A New Paradigm in Sources and Physics of High-Power Ionospheric Modification

Dennis Papadopoulos

University of Maryland

College Park

Invited Review

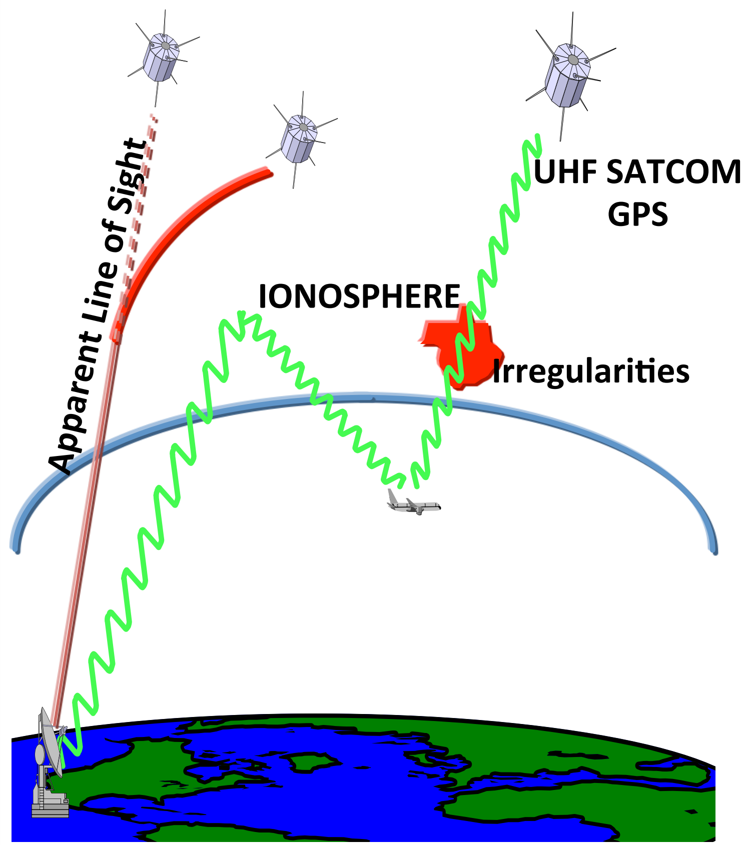
20th Annual RF Ionospheric Interactions Workshop

April 27-30, 2014 , Arecibo, Puerto Rico

AFOSR FY MURI TOPIC #13
A New Paradigm in Sources and Physics of High-Power Ionospheric Modification

Background

- The Ionosphere controls the performance of critical DoD & civilian systems [Communications range, radar, navigation, Geo-location accuracy, etc]
- DoD/civilian active research using traditional ionospheric heaters provided new capabilities and applications that allow control/exploitation of triggered processes (Virtual antennas in space, artificial clouds, irregularity control,…)
- The low power of traditional heaters resulted in large arrays and active elements, with complex and costly controls leading to fixed installations
- Fixed locations are associated with fixed magnetic geometry limiting the scope of the research investment



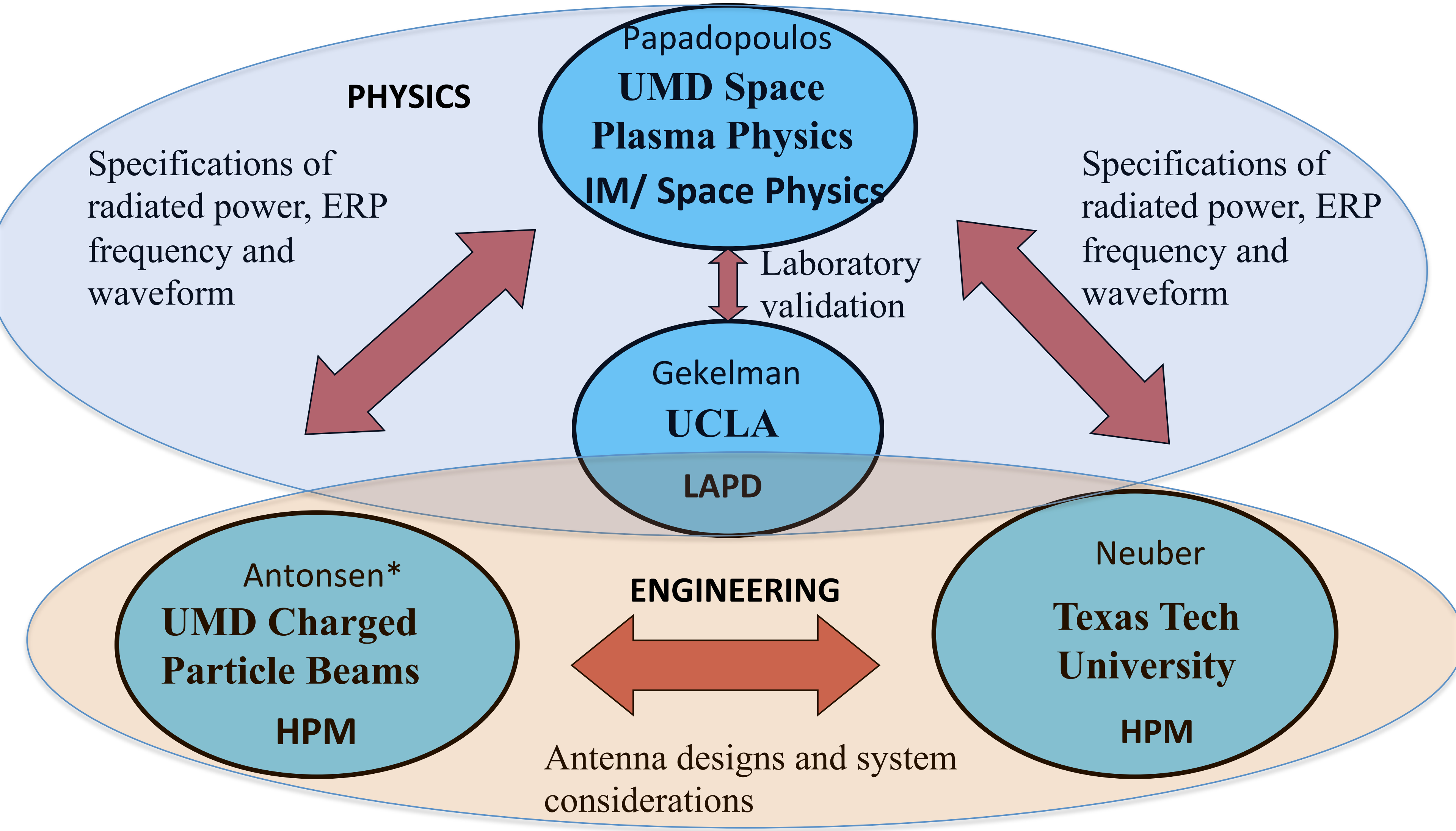
The Challenge

- Utilize new concepts of metamaterials active nonlinear materials operated at high power microwave (HPM) devices to replace the current large collection of sources used in traditional heaters with a single, mobile, and cheap high-power amplifier at the required HF frequencies
- Mobile inexpensive sources will revolutionize the science and operations of ionospheric modification

Objective

- Assemble team of physicist and engineers from space science , ionospheric modification (IM), plasma modeling and HPM to re-examine the coupling of EM energy to the ionosphere under different geomagnetic latitudes and conditions
- Outline research program to :
  - Determine the key properties of the EM source (frequency, ERP, Power, waveform, phase, modulation,..)required to explore EM-Plasma coupling and other the critical physics questions as a function of geomagnetic location and ionospheric conditions
  - Define and design modern, efficient, powerful, tunable EM sources for IM and provide hardware testing under typical university HPM laboratory conditions (vacuum loads and/or anechoic chamber)
  - Develop theoretical tools and framework to design feasibility experiments to demonstrate and test the results of the IM research.

The MURI Consortium - Expertise



* MURI PI

Team Members

UMD SPP

Dennis Papadopoulos
Gennady Milikh
Xi Shao
Alireza Mahmoudian
Bengt Eliasson

Students

Aram Vartanyan
Chris Najmi
Kate Zawdie
Blagoje Djordjevich

Texas Tech

Andreas Neuber
John Mankowski
James Dickens
Joel Perez, technician
Lee Waldrep, machinist

Students

Daniel Mauch,
David Thomas,
Paul Gatewood

UCLA

Walter Gekelmann
George Moralles
Yuhou Wang

UMD CPB

Thomas Antonsen
John Rodgers
Brian Beaudoin
Tim Koeth

Students

Kiersten Ruisard
Dmytro Kashyn

Advisors

Simon London
Irv Haber
Edward Wright

Examples of Investigations

1.

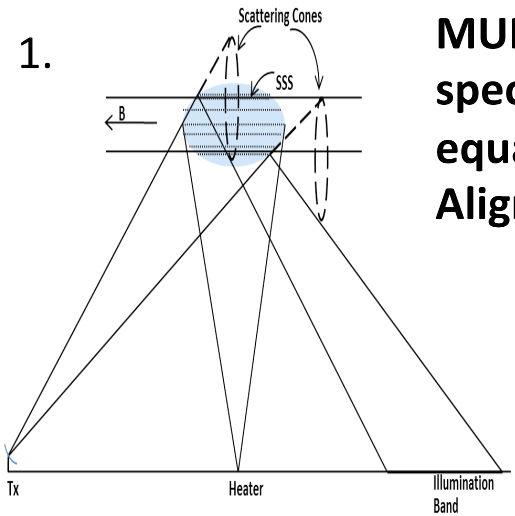
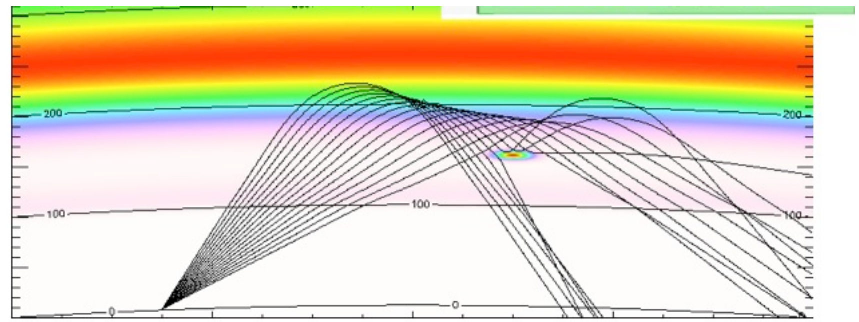


Fig. 1: Schematic of SSS FAS system at GHz.

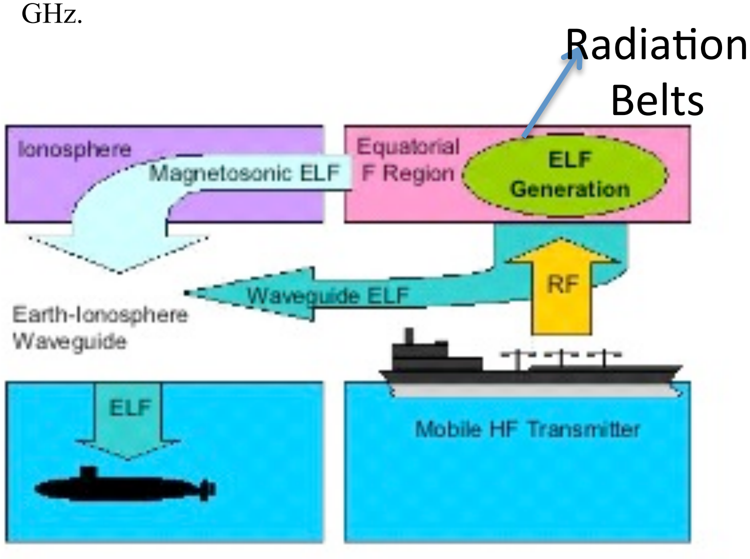
MUF at 1-2 GHz – Learning to control the irregularity spectrum at Super Small Size (few cm) scales at equatorial and mid-latitudes and use it to create Field Aligned Scattering (FAS) mirrors

2.



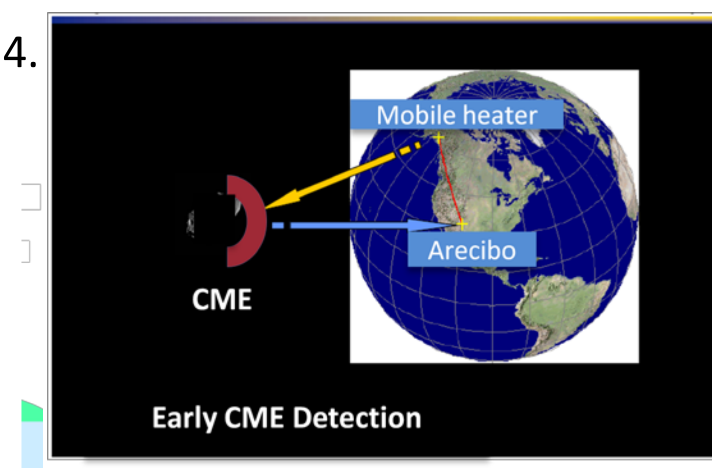
C3 Artificial Ionization

3.



Virtual Antennae in Equator

4.



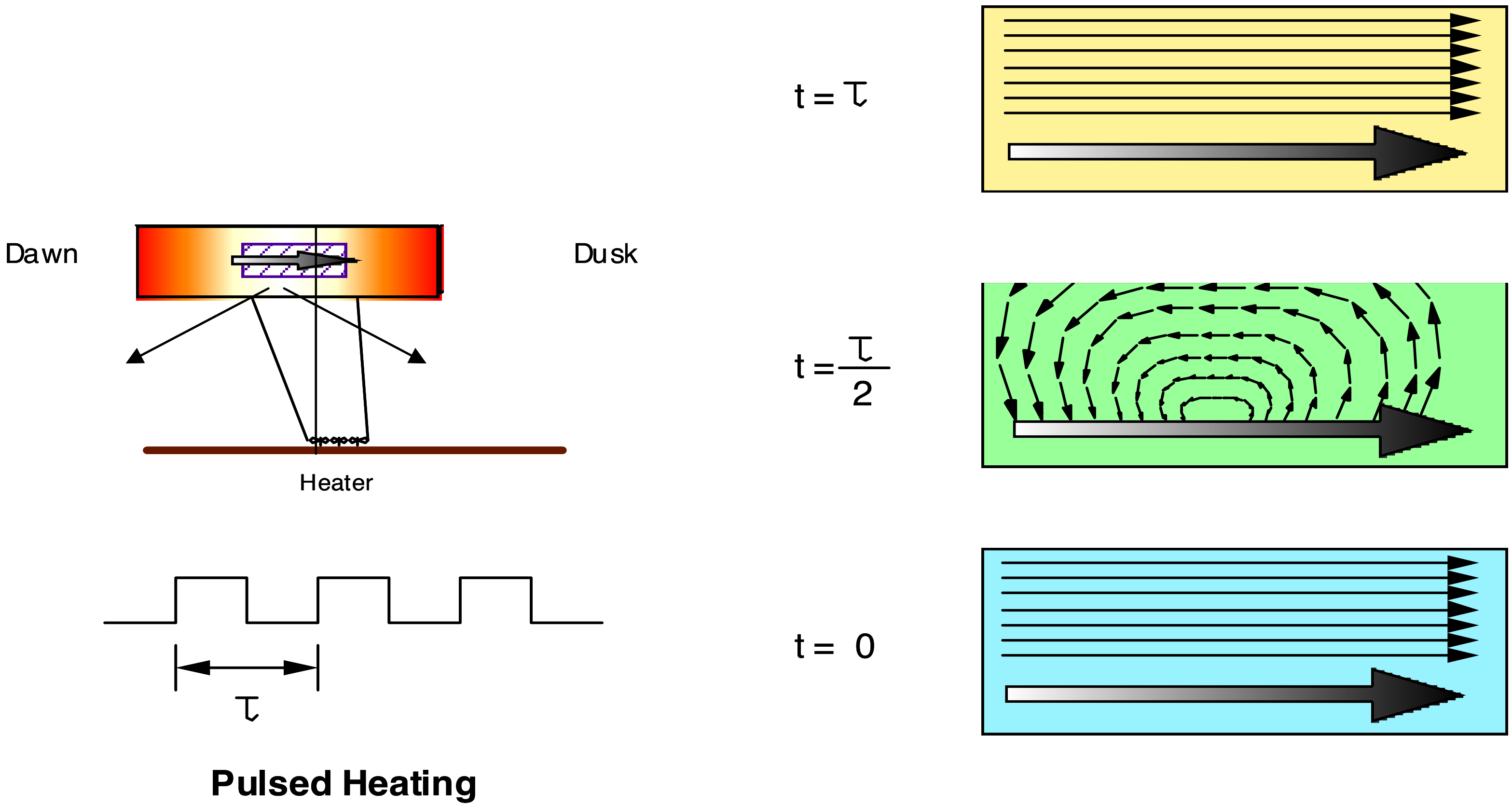
Bi-static Early CME Monitoring

Application	Region	Frequency	Power	ERP	Polarization
Virtual Antenna	Equator	4-10 MHz	>1MW	>75dBW	O,X
FAS SSS clouds for GHz ground-to-ground channel	Equator Mid latitude	4-12 MHz	>2 MW	>85dBW	
Artificial Plasma Layers	Mid latitude	4-12 MHz	>2 MW	>85dBW	O, X
CME detection	Mid-latitude	10-30MHz	>2 MW	>85dBW	O
Substorm effects	Polar	4-8 MHz	>2 MW	>80dBW	O, X

