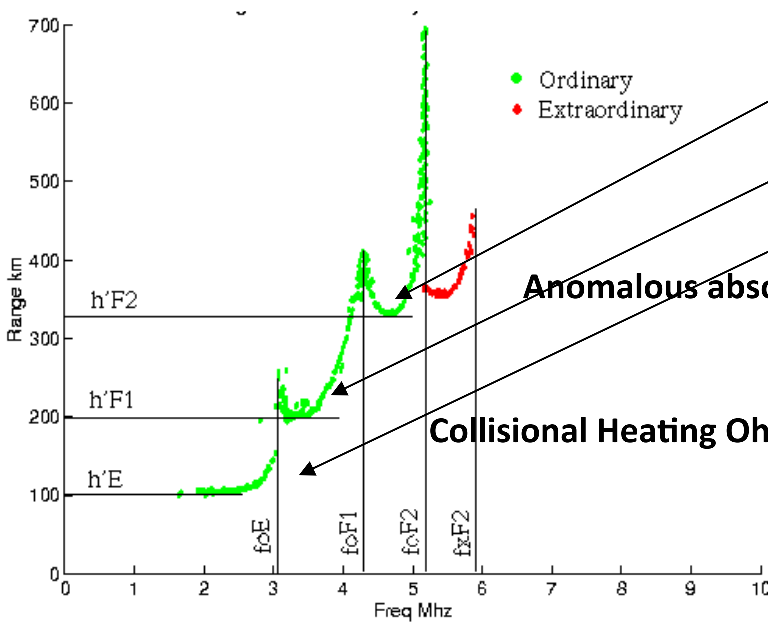


3.5 V/m

Strongly anisotropic Heating

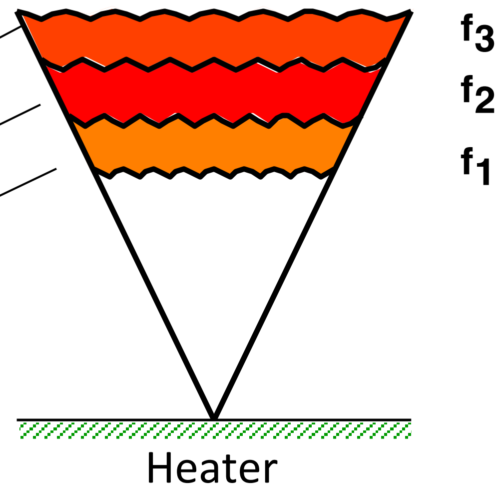


How to control location and profile of electron heating



Anomalous absorption

Collisional Heating Ohmic



$$\frac{dT_e}{dt} = \nu_{en}\varepsilon - losses$$

$$\varepsilon = \frac{1}{2} m \left(\frac{eE}{m\omega_{eff}}\right)^2$$

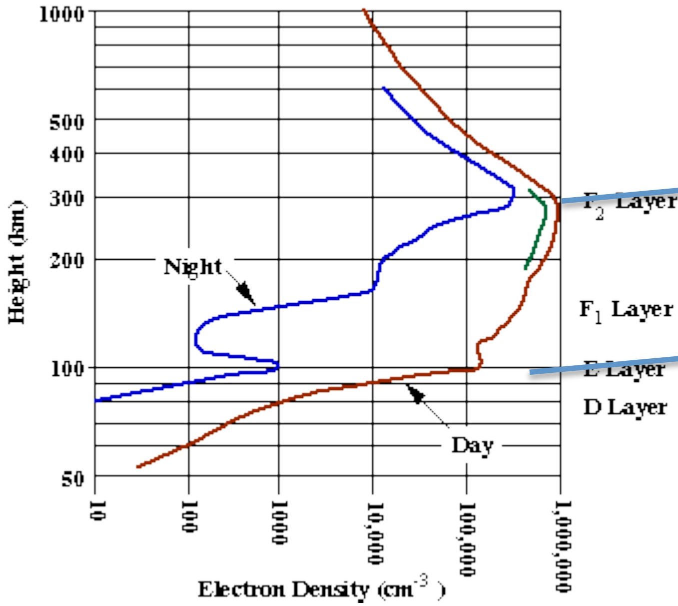
$$\omega_{eff}^2 \approx (\omega \pm \Omega_e)^2 + \nu_{en}^2$$

