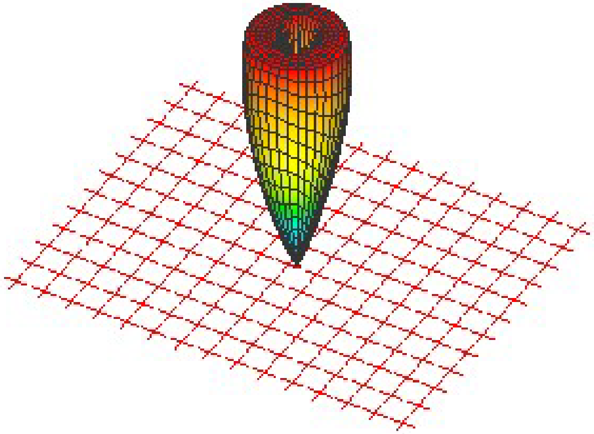

Physics and Measurements of Stimulated Electromagnetic Emissions

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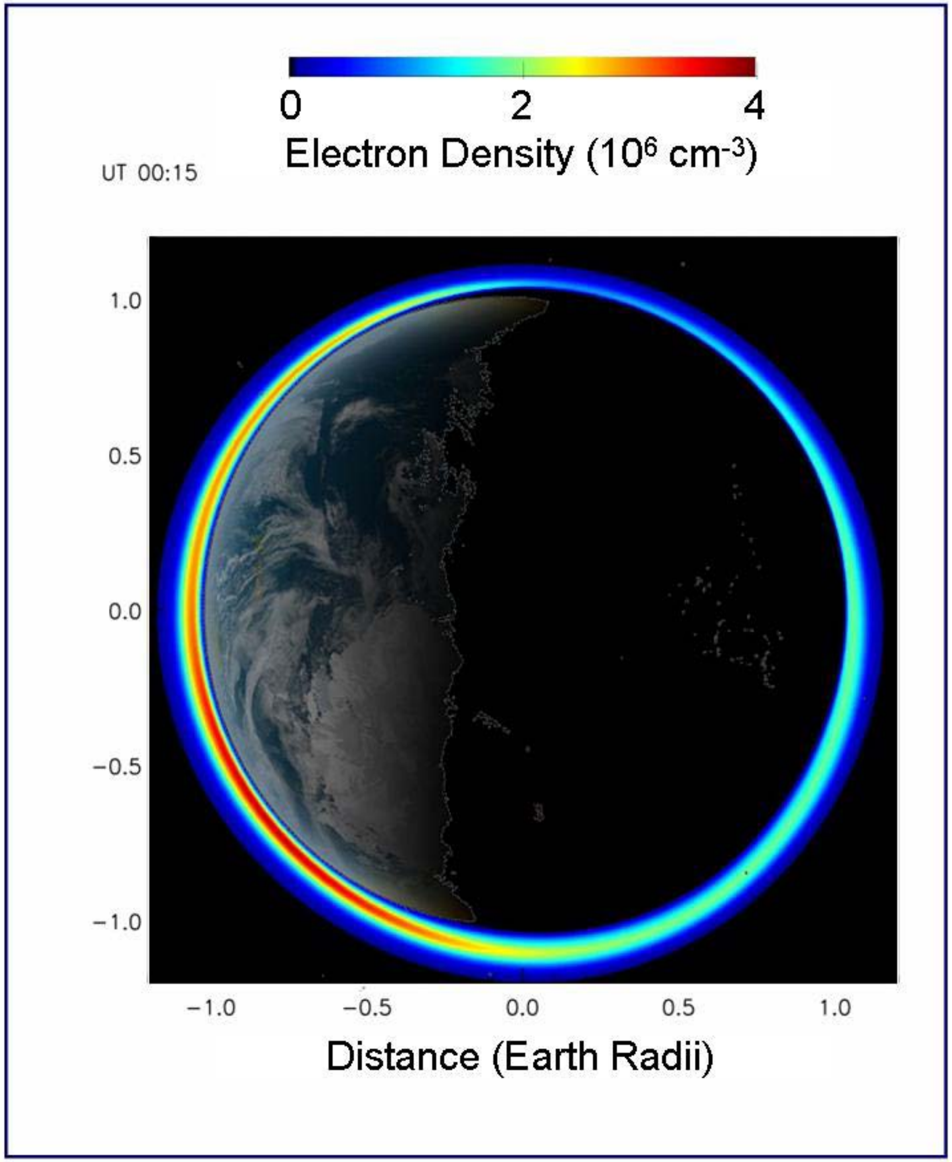
8 November 2011