UMD SPP Objectives

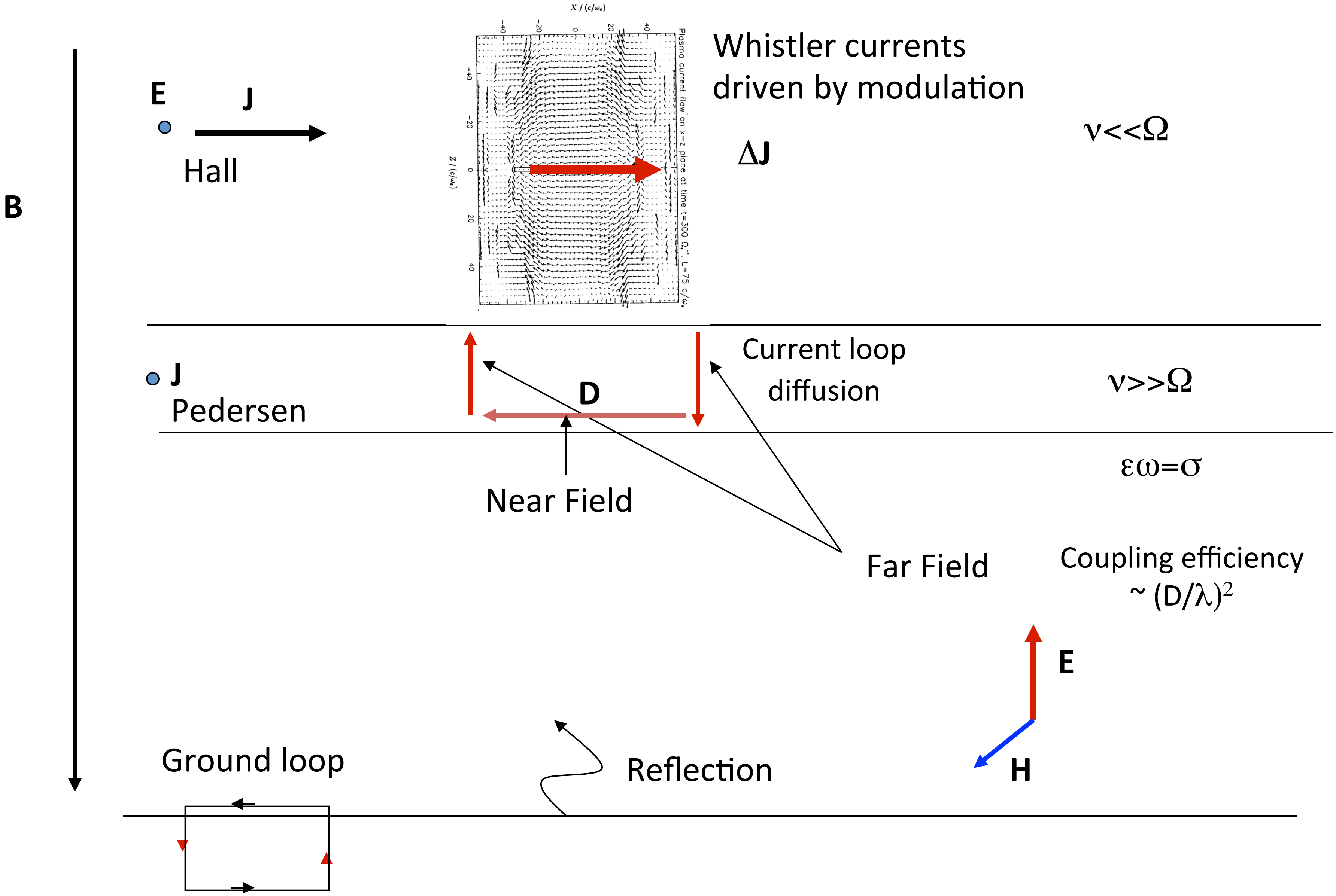
- **Identify and Explore the Ionospheric Modifications (IM) Physics Areas impacting the design of Mobile Ionospheric Heating sources (MIHs) where**
  - **No heating experiments were performed (e.g. equatorial regions)**
  - **Heating experiments were performed using low power heaters (e.g. mid-latitude)**
  - **Important new high latitude experiments with incomplete or controversial understanding (e.g. artificial ionization)**
  - **New concepts requiring mobile sources (e.g. monitor Coronal Mass Ejections)**
- **Design and, in collaboration with UCLA, conduct PoP experiments of the new physics concepts**
- **Collaborate with the Arecibo, HAARP, SURA and EISCAT experimental programs**
- **Provide design input to the source development teams**

Principle of ELF Generation



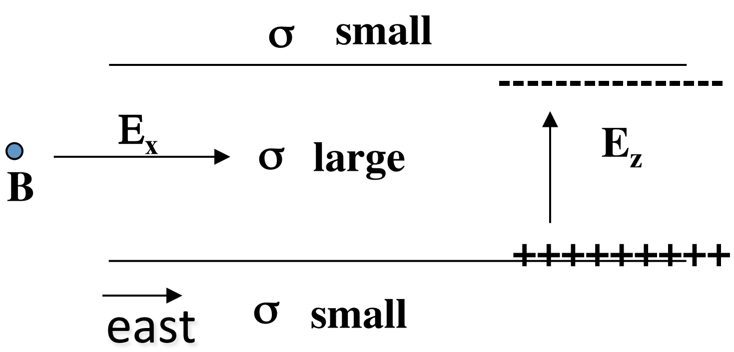
BAE SYSTEMS

AURORAL MAGNETIC GEOMETRY



Electric Field and Current Structure in the Dip Equator

BAE SYSTEMS



σ_P conductivity along E (Pedersen)

σ_H conductivity across E and B (Hall)

$E_x \sim .5\text{-}.7$ mV/m

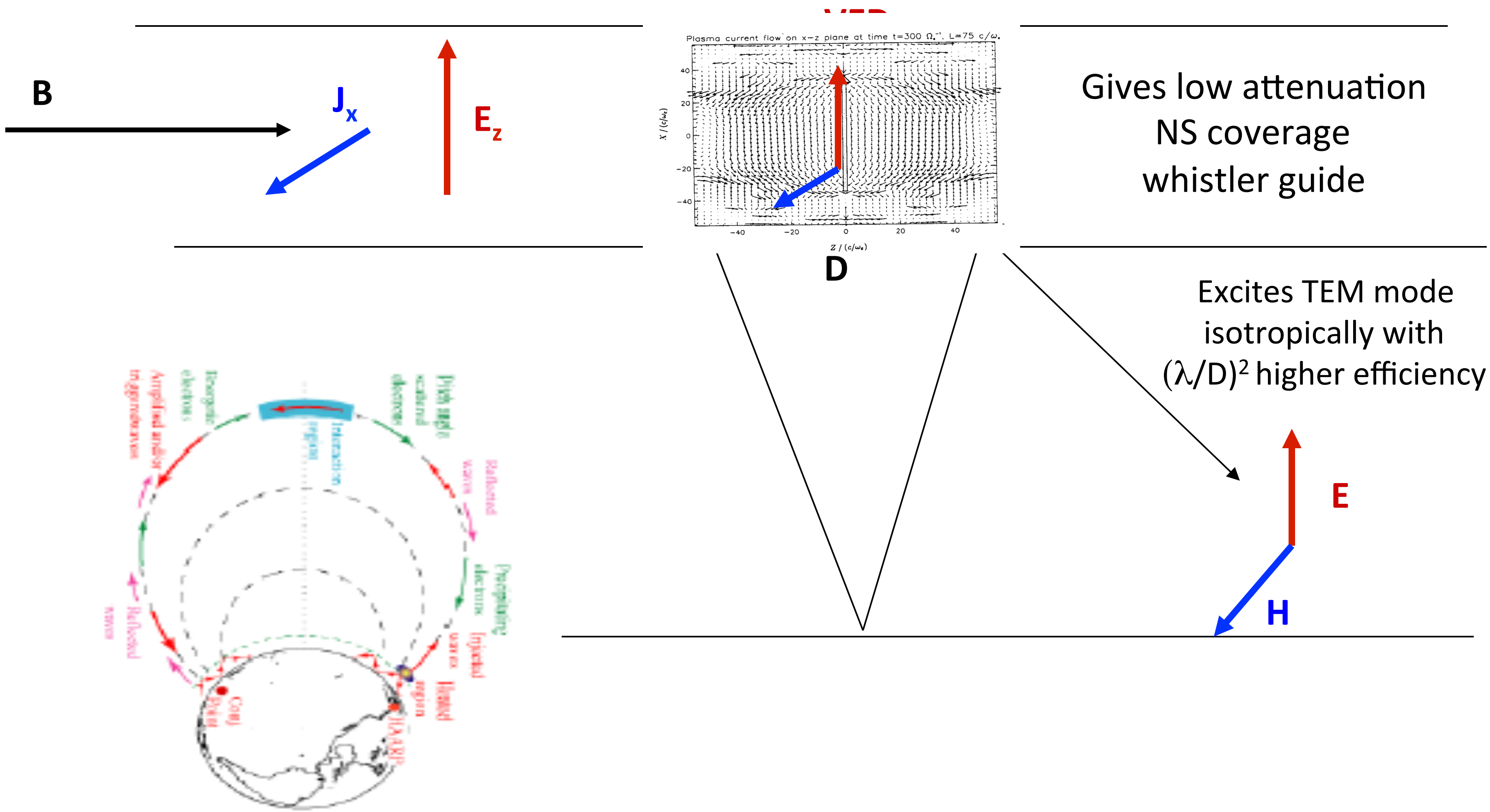
$j_z = -\sigma_H E_x + \sigma_P E_z = 0$

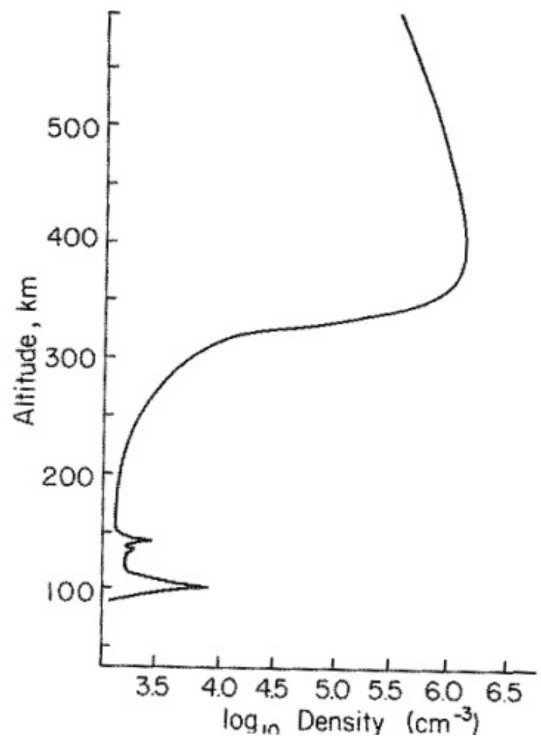
$E_z = (\sigma_H/\sigma_P)\, E_x$: for $(\sigma_H/\sigma_P) = 20$ field amplification, $E_z = 10\text{-}15$ mV/m

$j_x = \sigma_c E_x$, eastward j_x known as COWLING current
$\sigma_c = [(\sigma_H/\sigma_P)^2 + 1]\, \sigma_P$ -> COWLING conductivity

Typical equatorial structure has a Cowling current j_x of 8-12 A/km^2 and a vertical electrical field of 10-15 mV/m

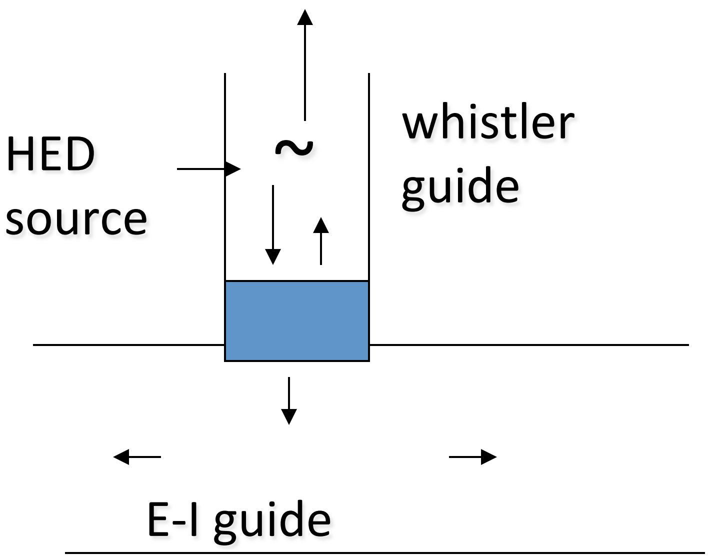
Equatorial ELF/VLF Generation and Propagation



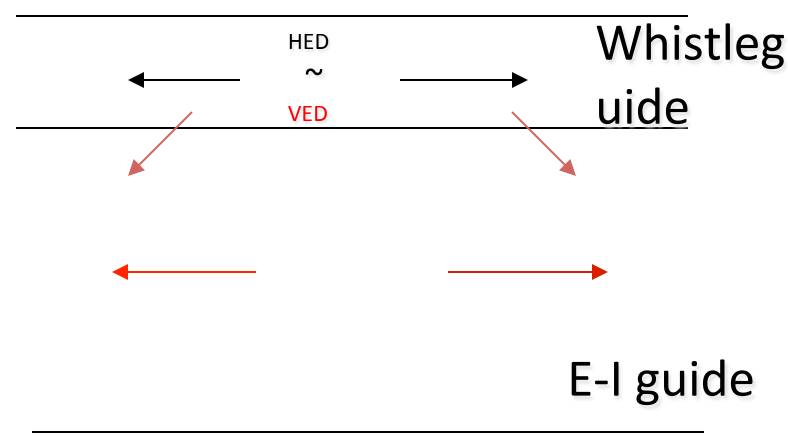

500
400
300
200
100
Altitude, km
3.5
4.0
4.5
5.0
5.5
6.0
6.5
log10 Density (cm-3)

Equatorial vs. Auroral ELF/VLF Source

Engineering Equivalents



Auroral, T- guide



Equatorial, Coupled-guides

Other Advantages of Equatorial ELF/VLF

BAE SYSTEMS

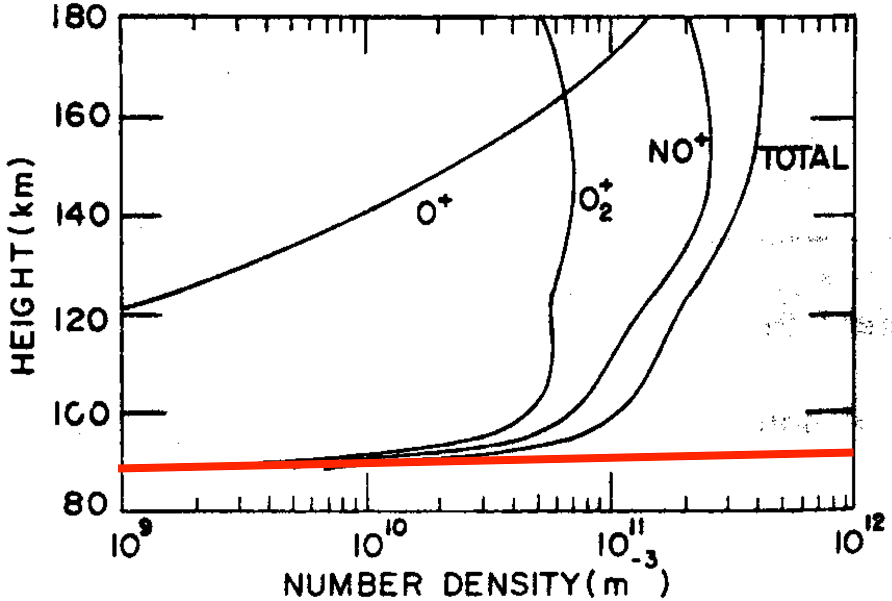


Fig. 27. Vertical profiles of positive ion composition for noontime uatorial equinox conditions and average solar activity. (Figure is om *Forbes* [1975].)