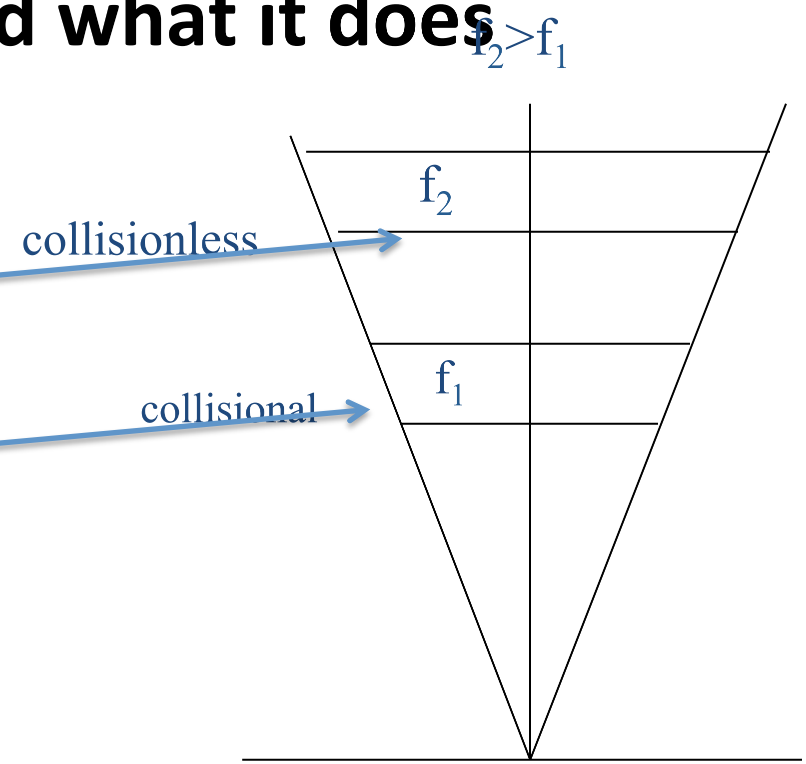
Ionosonde - Radar

$$\omega_{pr} = \omega_e(h) = 5.6x10^4\sqrt{n(h)} \quad \text{O-mode}$$

$$\omega_{pr} = \omega_e(h) + \Omega_e / 2 \qquad \text{X-mode}$$

The Alternative Ionospheric Heater
What it is and what it does





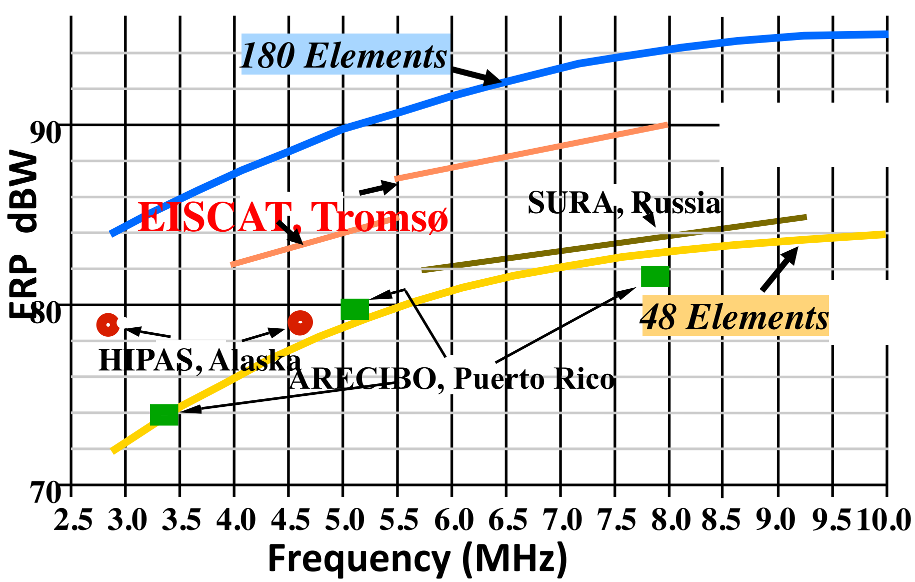
High power RF transmitters between 2.5-10 MHz that deposit energy into the electrons at altitudes 70-100 km (D/E region) or 200-300 km (F-region) in a controlled fashion.