Studying the Ionosphere with Active Experiments

- Active Experiments with High Power Radio Waves
  - Frequency Range (2.6 to 10 MHz)
  - Global Distribution of HF Facilities
- Physics of High Power Radio Waves
  - Density, Temperature, Composition, and Irregularities
  - Active Technique
    - Field Aligned Irregularity Glow with HF Excitation
    - Stimulated Electromagnetic Emissions (SEE)
  - Plasma Wave Generation and Propagation
- Research Inspired by Uppsala University
  - Low Frequency
  - OAM HF Beam Interactions
- Dissertation Defense

The Ionosphere Described by NRL SAMI3 in 2010



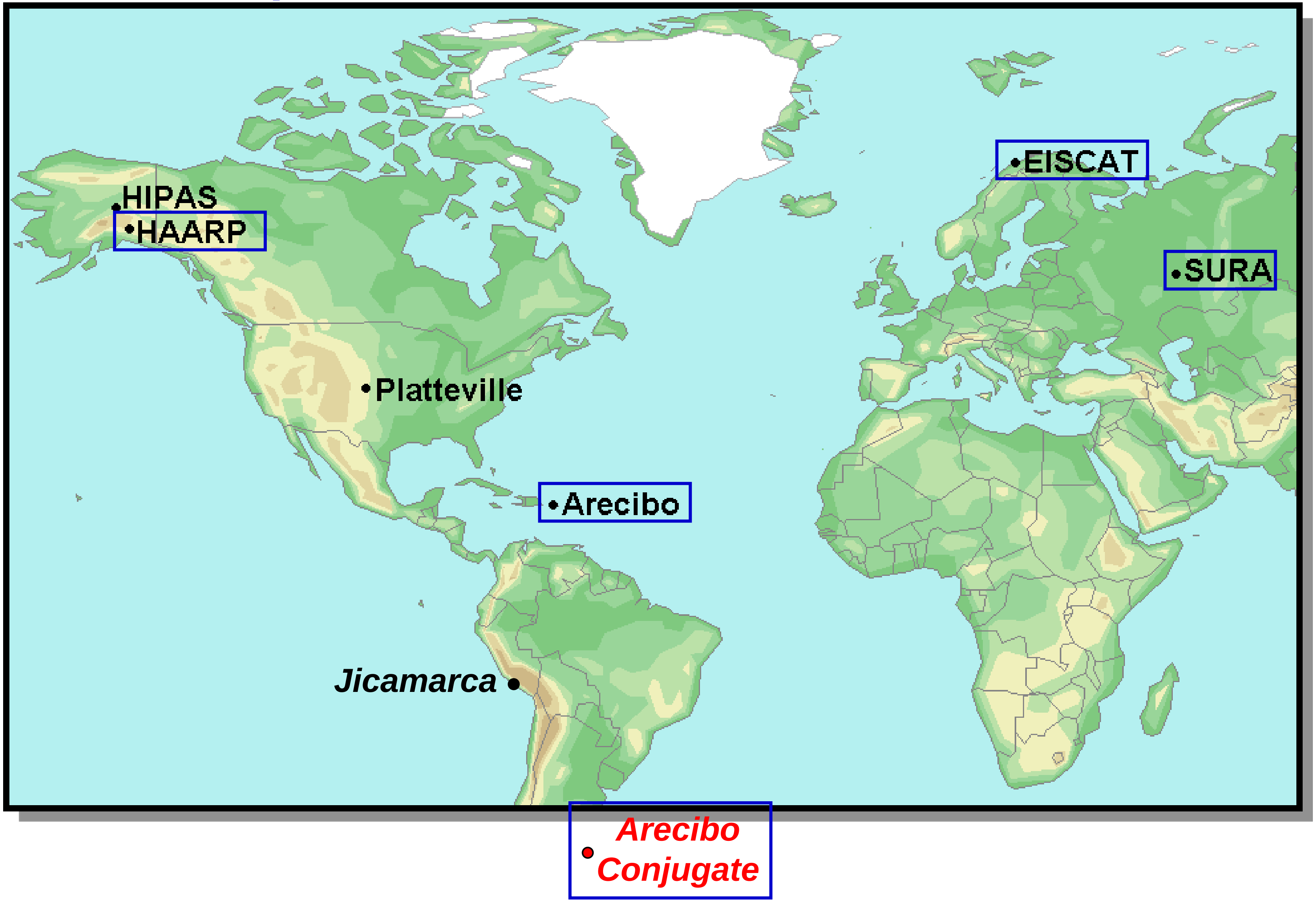
- Ref.: Huba, Krall, Joyce, SAMI3, 2010
- Plasma Density:

  10^3 to 10^6 cm^{-3}
- F-Layer Electron Temp.: 500 to 3000 K (0.05 to 0.3 eV)
- F-Layer O^+ Ion Temp.: 500 to 2000 K
- Magnetic Field Strength: $B_0 \approx 28\ 10^{-6}$ T
- Plasma Pressure Versus Magnetic Pressure

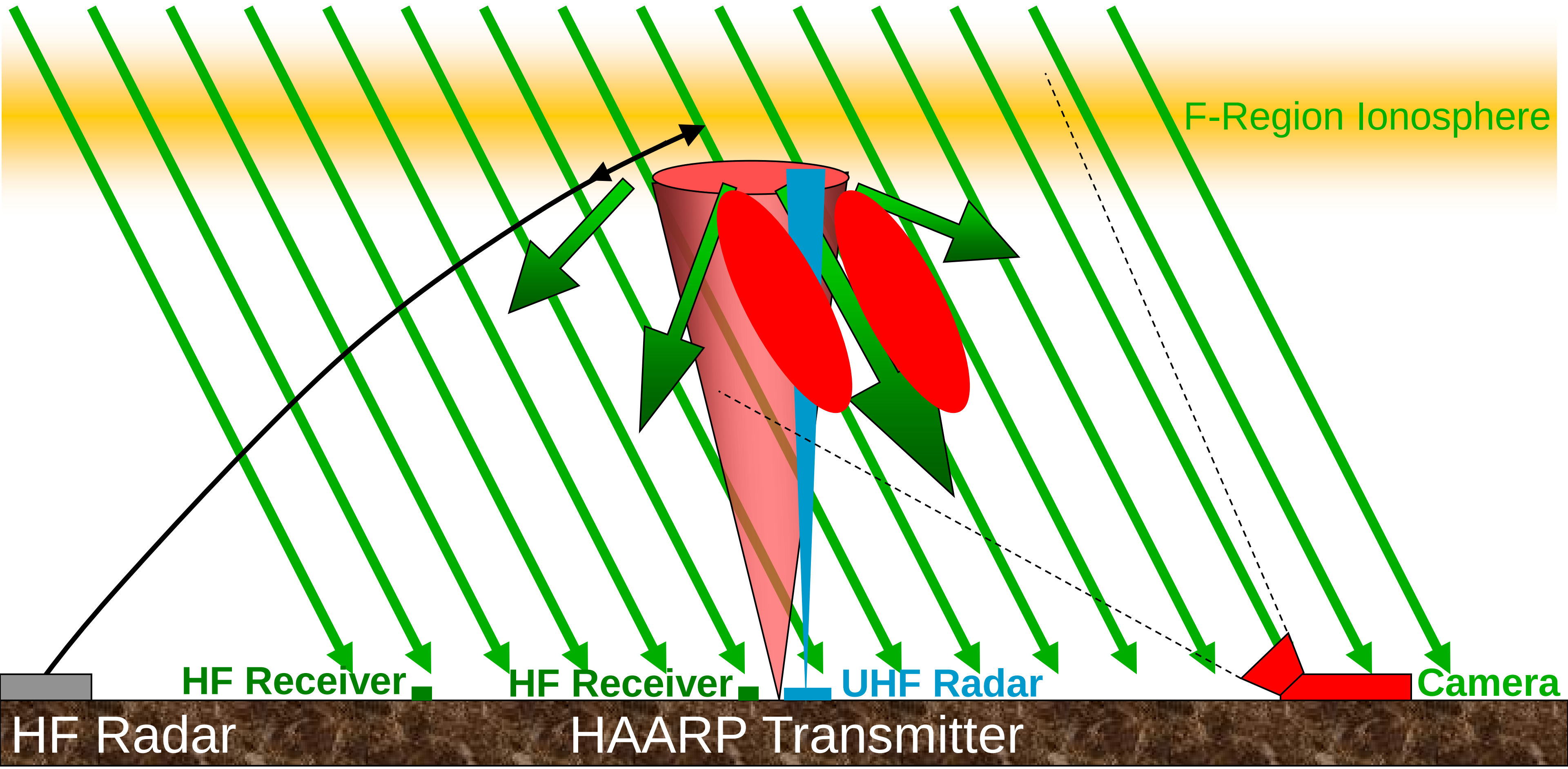
  $\beta \approx nkT/(B^2/2\mu_0) = 10^{-8}$
- Ion Collisions Versus Ion Gyro Orbits