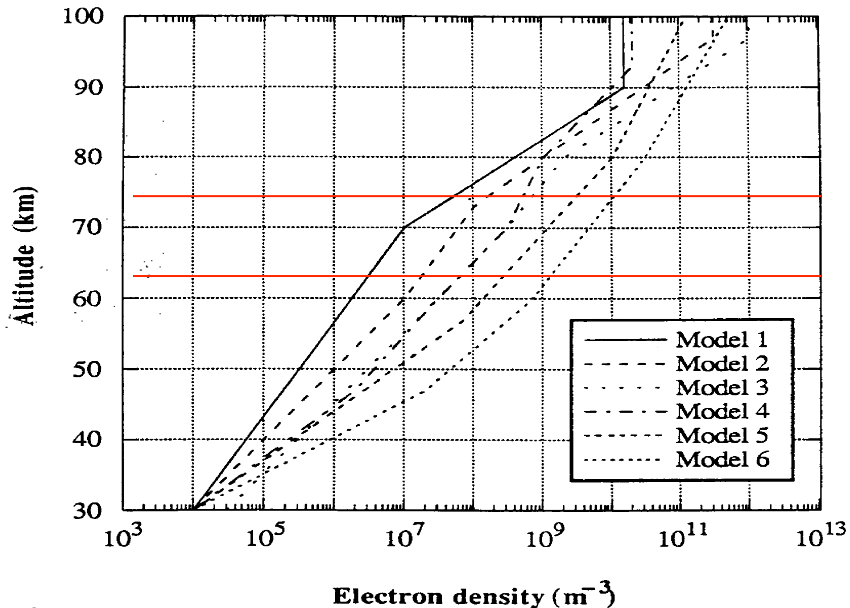
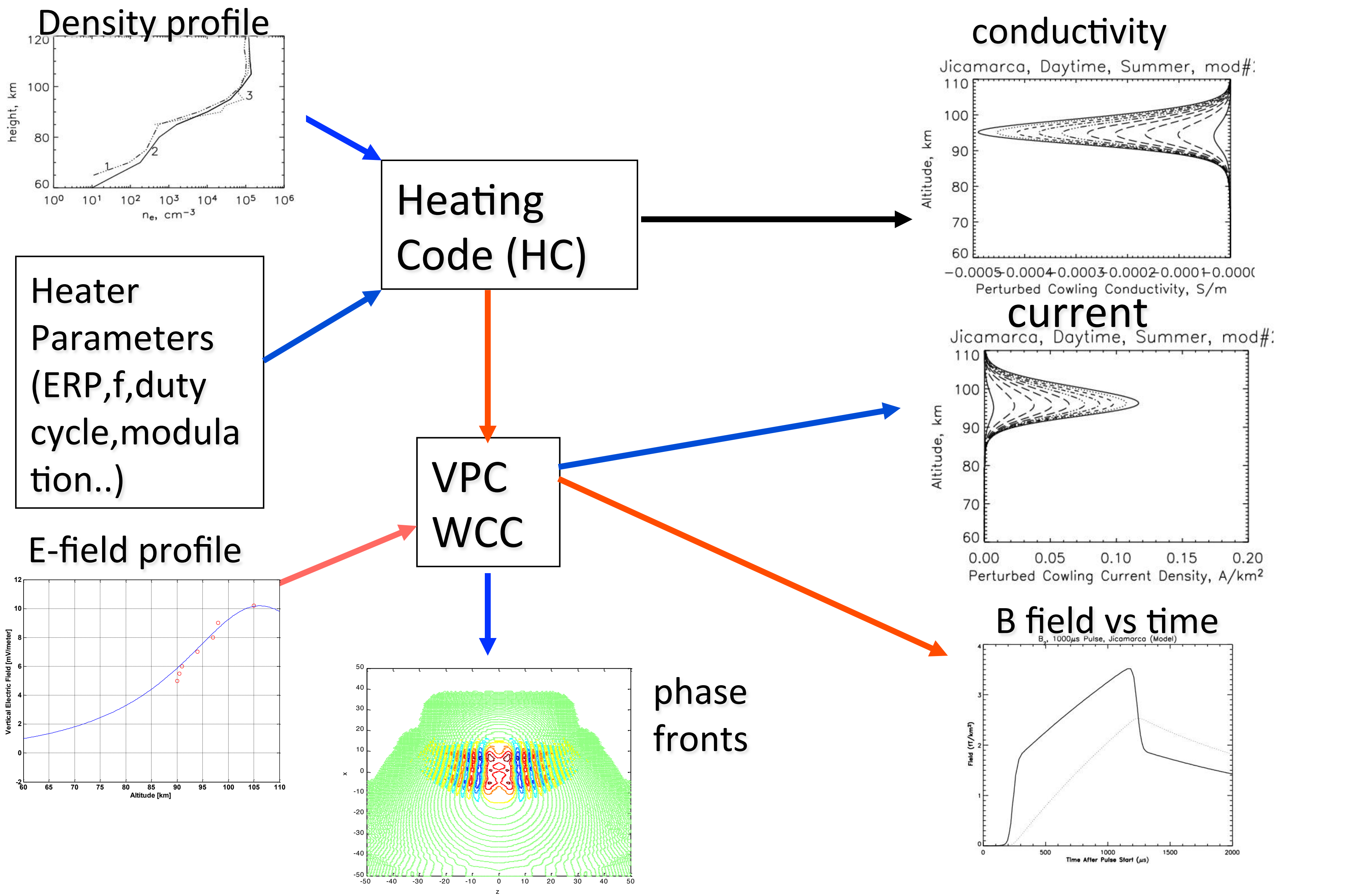


Figure 3-9 (U) Electron Density Profiles from [Barr and Stubbe, 1984]

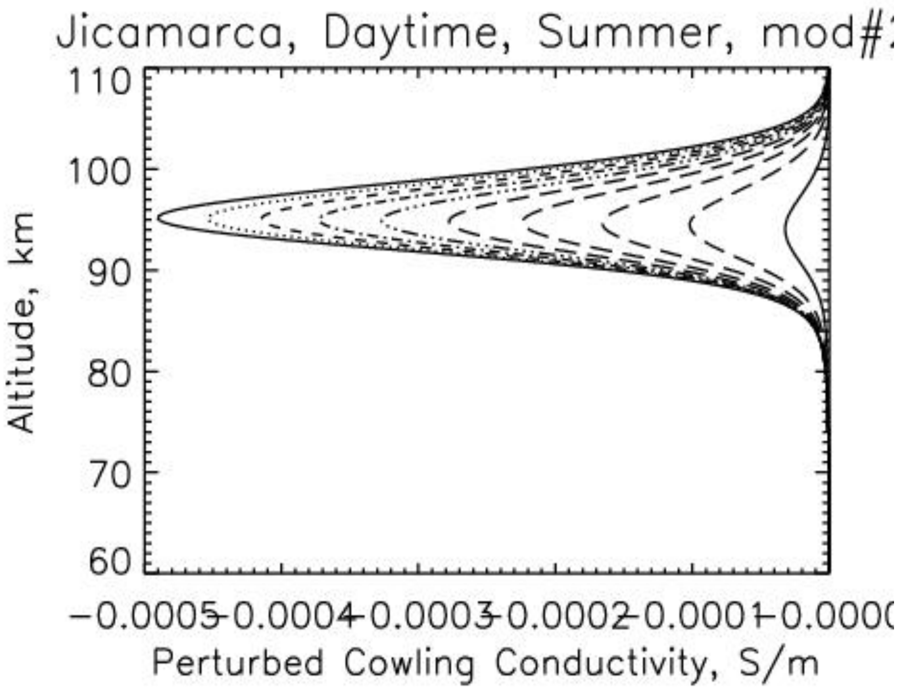
- SMALL SELF ABSORPTION FOR HF
- WAVE-GUIDE TOP AT HIGHER ALTITUDE
  - BETTER INDUCTIVE COUPLING TO WAVE-GUIDE
  - NO ELF/VLF ABSORPTION