Discussion topics : 1. Virtual ULF/ELF/VLF antennas
2. The Physics of Artificial Plasma Layers

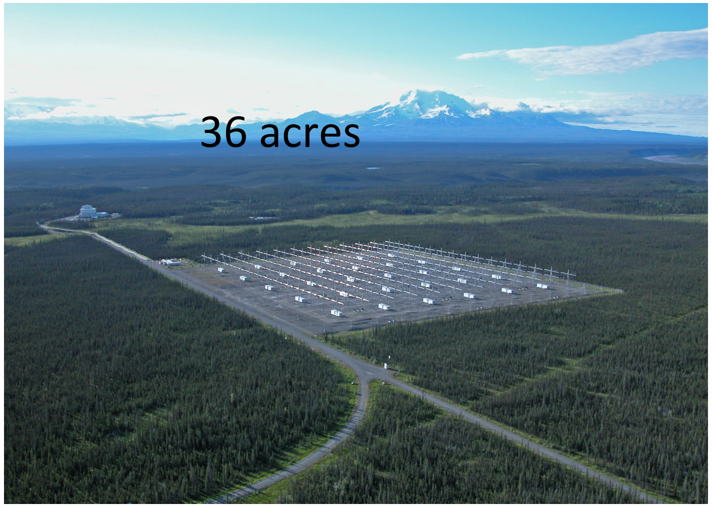
THE ALTERNATIVE-IONOSPHERIC HEATERS

- Ionospheric heater - Powerful HF transmitter (2.8-10 MHz) that induces controlled temporary modification to the electron temperature at desired altitude.

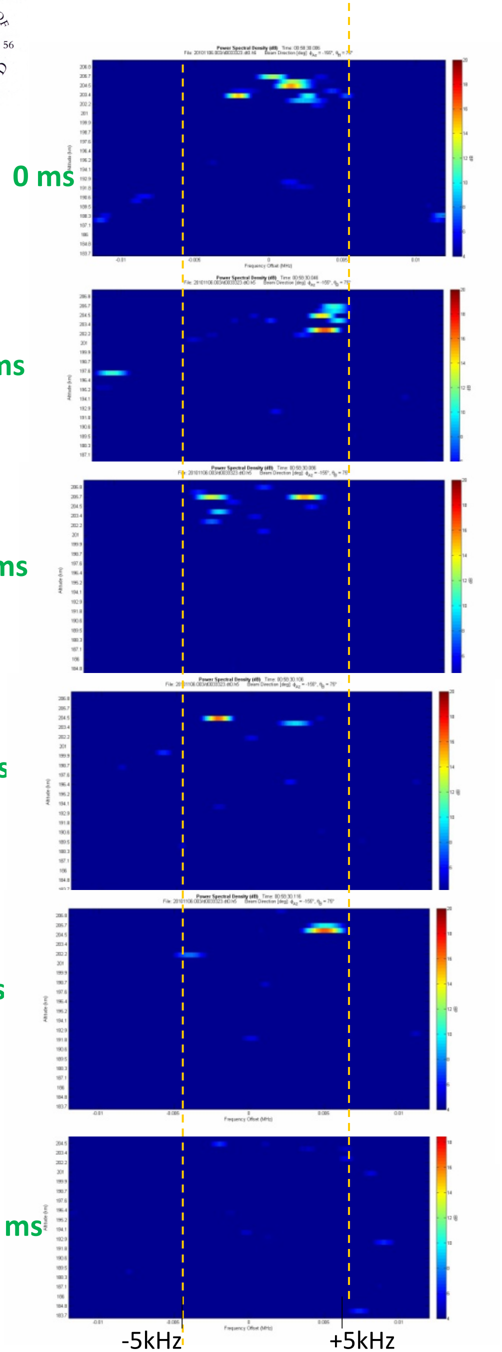
- Use in conjunction with diagnostics to study, in a cause and effect fashion:
  - EM propagation, plasma turbulence and instabilities
  - Response of magnetospheric plasma and Radiation Belts to controlled perturbations of the ionospheric plasma