  $\Omega_i \sim \nu_i$ at 100 km Altitude

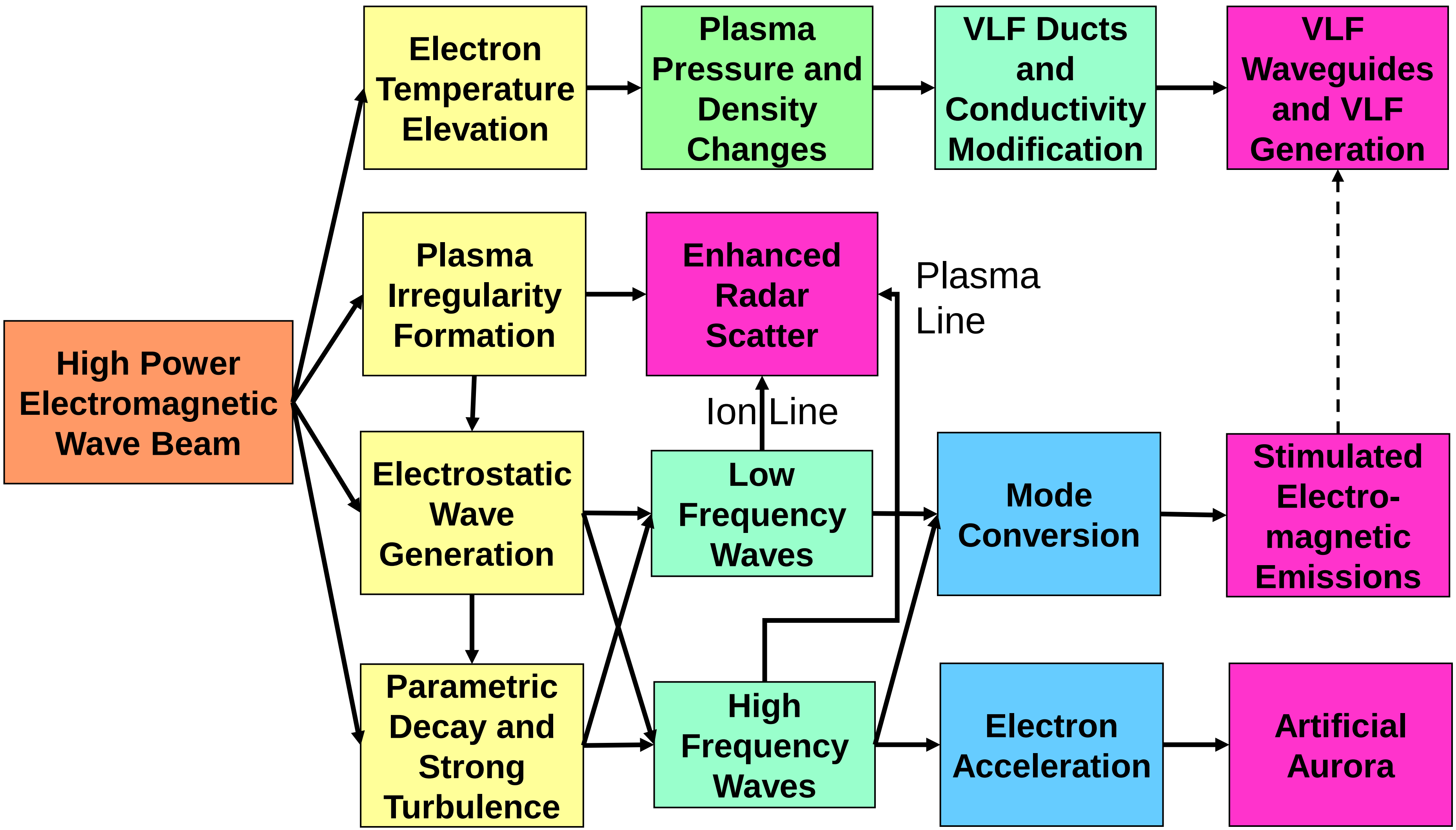
Past, Current and Future HF Ionospheric Modification Facilities