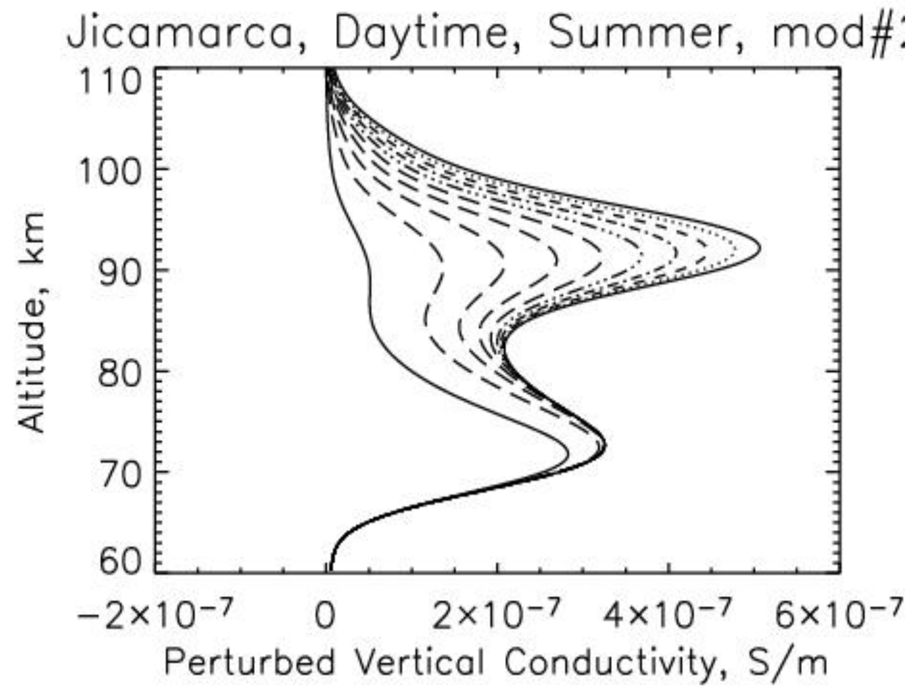
Equatorial Model



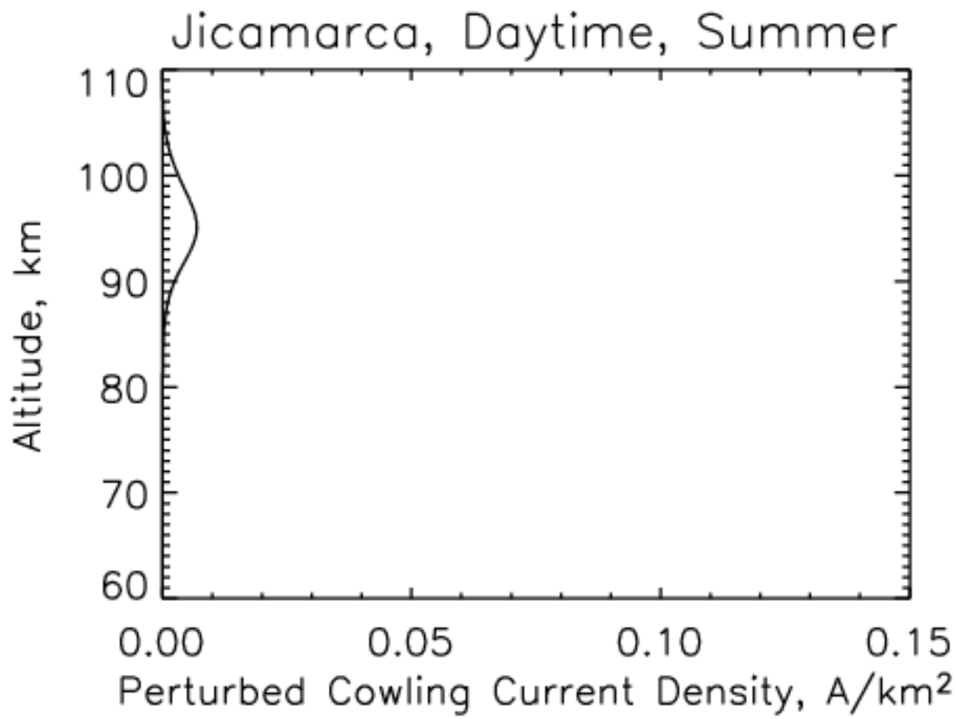
BAE SYSTEMS

Conductivity Perturbation

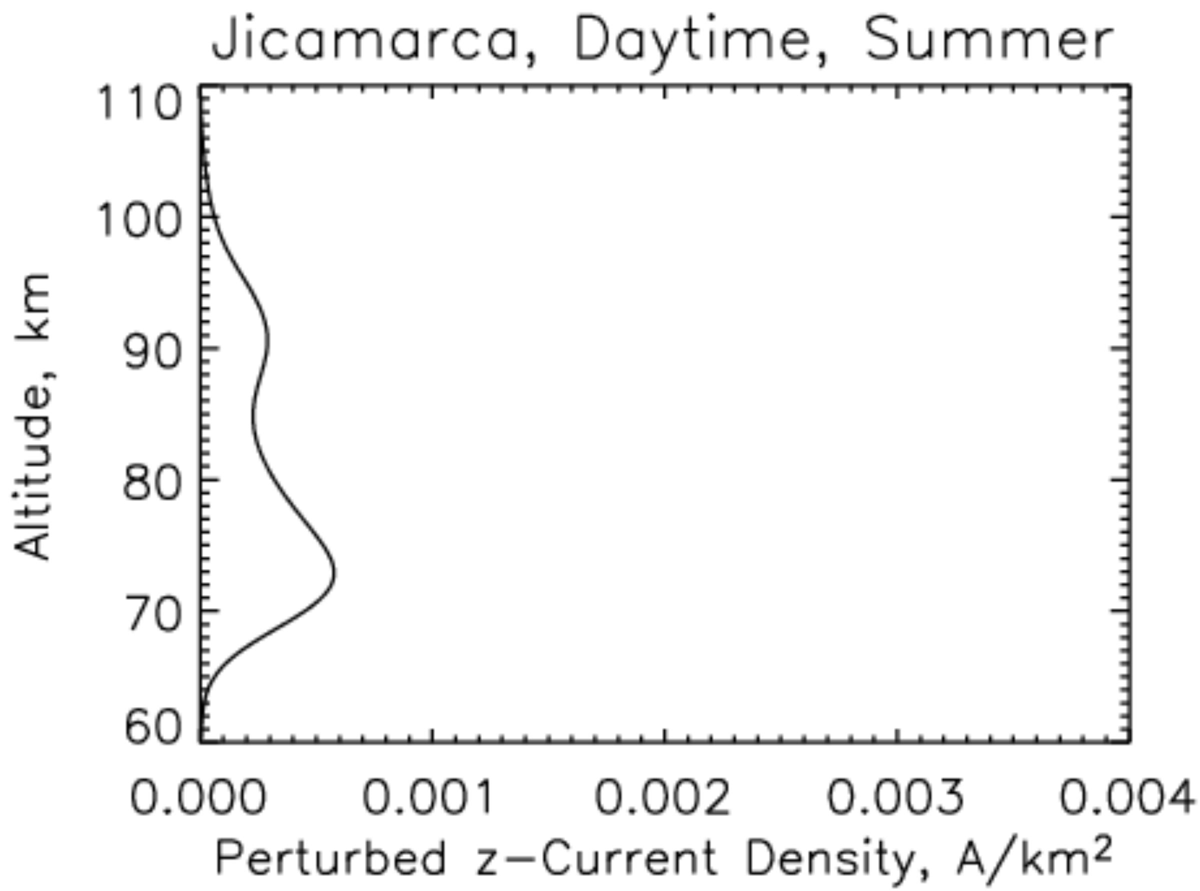




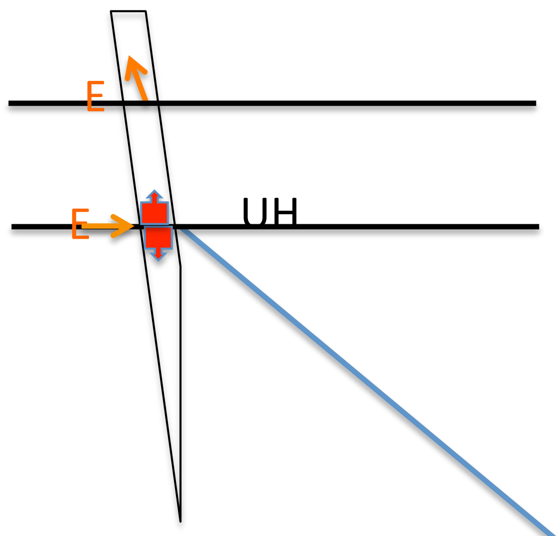
Evolution of Horizontal Current

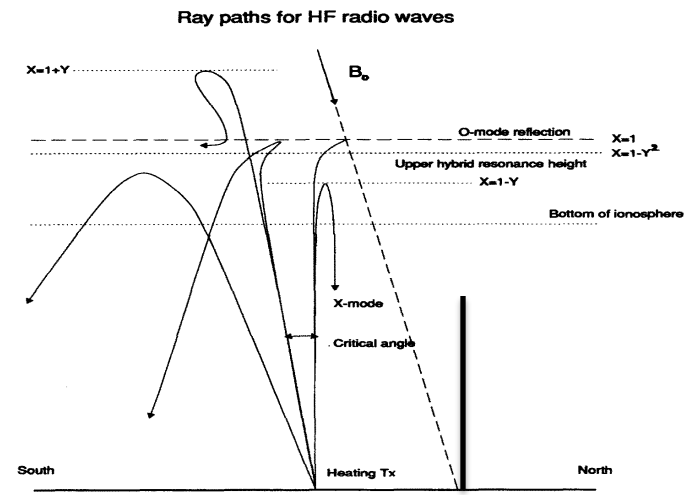


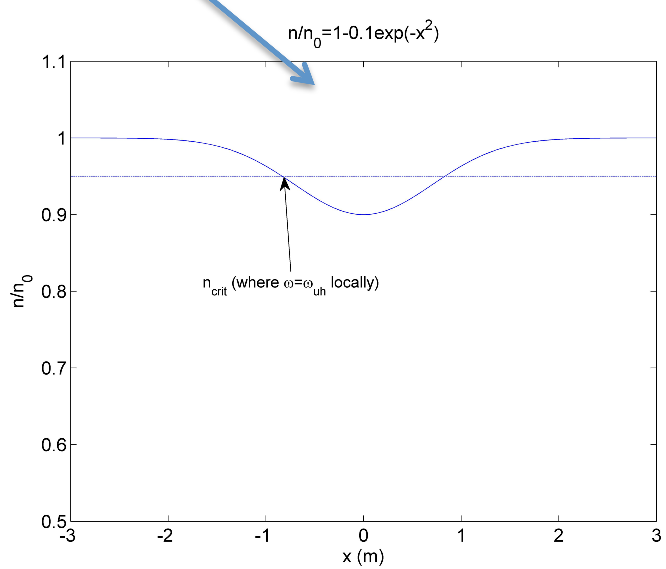
Evolution of Vertical Current

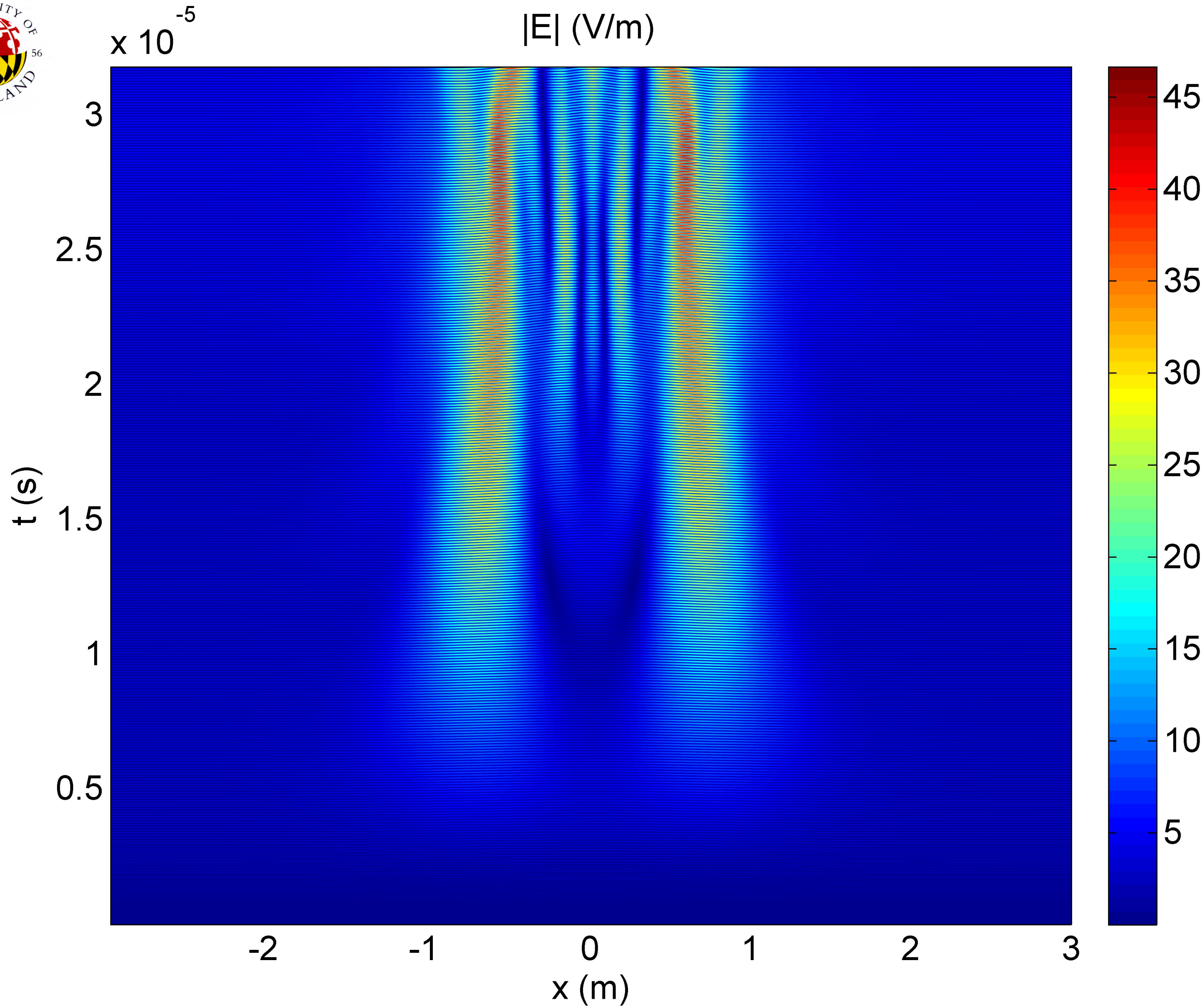


UPPER HYBRID – ELECTRON HEATING – AIT Modeling



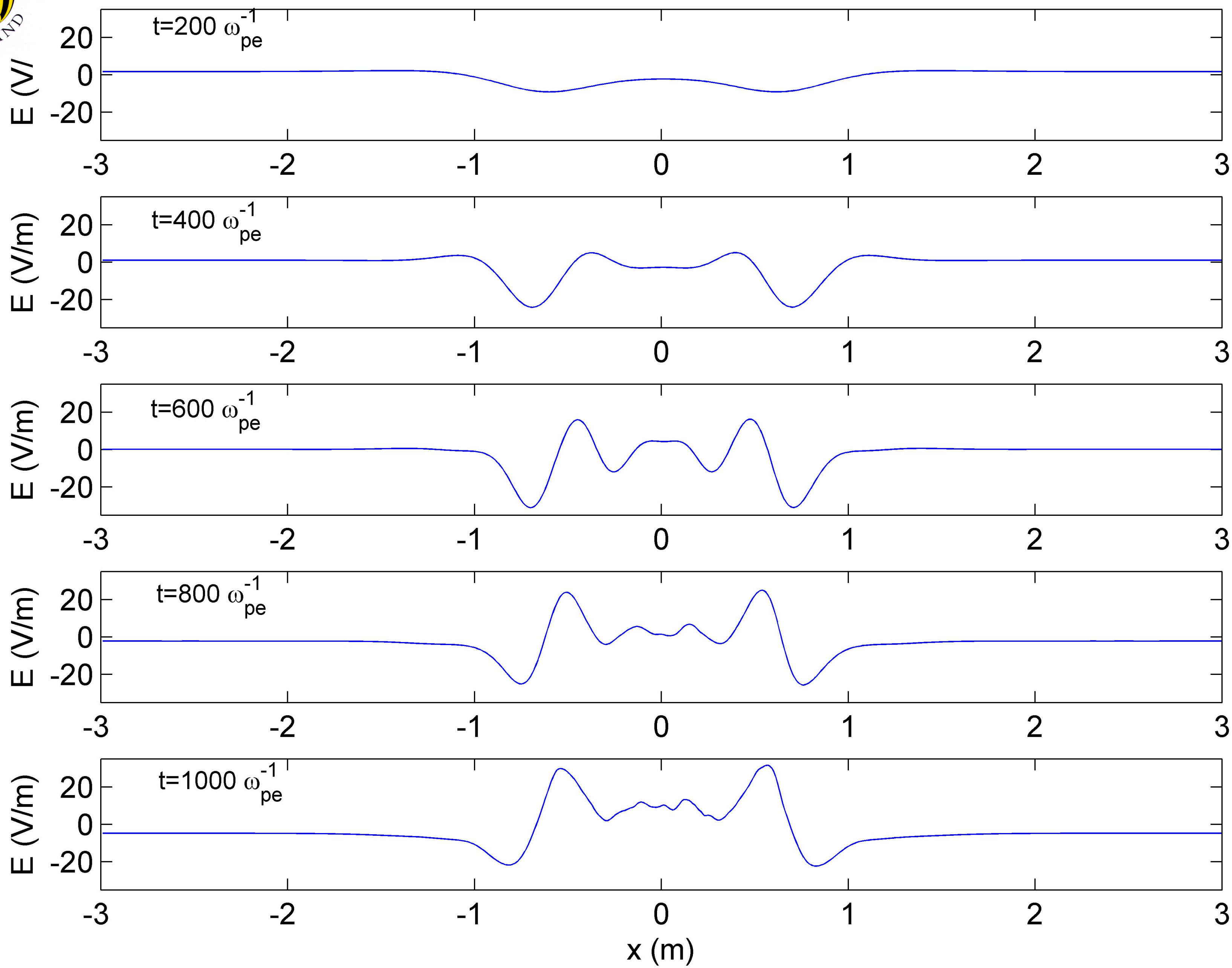


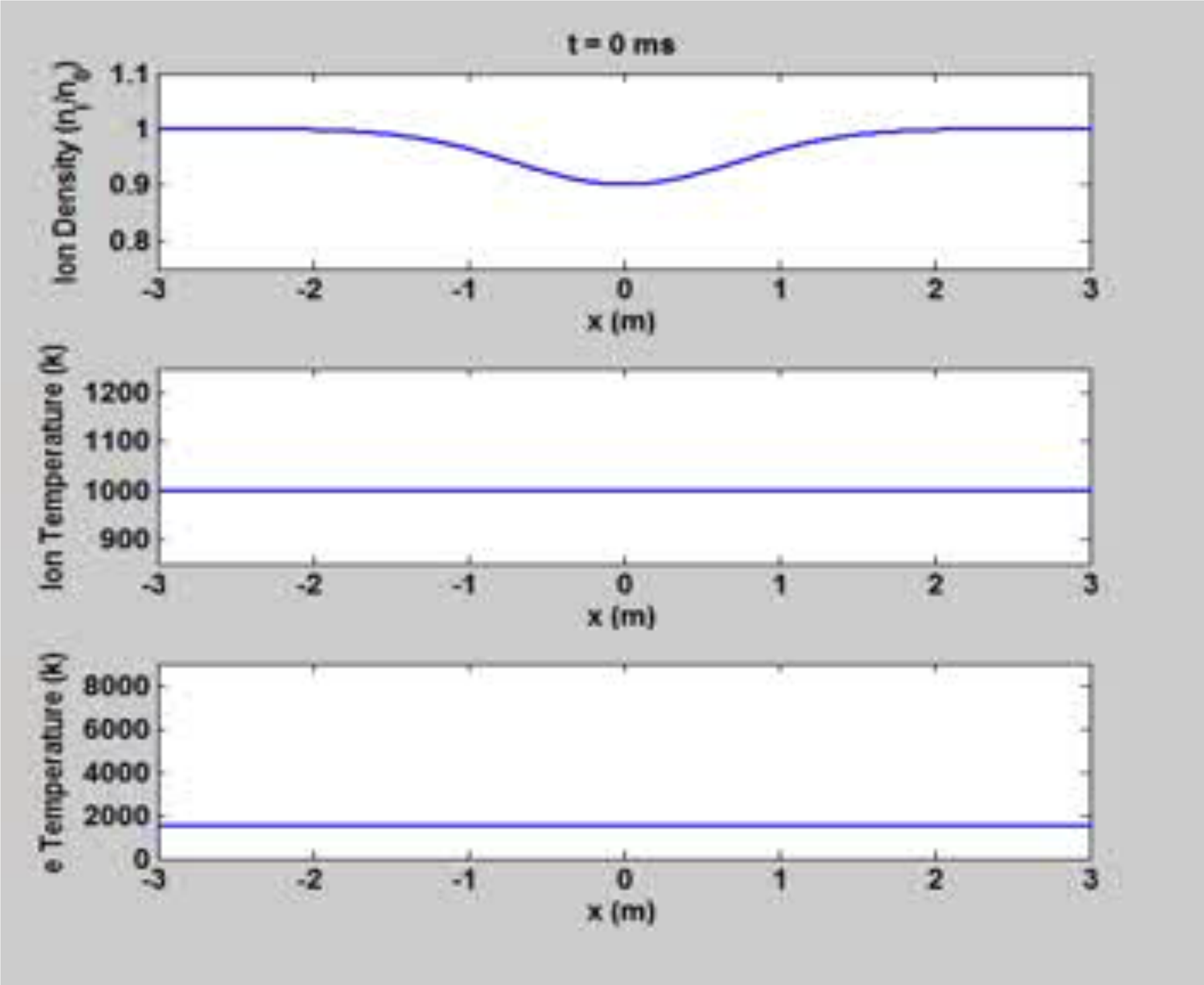


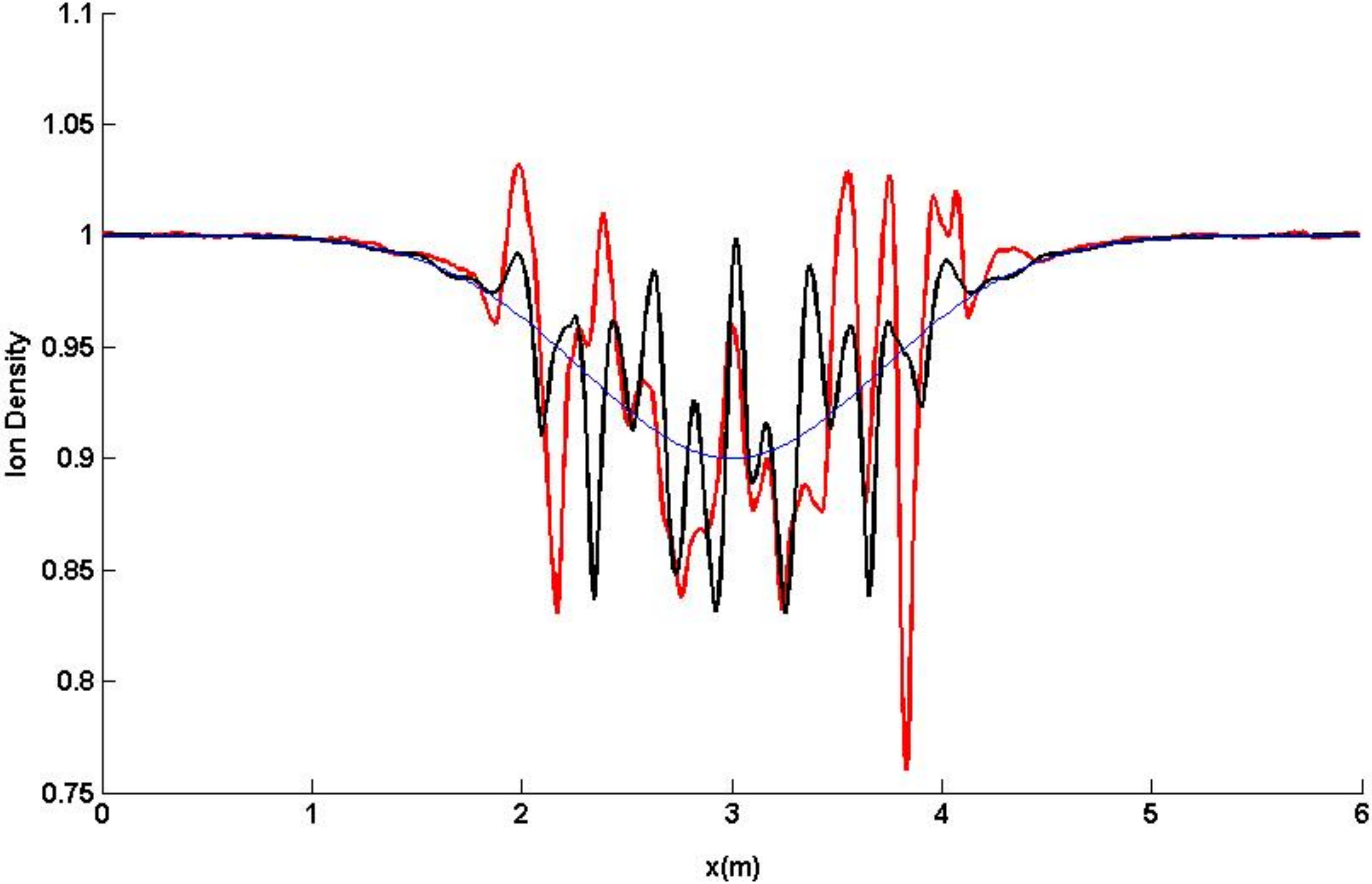


x 10^-5
|E| (V/m)
t (s)
3
2.5
2
1.5
1
0.5
-2
-1
0
1
2
3
x (m)
45
40
35
30
25
20
15
10
5

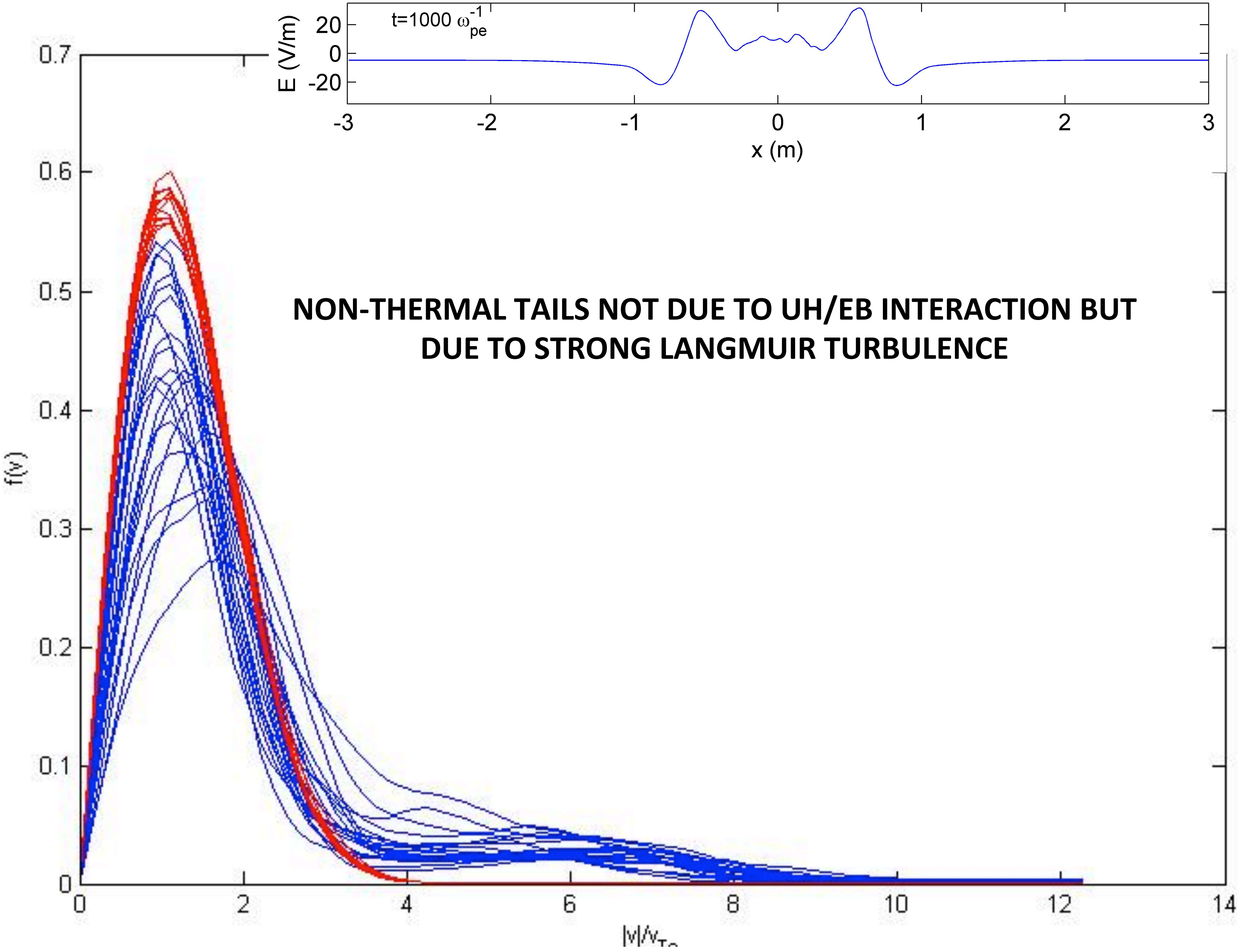
ω_{pe}=31.4×10^{6} s^{-1}, ω_{ce}=0.248ω_{pe}, ω_{UH}=1.030ω_{pe}, ω=1.004ω_{pe}