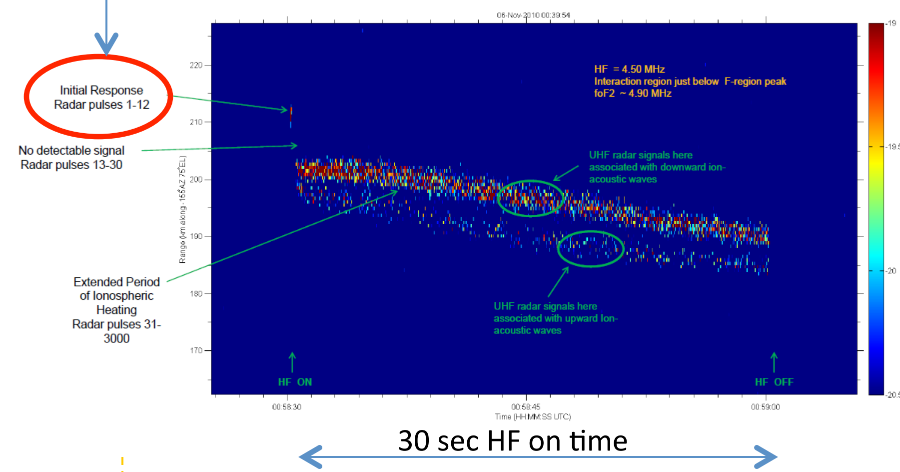


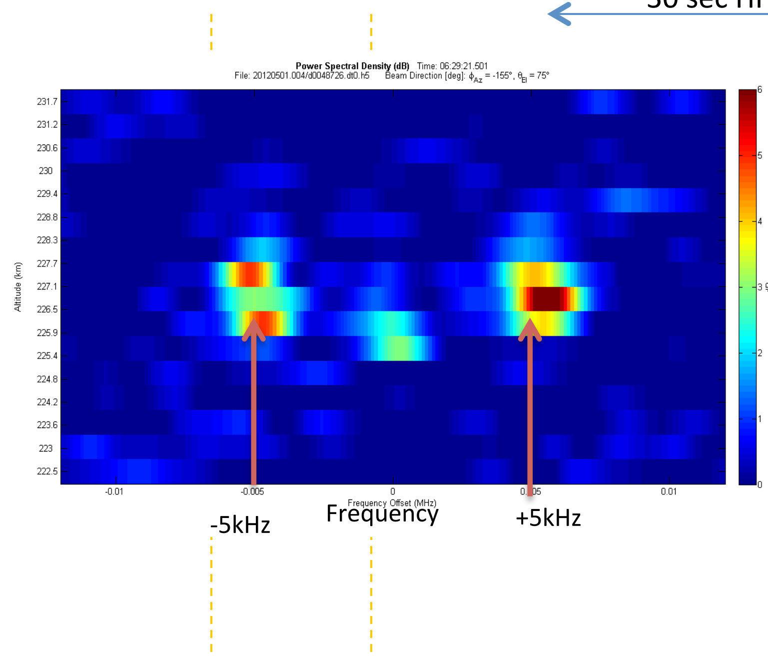
HAARP HEATER



UHF Power Spectra During Initial Response Time
(First 12 pulses after HF turn on - 120 milli-sec)







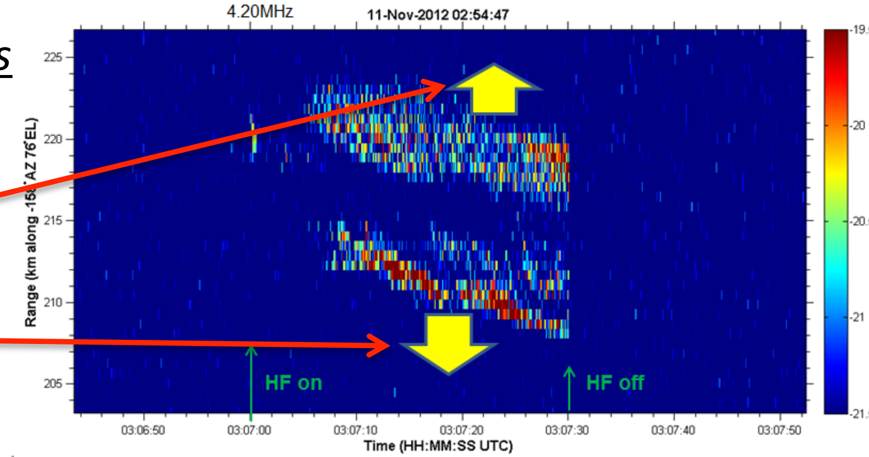
UHF Radar Doppler Power Spectra Observations