Stimulated Electromagnetic Emissions, Radar Backscatter, Enhanced Plasma Waves and Artificial Aurora



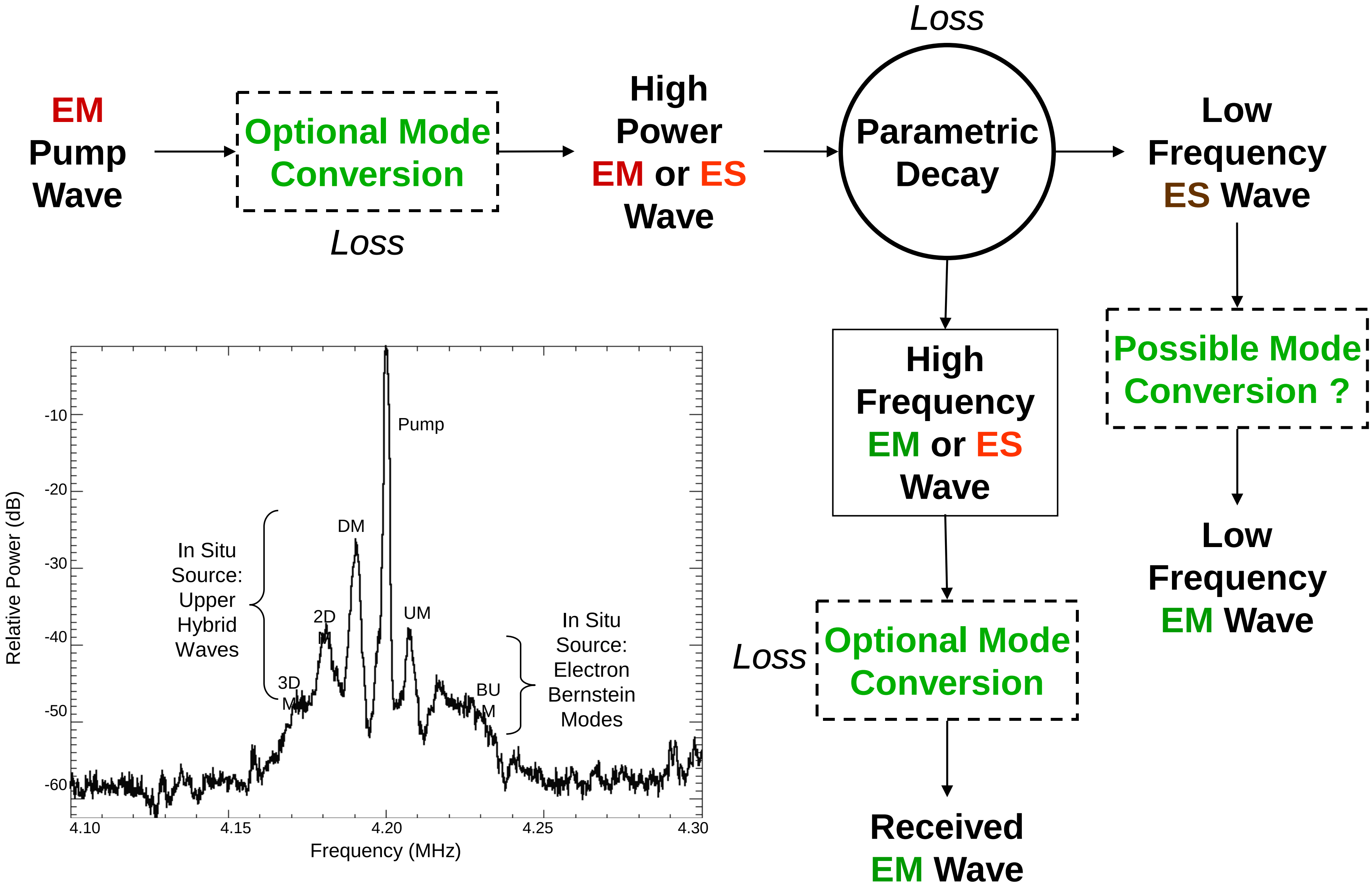
Plasma Physics of Ionospheric Modification with High Power Radio Waves