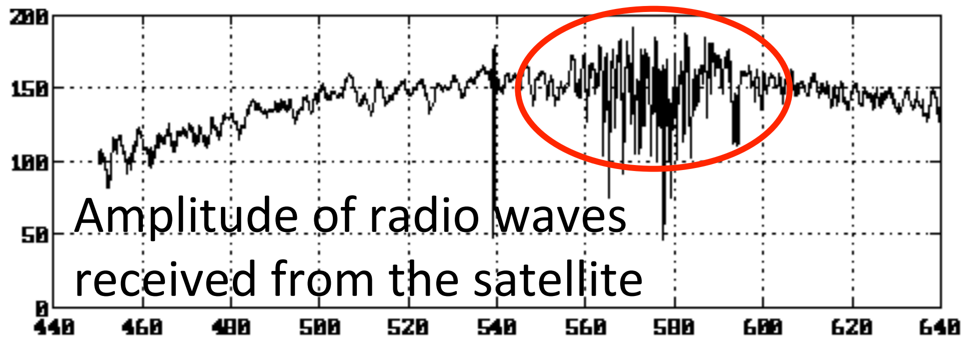


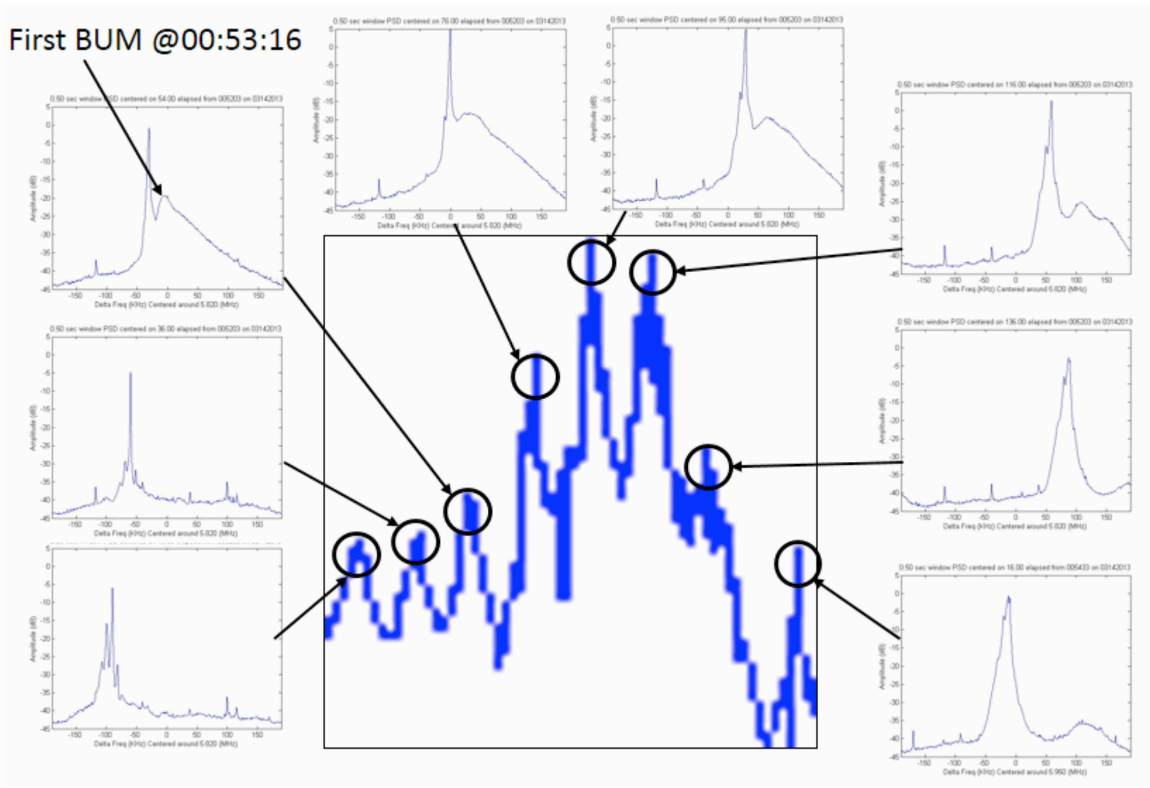

t = 0 ms
Ion Density (n_i/n_0)
1.1
1
0.9
0.8
-3
-2
-1
0
1
2
3
x (m)
Ion Temperature (k)
1200
1100
1000
900
-3
-2
-1
0
1
2
3
x (m)
e Temperature (k)
8000
6000
4000
2000
0
-3
-2
-1
0
1
2
3
x (m)


1.1
1.05
1
0.95
0.9
0.85
0.8
0.75
Ion Density
0
1
2
3
4
5
6
x(m)

NON-THERMAL TAILS NOT DUE TO UH/EB INTERACTION BUT DUE TO STRONG LANGMUIR TURBULENCE




200
150
100
50
0
440
460
480
500
520
540
560
580
600
620
640
Amplitude of radio waves
received from the satellite


First BUM @00:53:16

FRANZ ET AL.: RADAR SCATTERING FROM FIELD-ALIGNED IRREGULARITIES

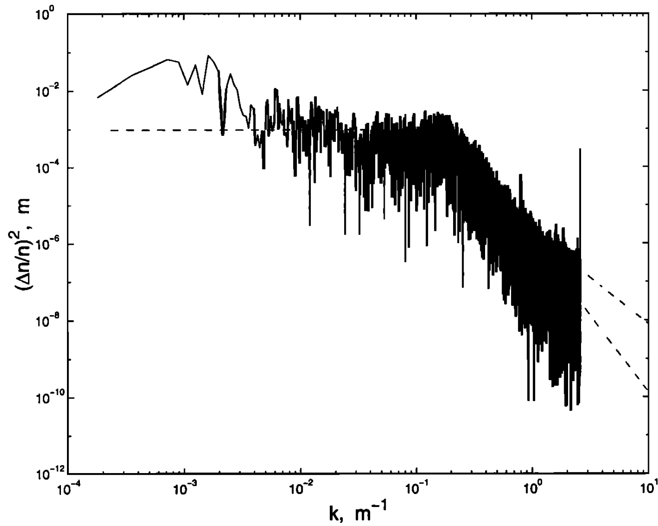


Figure 2. The $k_\perp$ spectrum of the data plotted in Figure 1. The dashed line superimposed on the $k_\perp$ spectrum is our model (equation (1)). This figure has been corrected for an error in perpendicular velocity used in a similar figure by *Kelley et al.* [1995].

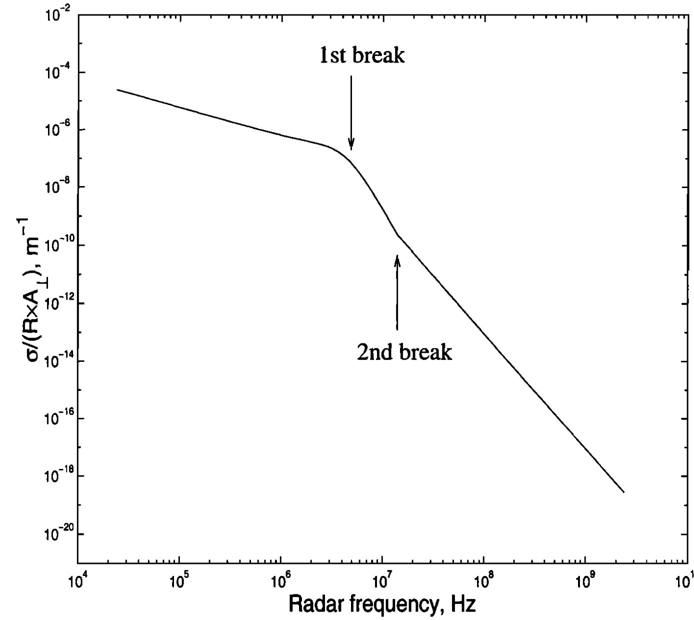
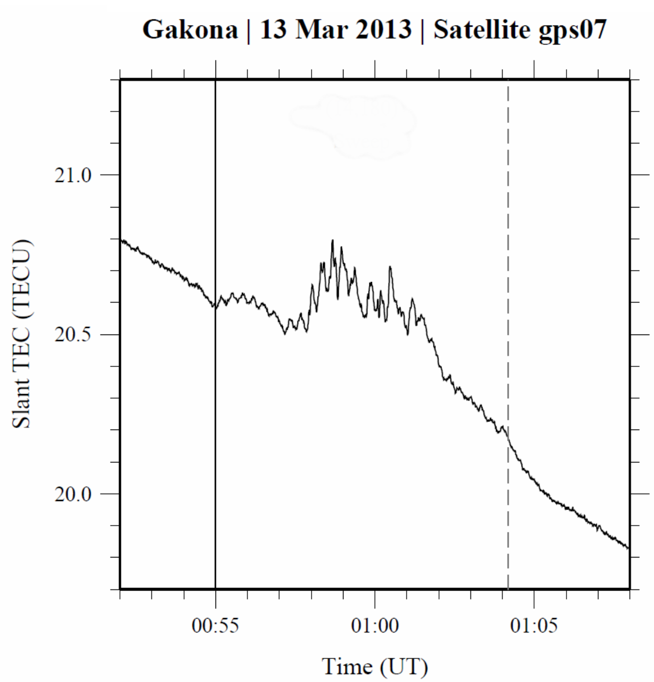


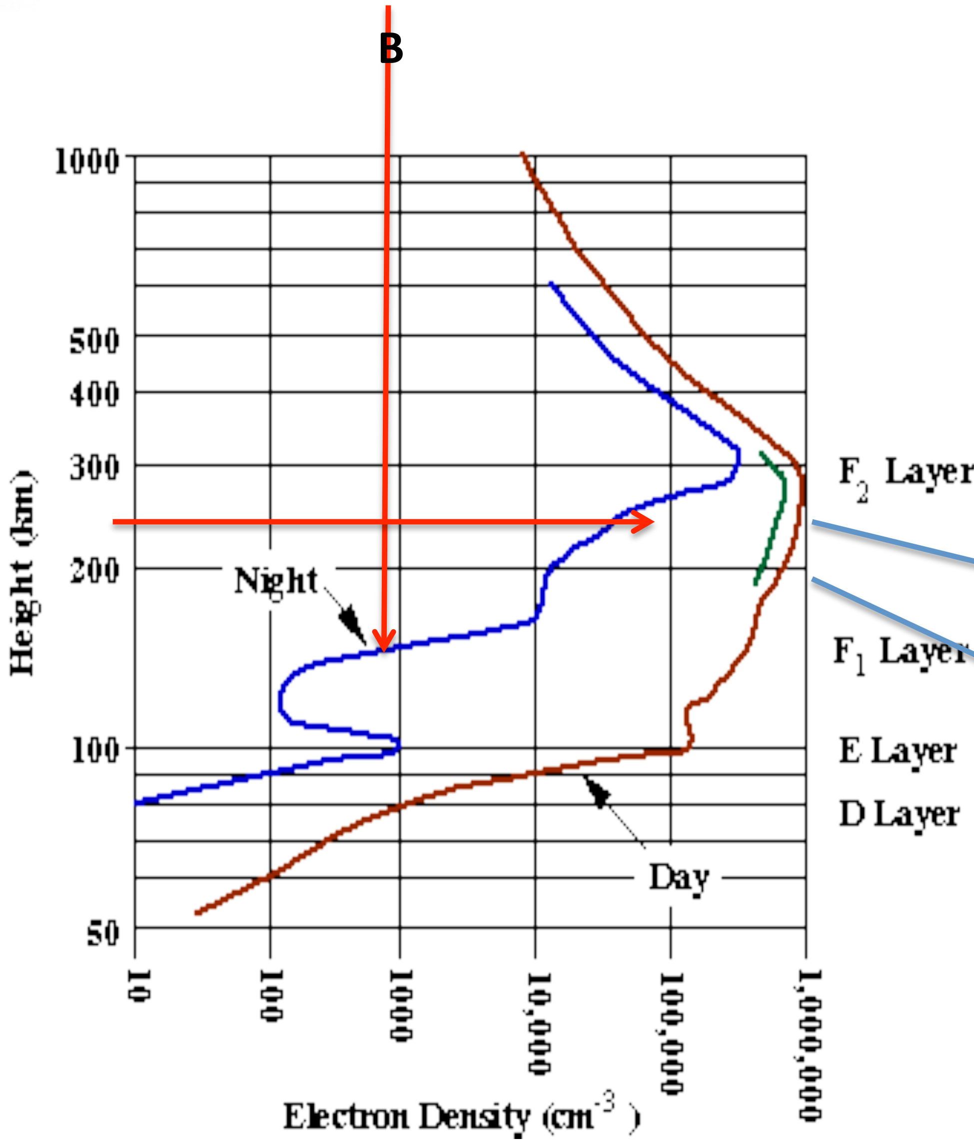
Figure 3. A prediction of the scattering cross section for infinitely field-aligned irregularities. The cross section has been normalized to $A_\perp$ and R where $A_\perp$ is the radar volume projected onto the plane perpendicular to **B** and R is the range to target.

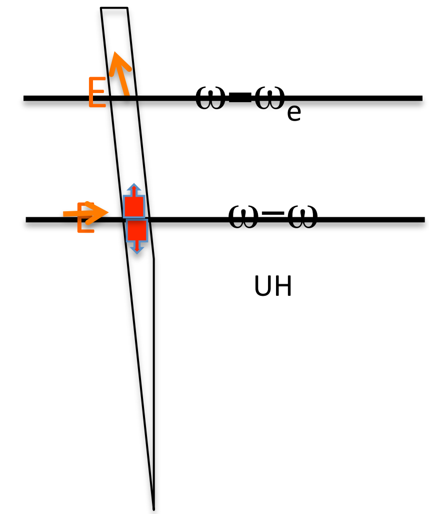


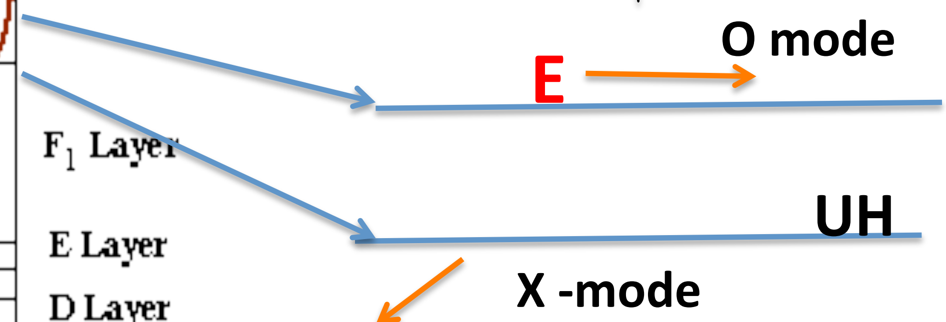
STEC:

- L1/L2 ~1.2->1.6 GHz
- λ~ 18-20cm
- Striations < λ /2 scatter STEC

Equator vs. Auroral latitude



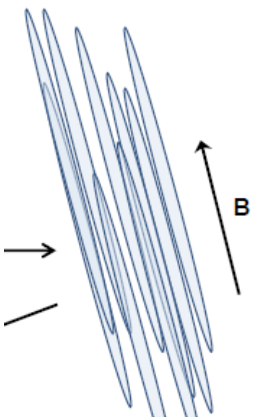




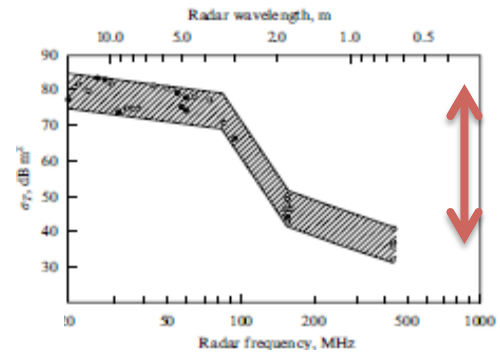
Mapping of High Latitude to equatorial processes

Propagation, Resonances, Thresholds, UH turbulence, Bernstein modes, Ionization, Structure, Parametric Instabilities

Raising MUF to GHz



Platteville FAS:



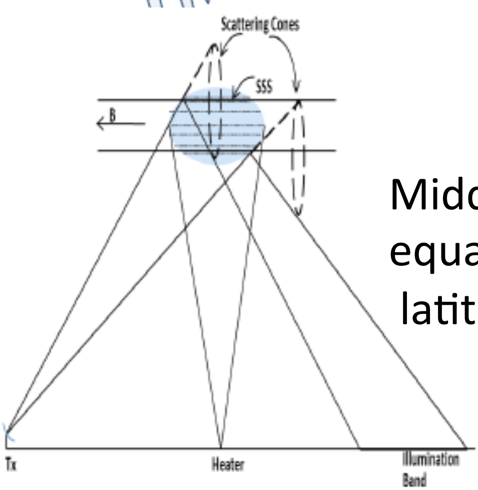
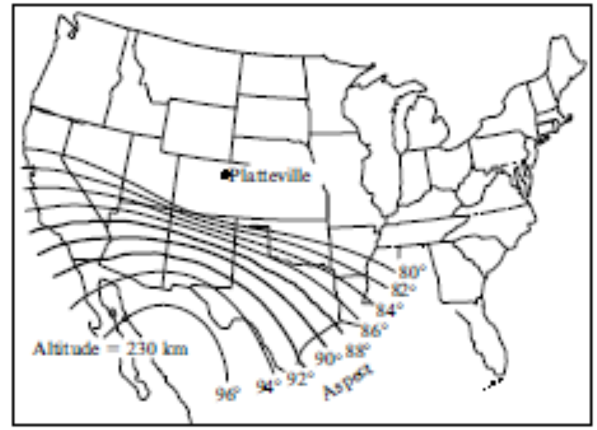


Fig. 1: Schematic of SSS FAS system at GHz.

Middle or equatorial latitude



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

Combining lab exp with modeling

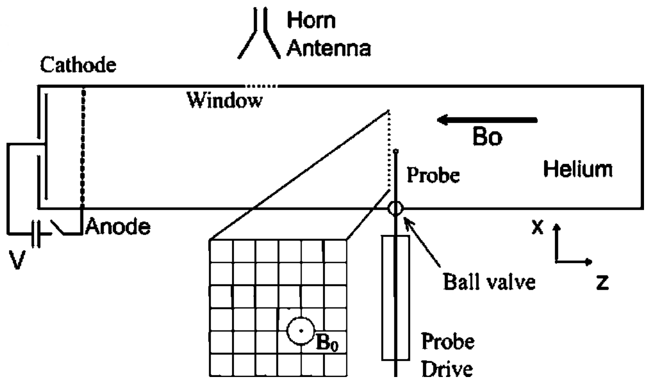


FIG. 1. Schematic of the experimental setup (not to scale). The plasma is formed by a pulsed discharge ($I_d \approx 3.5$ kA) between the anode and cathode which are 52 cm apart. The plasma has a duration of 10 ms, is reproducible and pulsed at 1 Hz. The probe drive moves probes to each point on the preprogrammed planar x-y grid, and can be positioned at different axial locations. Microwaves are launched into the radial density gradient, across the background field $\mathbf{B}_0$. The center of the plasma is optically thick to the microwaves.