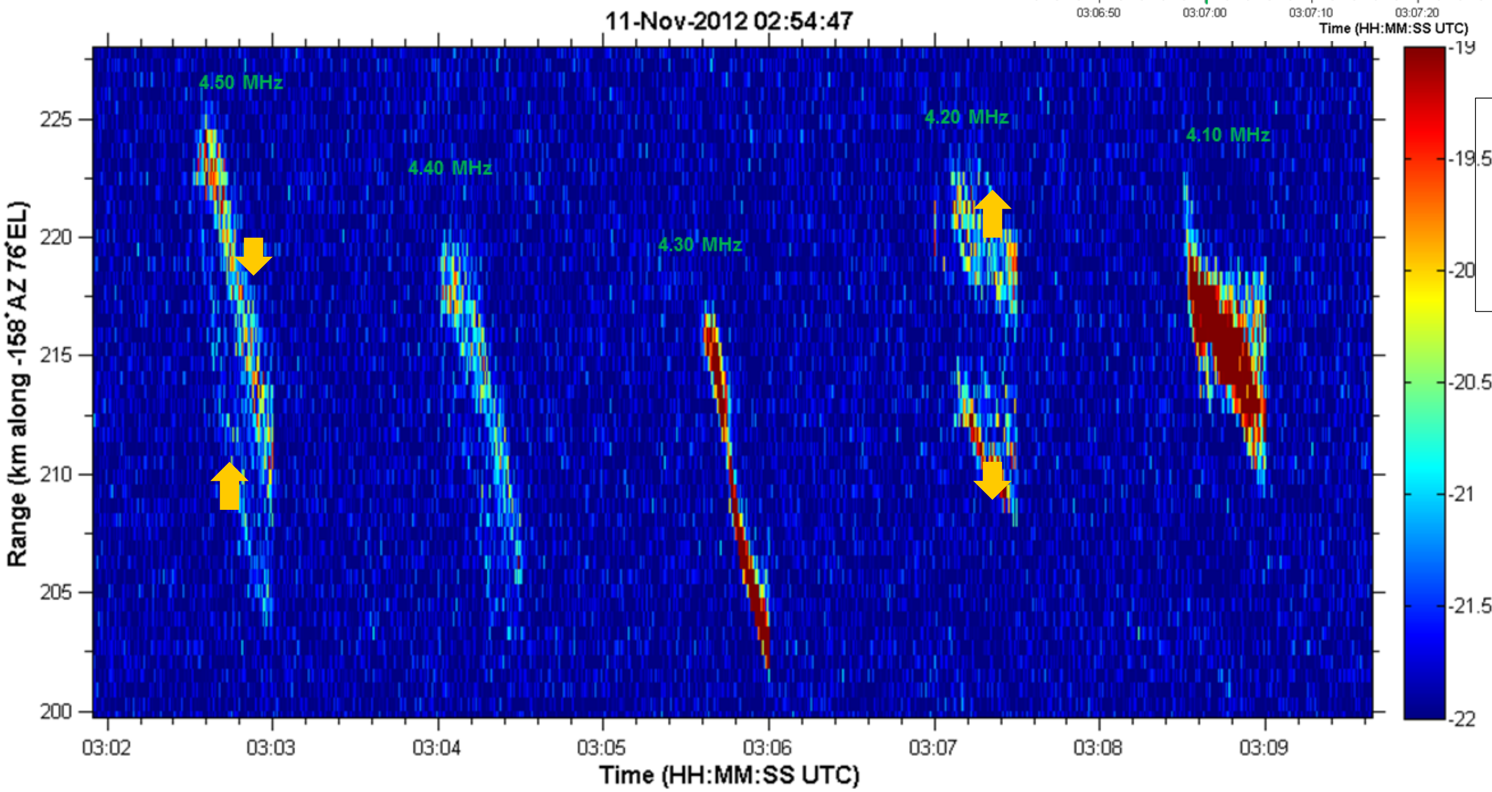
Courtesy of B. Watkins

IA asymmetry ?