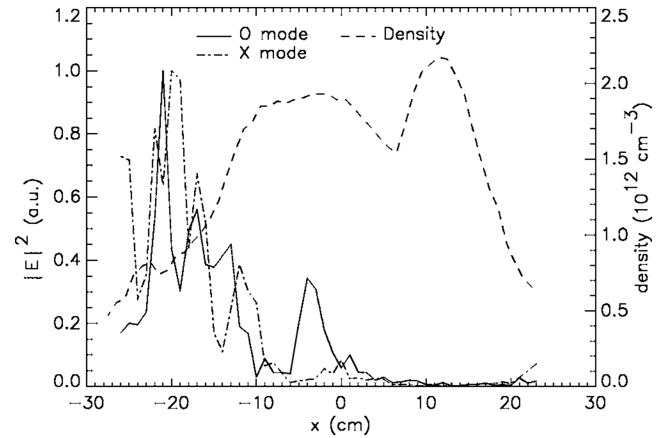


FIG. 5. Radial profile of $|E|^2$ for the O mode and X mode, at 1.5 kG. The density profile is overplotted. These radial profiles were used to obtain the location of the peak $|E|^2$ with respect to plasma density, as displayed in Figs. 6 and 7.

Van Campenolle et al., 2006

O vs. X scaling in accelerated electrons which Cerenkov emitted Alfven waves

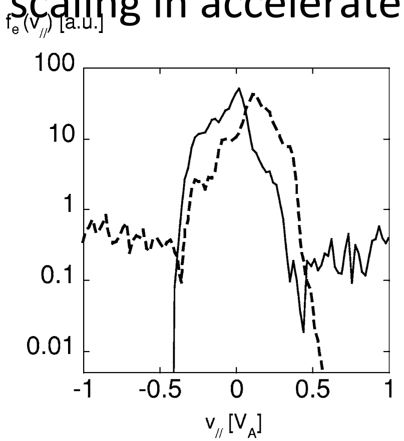
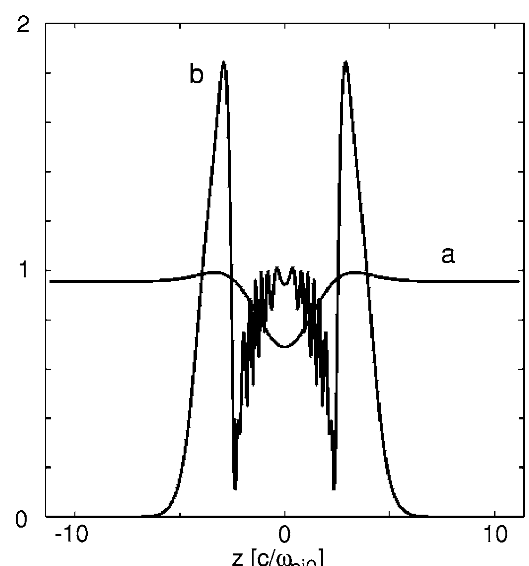
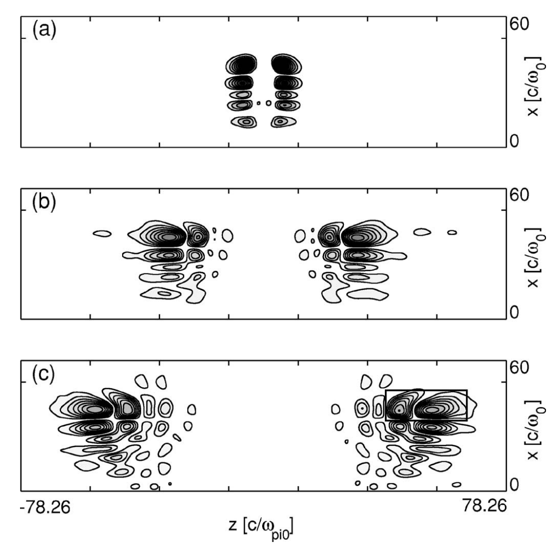


FIG. 5. Parallel (z direction) velocity distribution function (logarithmic scale) of electrons at position $x=31c/\omega_0$ indicated by the dashes in Figs. 4(b) and 4(c). Dashed curve is for $z=-4.47c/\omega_{pi0}$ and solid for $z=4.47c/\omega_{pi0}$. The distribution functions exhibit bulk heating and fast tails. The bulk particles experience a net drift that provides a return current.



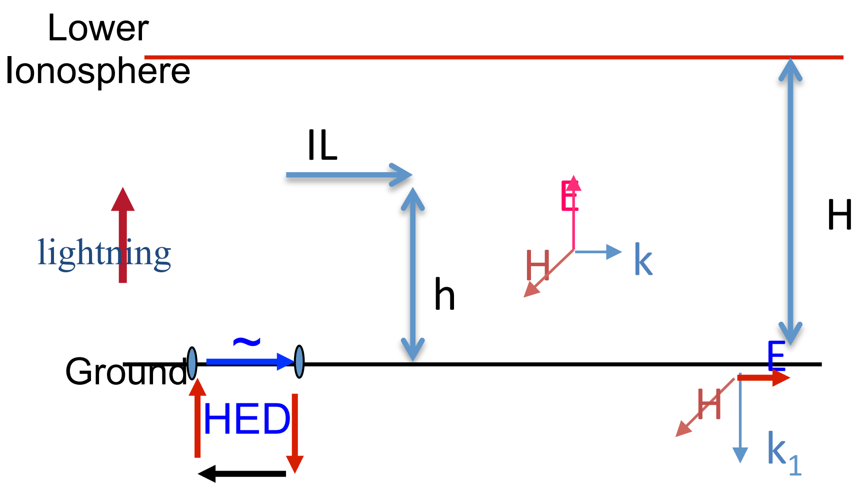


Simulations Tsung et al. 2007

FRONTIER IM TOPICS
VIRTUAL ANTENNAE AT ELF/VLF

WHY?

Return Current Problem



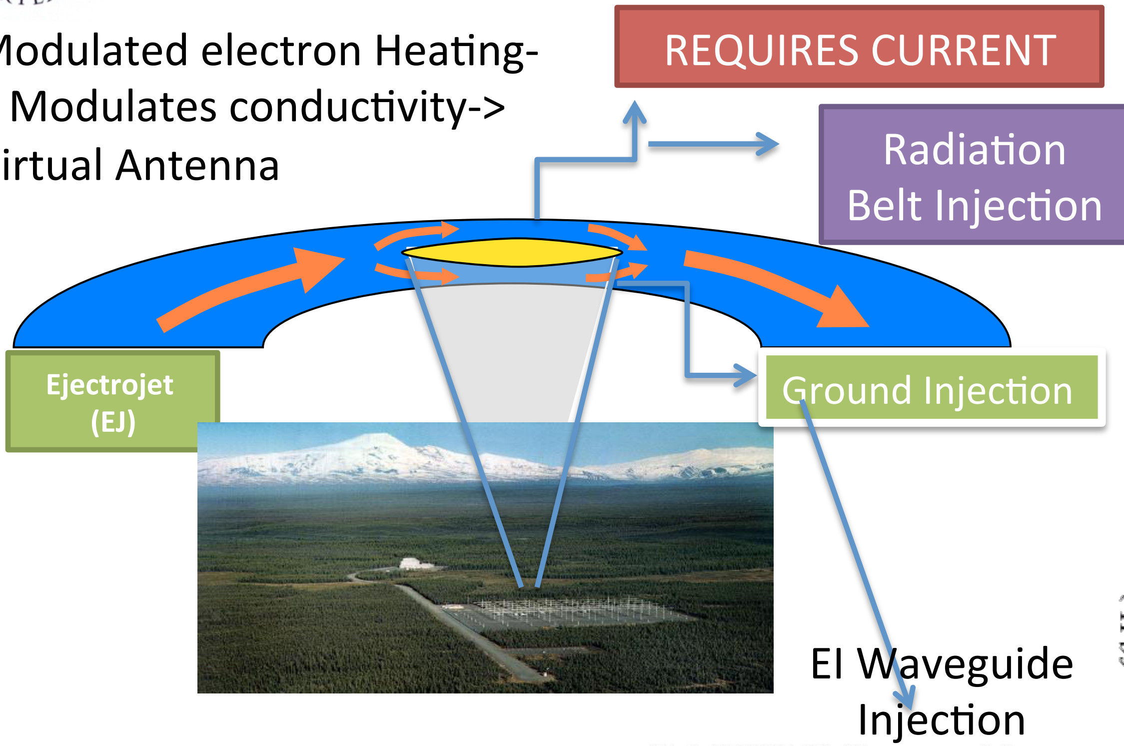
$M \approx IL(\delta/H)$

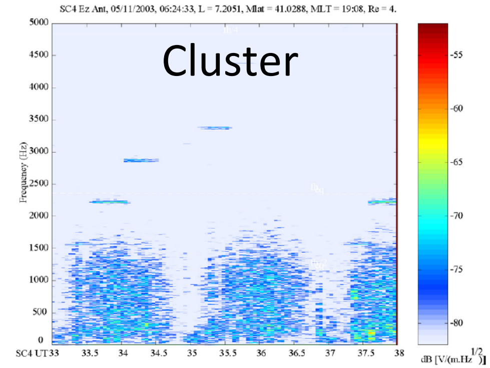
$\mathbf{M \approx IL(h/H)} \quad \mathbf{h >> \delta}$

Virtual Antenna: Drive currents on the top of the ionosphere

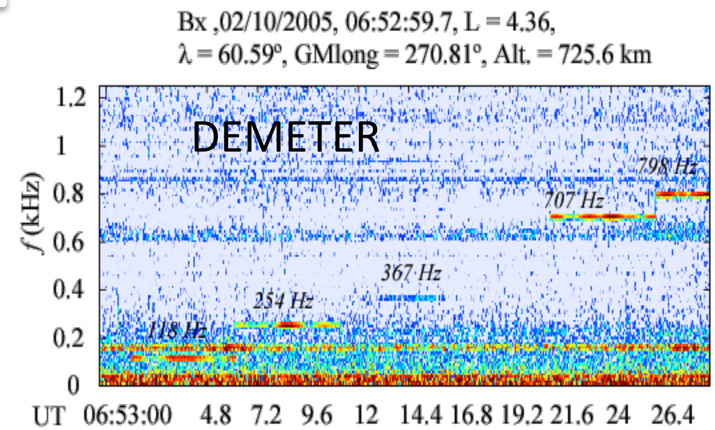
VIRTUAL ANTENNA - CURRENT MODULATION (PEJ)

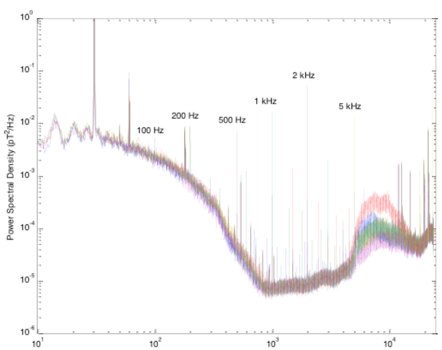
Modulated electron Heating-> Modulates conductivity-> Virtual Antenna



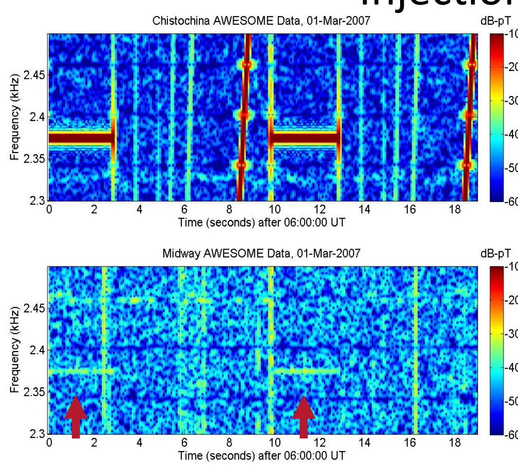


Platino et al., JGR 2004, 2006

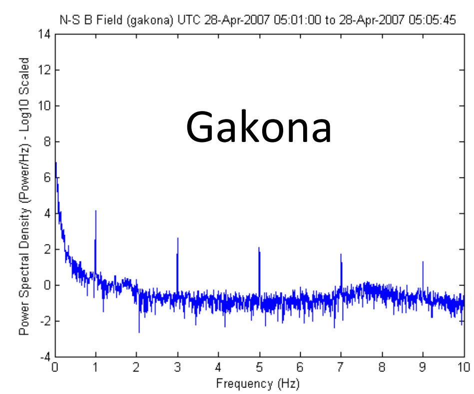




DELTA Mine – Papadopoulos, PARS, 2007



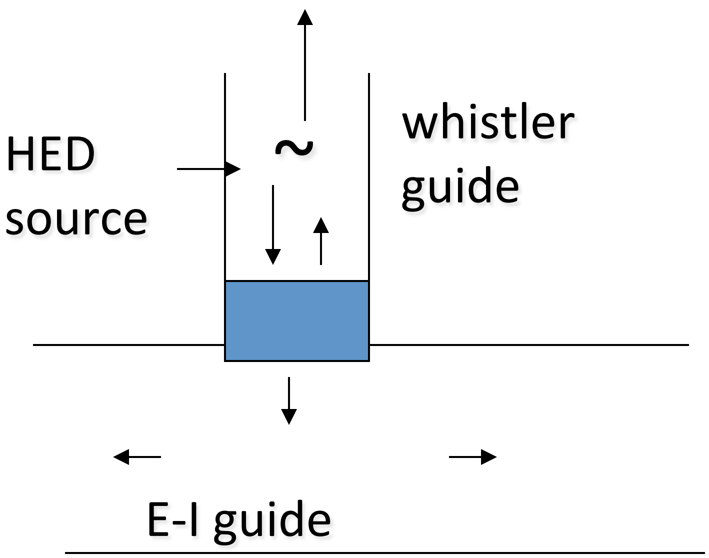
5400 km away Midway, Moore et al., JGR 2007



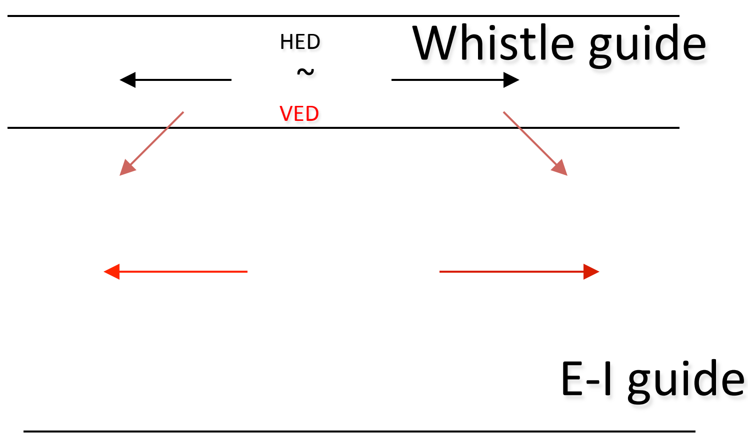
Papadopoulos et al., URSI, 2010; JGR 2005

Equatorial vs. Auroral ELF/VLF Source

Engineering Equivalents



Auroral, T- guide

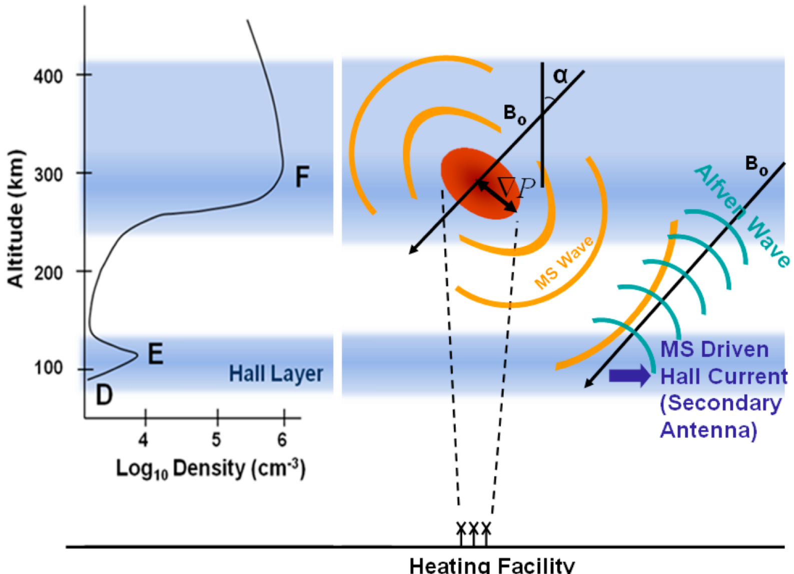


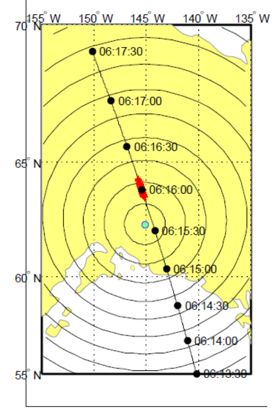
Equatorial, Coupled-guides

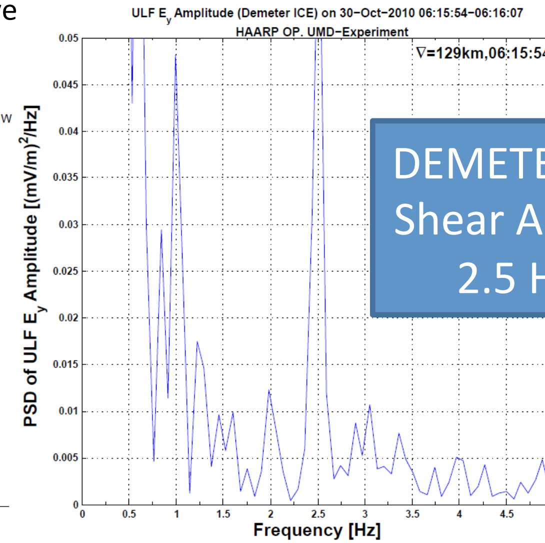
VIRTUAL ANTENNA – IONOSPHERIC CURRENT DRIVE (ICD)

DOES NOT REQUIRE CURRENT- f < 70 Hz

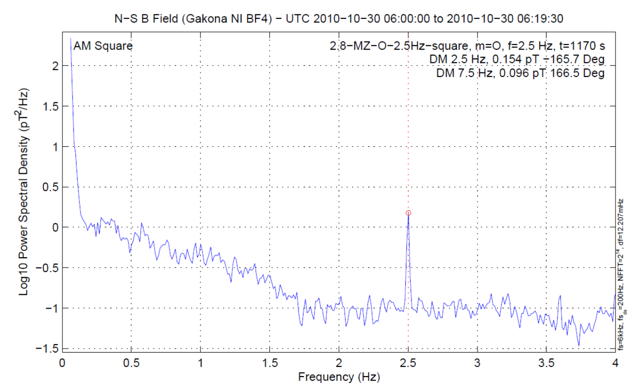
MS-> Magnetosonic
SAW-> Shear Alfven Wave
EJ-> Electrojet

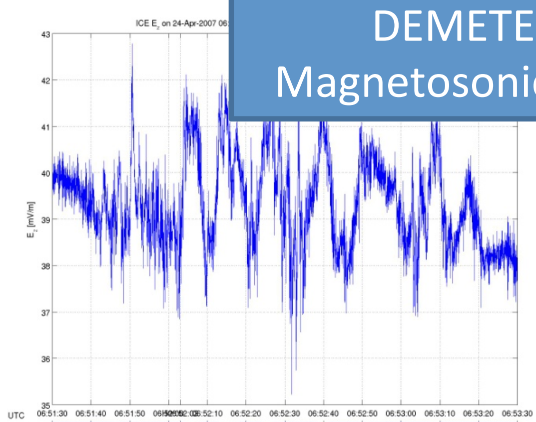




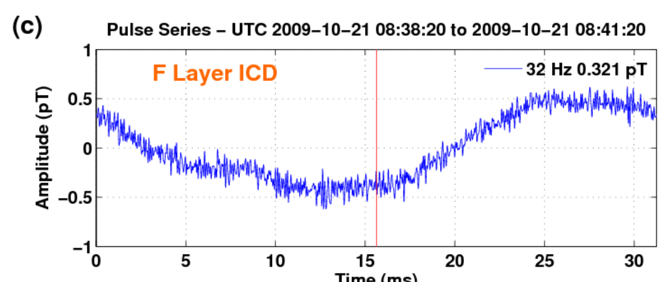


DEMETER
Shear Alfven
2.5 Hz





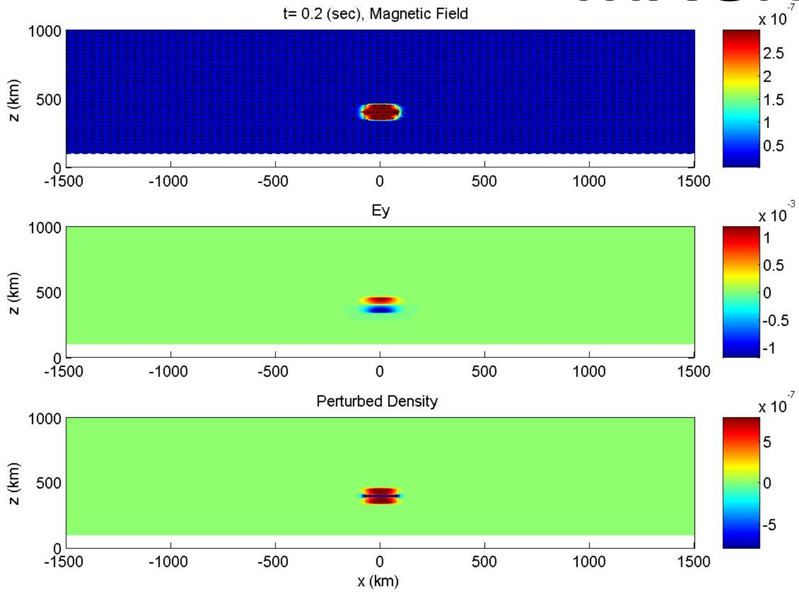
DEMETER
Magnetosonic .1 Hz

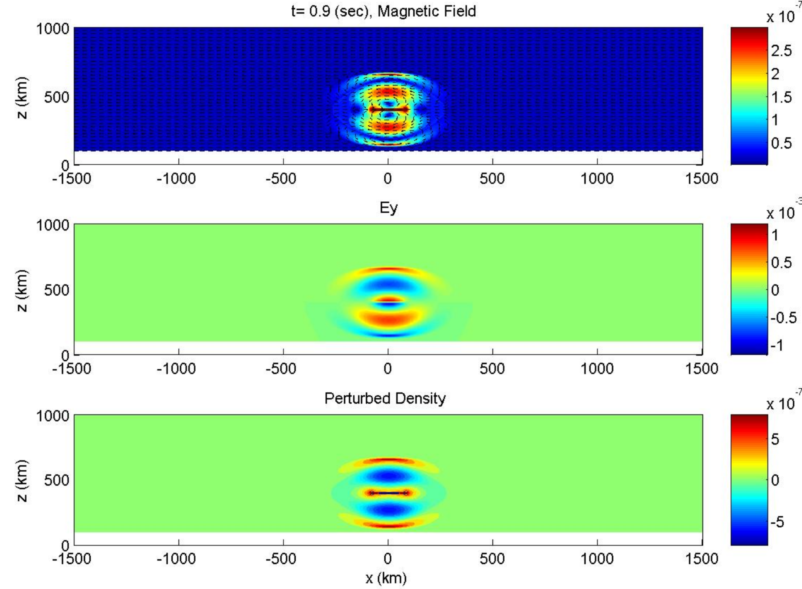


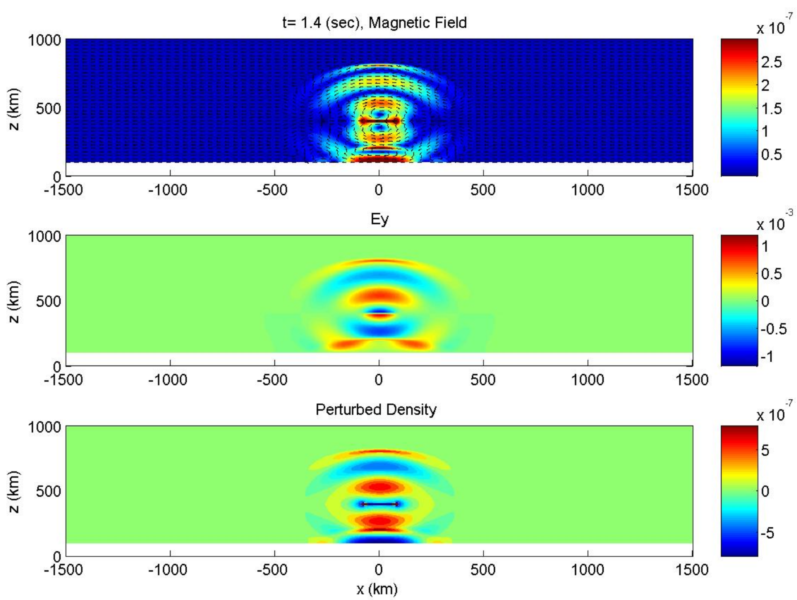
GROUND

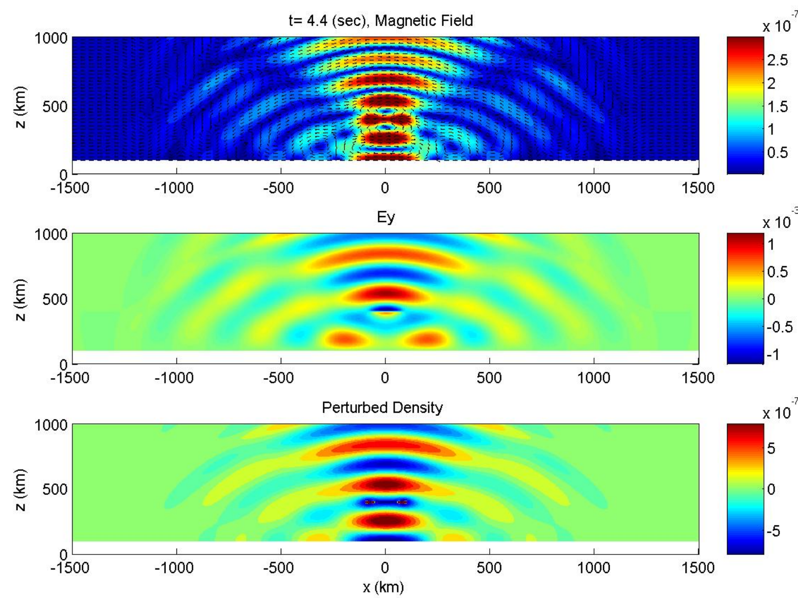
Papadopoulos et al. GRL, 2011 a,b; Eliasson et al. JGR, 2012

MAGNETOSONIC



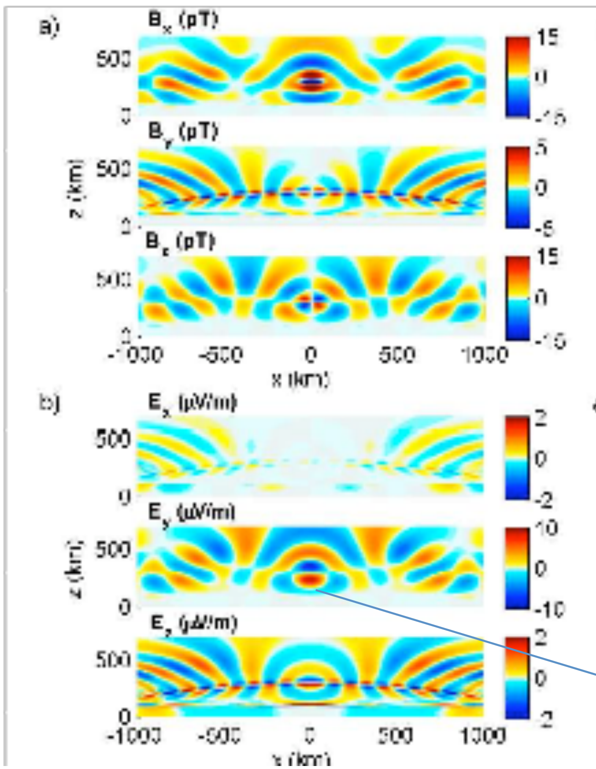


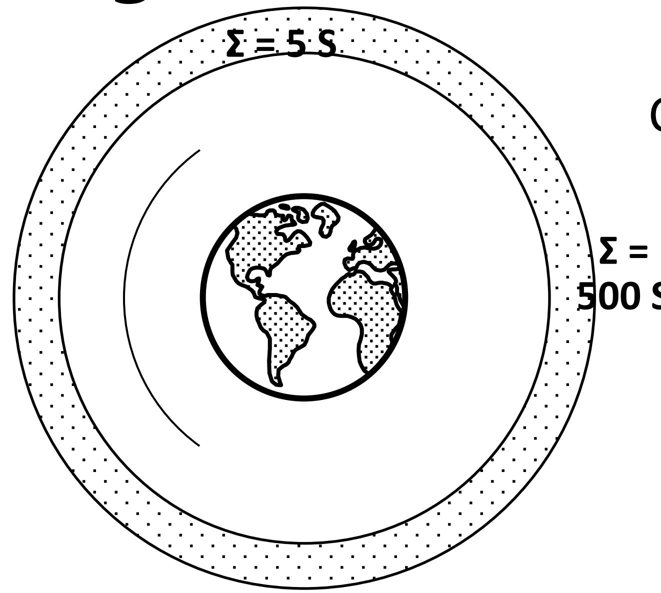




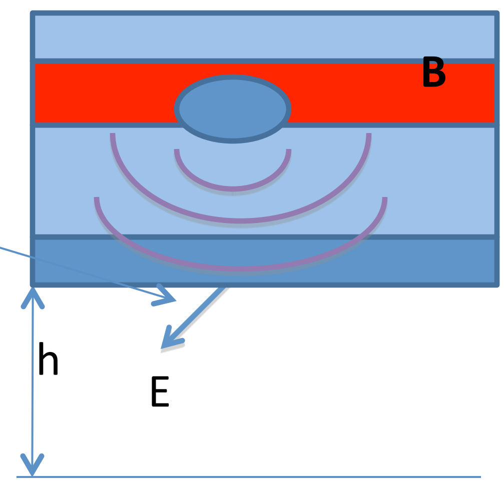
ICD Scaling with Geomagnetic Latitude

Dip Equator





Cowling effect

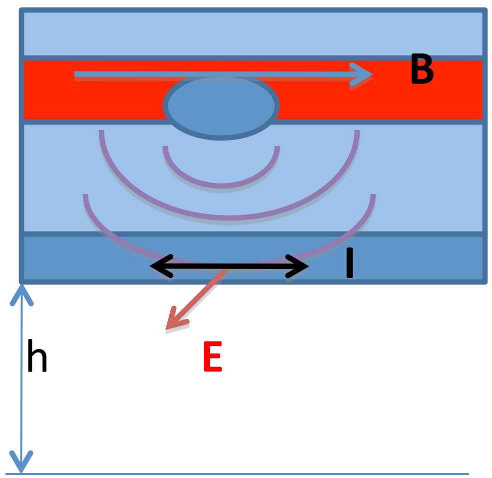


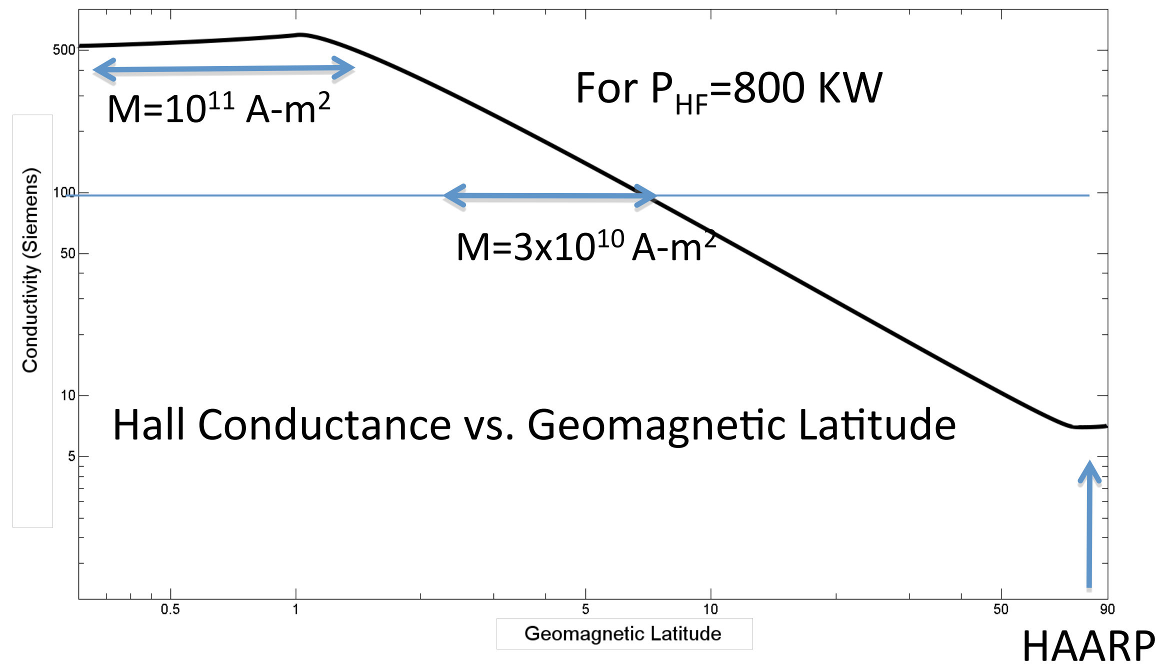
M≈ΣELh~Σ, Σ(λ=0)/Σ(λ=90)≈100

$$M(\lambda, P_{HF}, f) = M_o[\Sigma(\lambda)/\Sigma_o][P_{HF}/3.6MW][12Hz/f]$$

$$M_o \approx 4\times10^9\, A-m^2$$

ICD Scaling with Geomagnetic Latitude





$$M_{eff} \approx ILh \approx (\Sigma EL)Lh$$

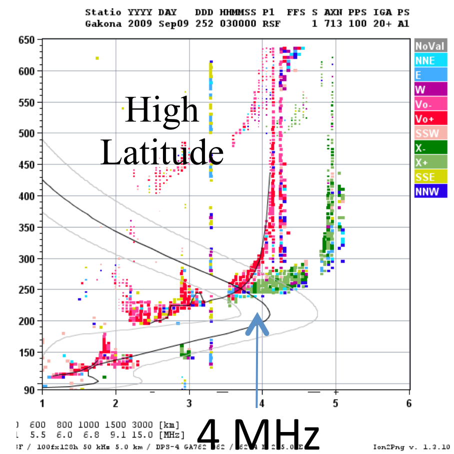
$$M_{eff}(\lambda) \approx (4\times10^{9})[\frac{\Sigma(\lambda)}{5S}](\frac{P_{HF}}{3.6MW})A-m^{2} \approx$$

$$\approx (2.4\times10^{8})\Sigma(\lambda)(P_{HF}/MW)A-m^{2}$$

For P_{HF}=800 kW we get
$M_{eff} \approx 10^{11}$ A-m^2 at $\lambda \approx 0$
$M_{eff} \approx 3\times10^{10}$ A-m^2 at $\lambda \approx 6°$