Upward

Downward





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

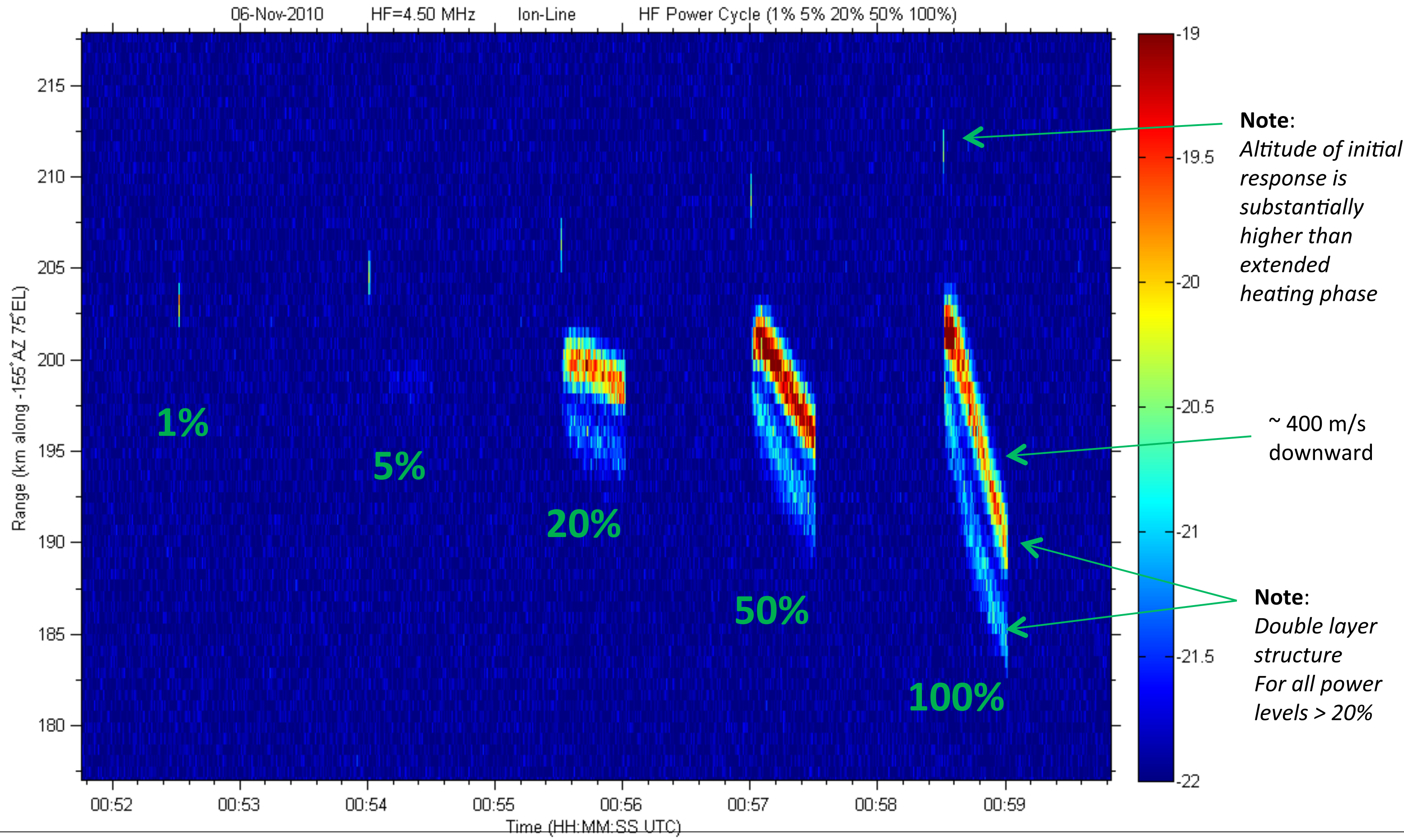
1. The 4.20 MHz frequency results show two distinct layers. (3rd gyro harmonic between 4.20 and 4.30 MHz)
2. Rate of descent approx same for 4.3, 4.4, 4.5 MHz. Lower descent rates for 4.1 and 4.2 MHz
3. Note direction of ion-acoustic waves for double layers that occur for 4.50 and 4.20 MHz. (yellow arrows)