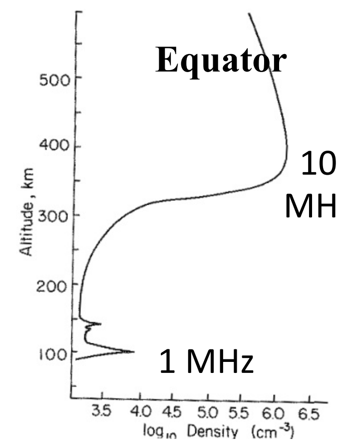
Parameters allow us to consider an equatorial barge basing of the HF transmitter

Barge or Shipboard Option



Strawman HF Array

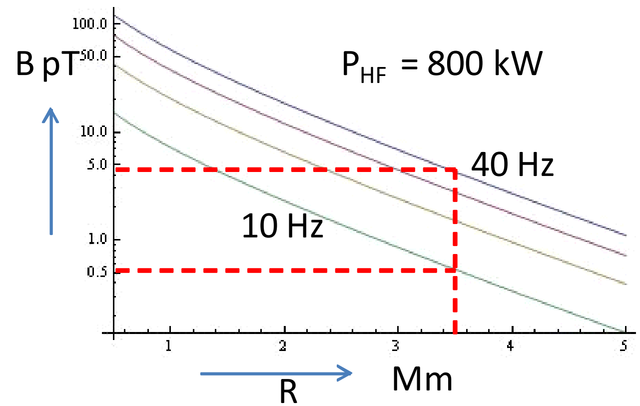
- HF frequency 5-8 MHz
- Linear polarization
- Power on ship or self-propelled platform

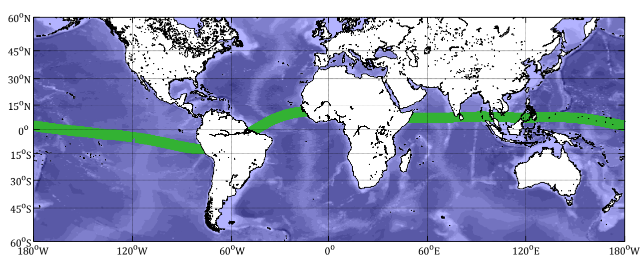


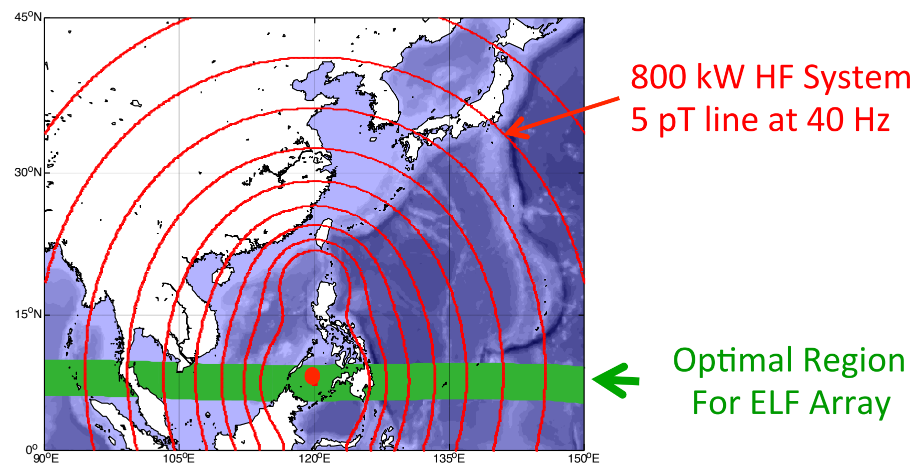
- Can provide strategic and tactical sub communications

ELF Mobile Array Performance

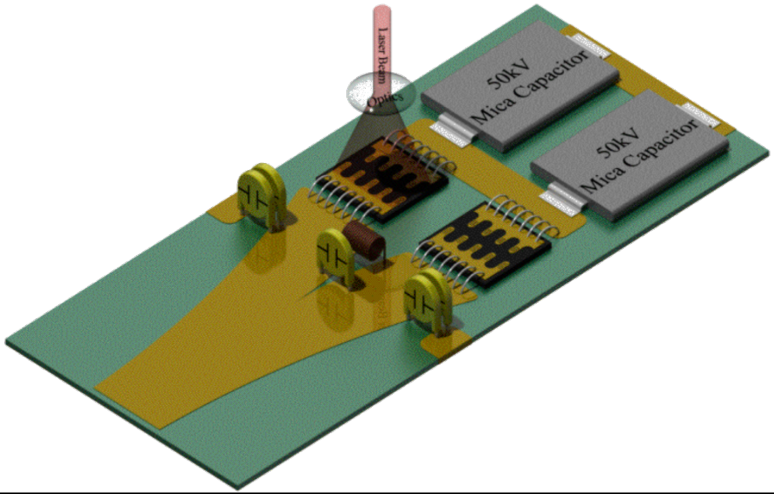
- Optimal area for Mobile Array along Magnetic Equator (green band, within 2° from dip equator)
- Power requirements depend on location
  - Example: Korea - Yellow Sea
    - 800 KW system can provide data rates in the tens of bit/sec
    - Signal as large as 5 pT at 40 Hz or more at range of 3500 km
    - Typical background noise at 40-80 Hz is 200-500 $fT/Hz^{1/2}$







Texas Tech Photoconductive Sources - PCSS



Background

- Switch geometry
- Material parameters and modification
    - Electron irradiation
    - Annealing
    - Laser enhanced diffusion
- Triggering Wavelengths
- Other switch design parameters

Project Objectives

Development of a compact, high voltage (10-25 kV) photoconductive switch capable of ~ 10 MHz operation at ~1-2 MW

Demonstrated Performance

- Blocking of DC electric fields up to 700 kV/cm
- Maximum switched current of 1kA at 30 kV
- Switched 250 A at 20 kV at a burst repetition frequency of 65 MHz

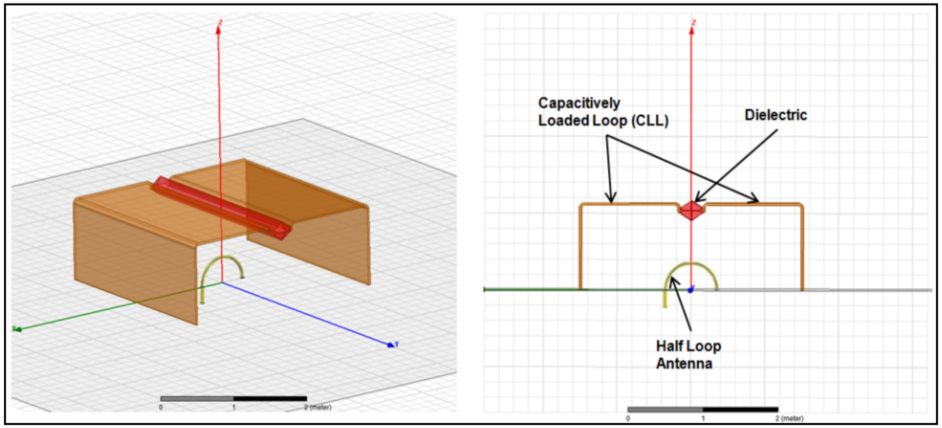
Texas Tech- PCSS

Challenges
- Device Efficiency
  - Recombination at defect sites
    - Mid-gap defect sites
    - Surface Recombination
  - Contact resistance
- Device Lifetime
  - Space charge effects
  - Current density at SiC/metal interface

Device Lifetime
- Vary current density, record any changes in switch properties (V-I curve)
- Simulation (Silvaco – Atlas)
  - Joule heating
  - Space charge effects
    - Hole mobility
    - Transient trapping effects
- AFM / SEM analysis of failed devices
- Sub-contact doping effects

Characterization of Defect States
- Thermally stimulated current spectroscopy (TSC)
- Extraction of trap parameters from experimental IV curves and simulation fitting
- Sub-bandgap IR illumination at cryogenic temperatures

Texas Tech Electrically Small Antennas



Design Goals

- Electrically small – a few meters in size
- High power – Megawatt output
- Instantaneous bandwidth – a few percent
- Tuning – adjust resonant frequency with structural modification

Project Objective

Design and simulate an electrically small antenna for the 2 – 10 MHz range capable of high power applications

Approach

•Simulate and optimize the design in HFSS for the operational frequency range
•Consider physical limits (electric breakdown)
•Build a scaled version of the design for operation around 100 MHz

Current Issues

- Tradeoff between size and bandwidth
  - Resonant structure
- High field on surface of dielectric
  - Limits input power
- Losses in the dielectric
  - Increase bandwidth, decrease efficiency

Future

- Evaluate magnetic materials (ferrites)

UMD Charged Particle Beam Group
Multi-beam Inductive Output Tube (MBIOT)
R&D Program

Goal: Design, develop and demonstrate a high power MBIOT operating as a class D amplifier.

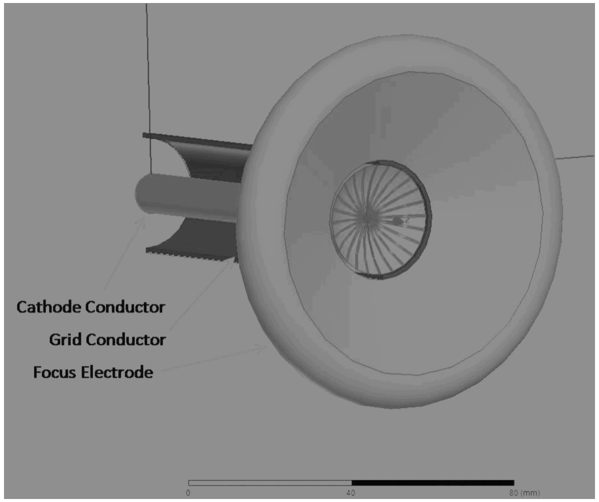
Advantages of Pulse Modulation:

Simplifies driver circuitry
Improves phase/frequency control
Enhanced efficiency

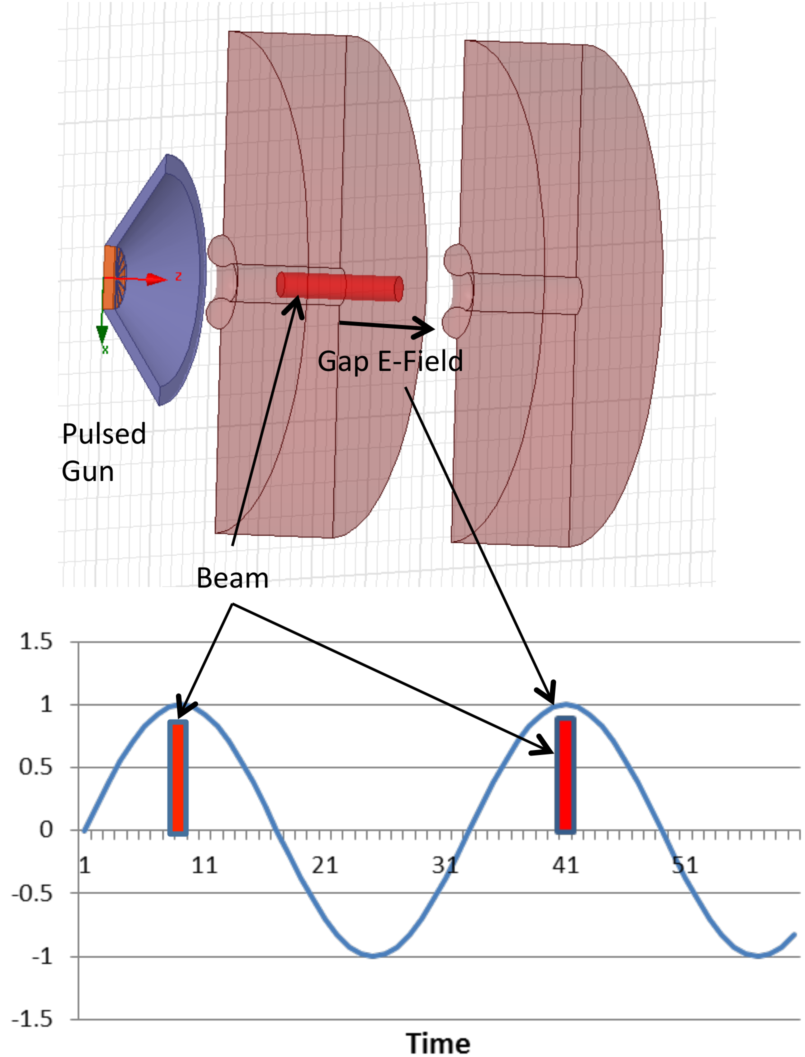
Technical Challenges:

Grid- beam interception and heat load
Cavity tuning over 3 octaves while maintaining matched R/Q
Guide field uniformity
Output matching

Device Concept

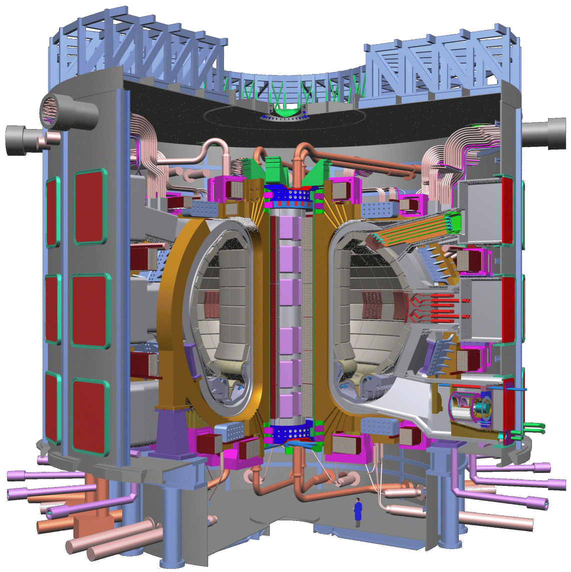


Electron gun w/ coaxial grid-cathode geometry



- RF frequency, phase and amplitude are pulse modulated
- Pulse Width → AM
- Pulse Period → FM
- Pulse Timing → Phase

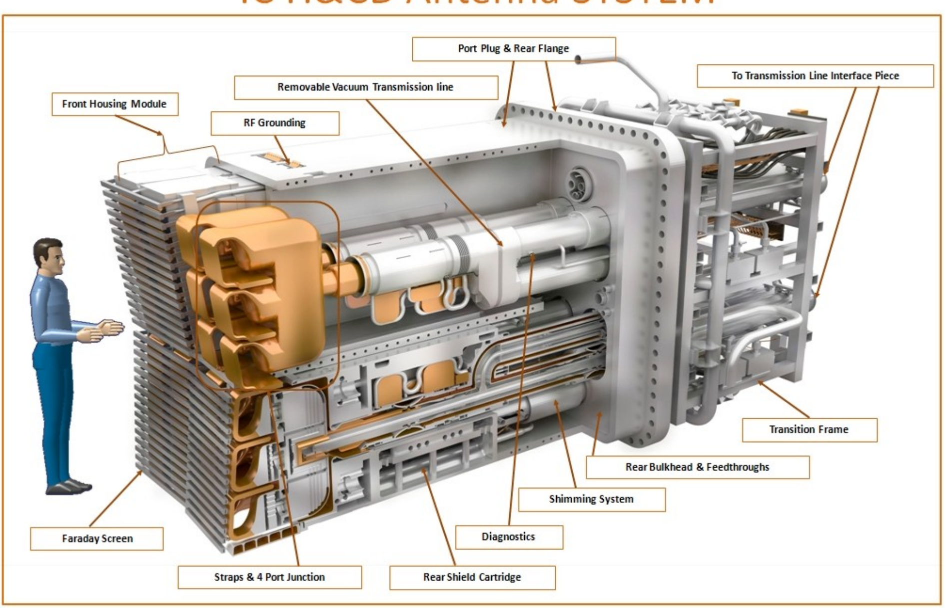
System Challenges - What might a more compact system look like?



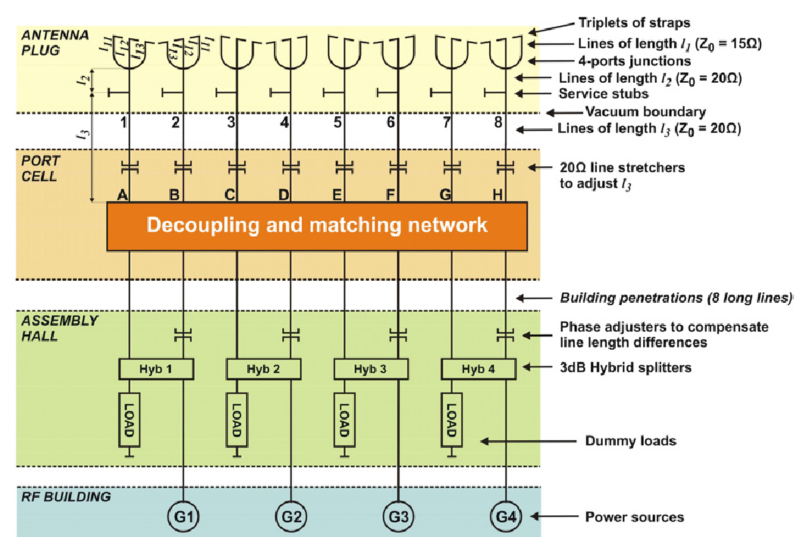
ITER and Compact are not usually mentioned in the same sentence

ICRH System: 2 antennas, 20 MW/each, 40-55 MHz

IC H&CD Antenna SYSTEM



Messian et al, Nucl. Fusion 2010.



AFOSR FY MURI TOPIC #13
A New Paradigm in Sources and Physics of High-Power Ionospheric Modification

Background

- **The Ionosphere controls the performance of critical DoD & civilian systems [Communications range, radar, navigation, Geo-location accuracy, etc]**
- **DoD/civilian active research using traditional ionospheric heaters provided new capabilities and applications that allow control/exploitation of triggered processes (Virtual antennas in space, artificial clouds, irregularity control,…)**
- **The low power of traditional heaters resulted in large arrays and active elements, with complex and costly controls leading to fixed installations**
- **Fixed locations are associated with fixed magnetic geometry limiting the scope of the research investment**