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.*

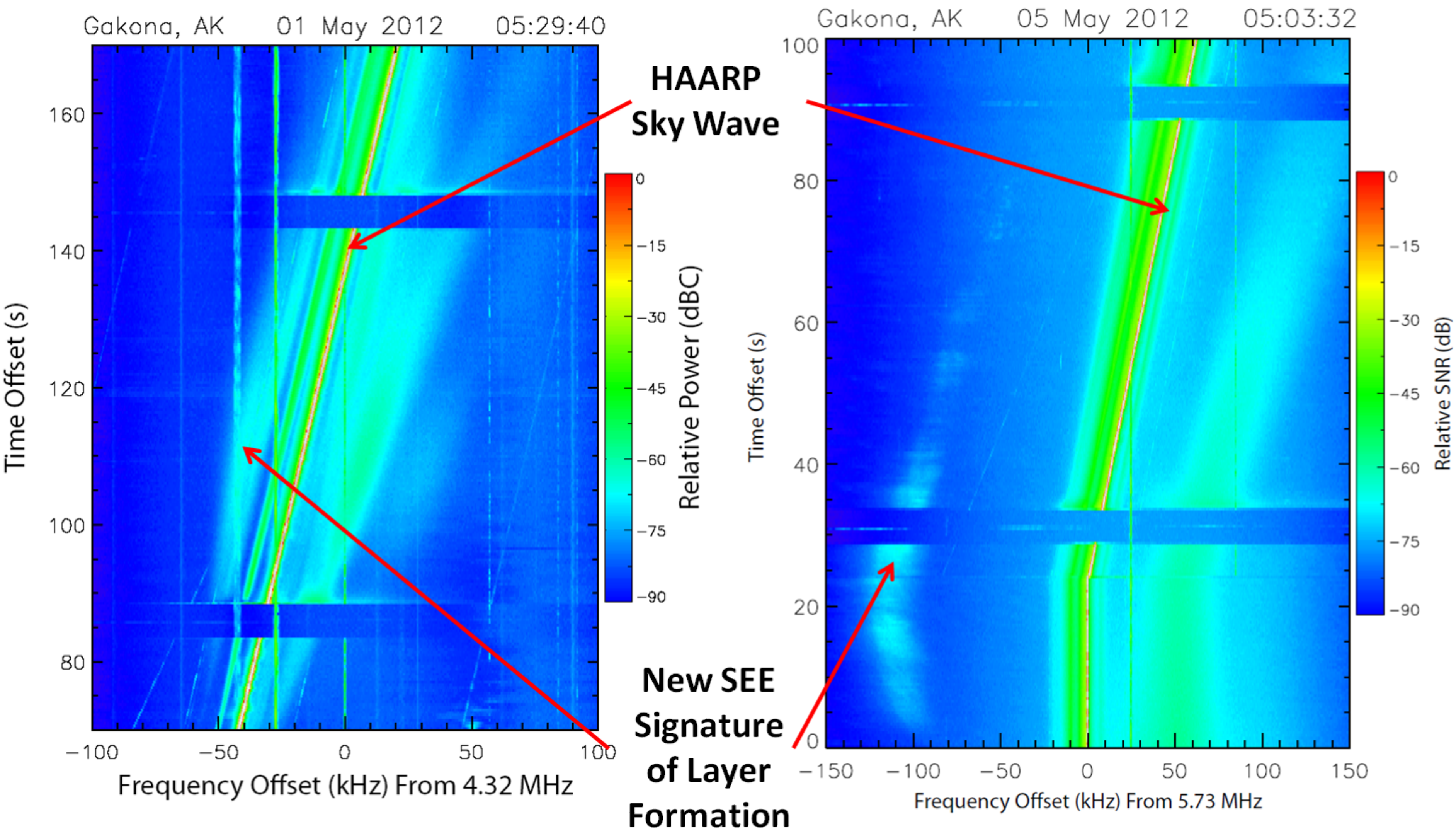
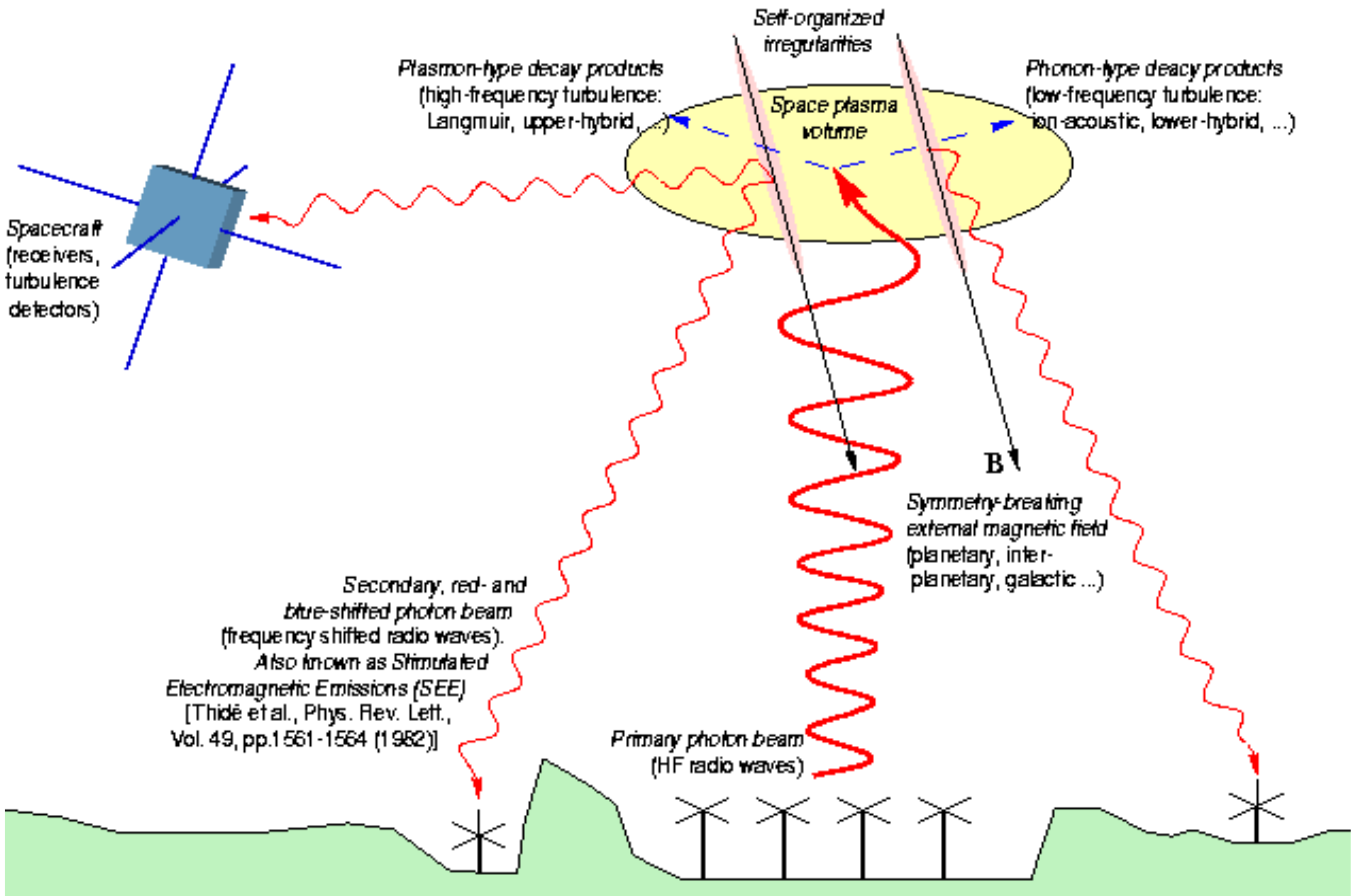


Figure 9: SEE signatures associated with APL formation {Berhardt and Briczinski}


Self-organized
irregularities
Plasmon-type decay products
(high-frequency turbulence:
Langmuir, upper-hybrid, ...)
Space plasma
volume
Phonon-type deacy products
(low-frequency turbulence:
ion-acoustic, lower-hybrid, ...)
Spacecraft
(receivers,
turbulence
detectors)
B
Symmetry-breaking
external magnetic field
(planetary, inter-
planetary, galactic ...)
Secondary, red- and
blue-shifted photon beam
(frequency shifted radio waves).
Also known as Stimulated
Electromagnetic Emissions (SEE)
[Thidé et al., Phys. Rev. Lett.,
Vol. 49, pp.1561-1564 (1982)]
Primary photon beam
(HF radio waves)