HF Antenna for Receiving Stimulated Electromagnetic Emissions from HAARP

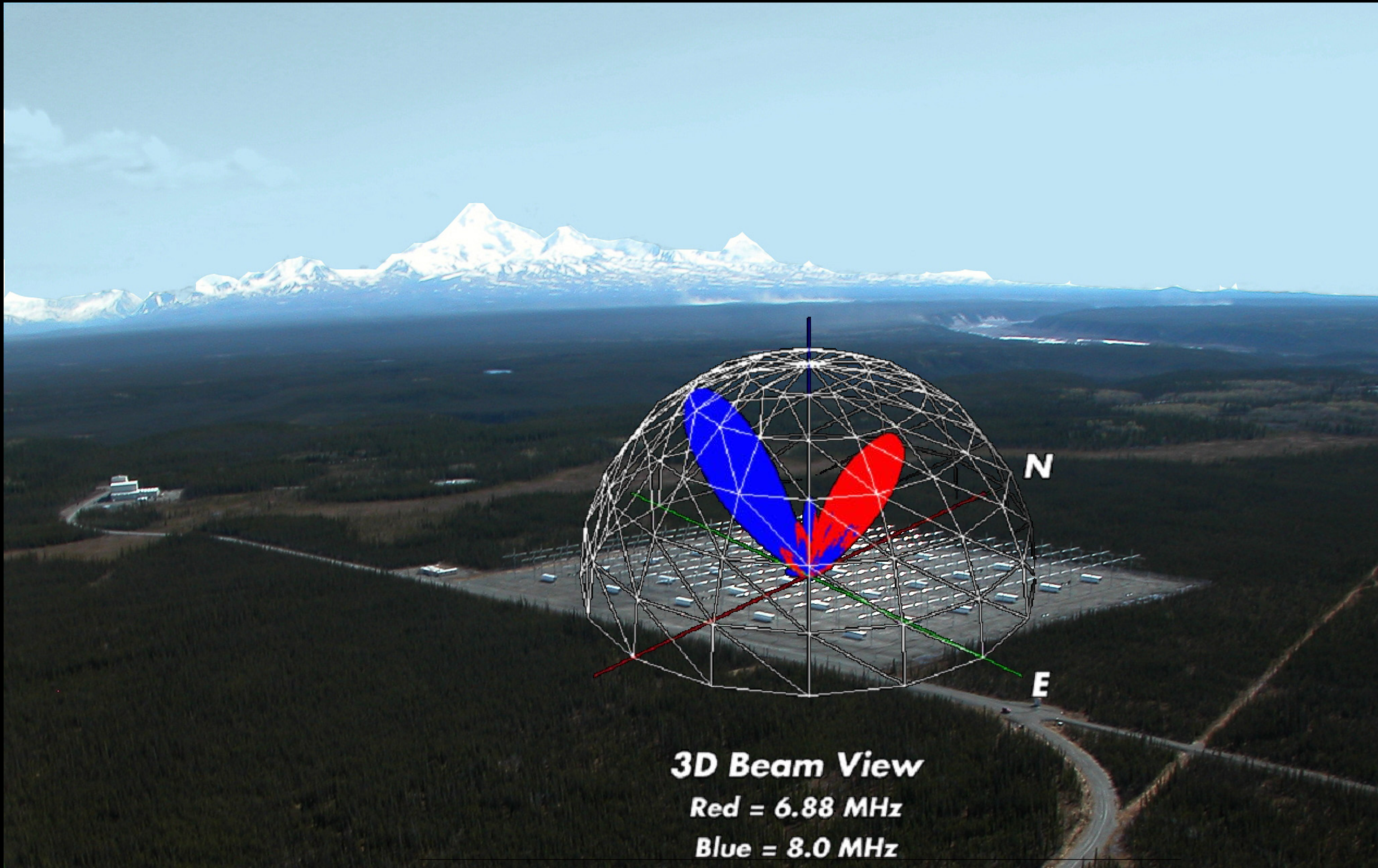
Real Time Display of Stimulated Electromagnetic Emissions near HAARP with the MARK-IID Receiver

ES and EM Wave Generation

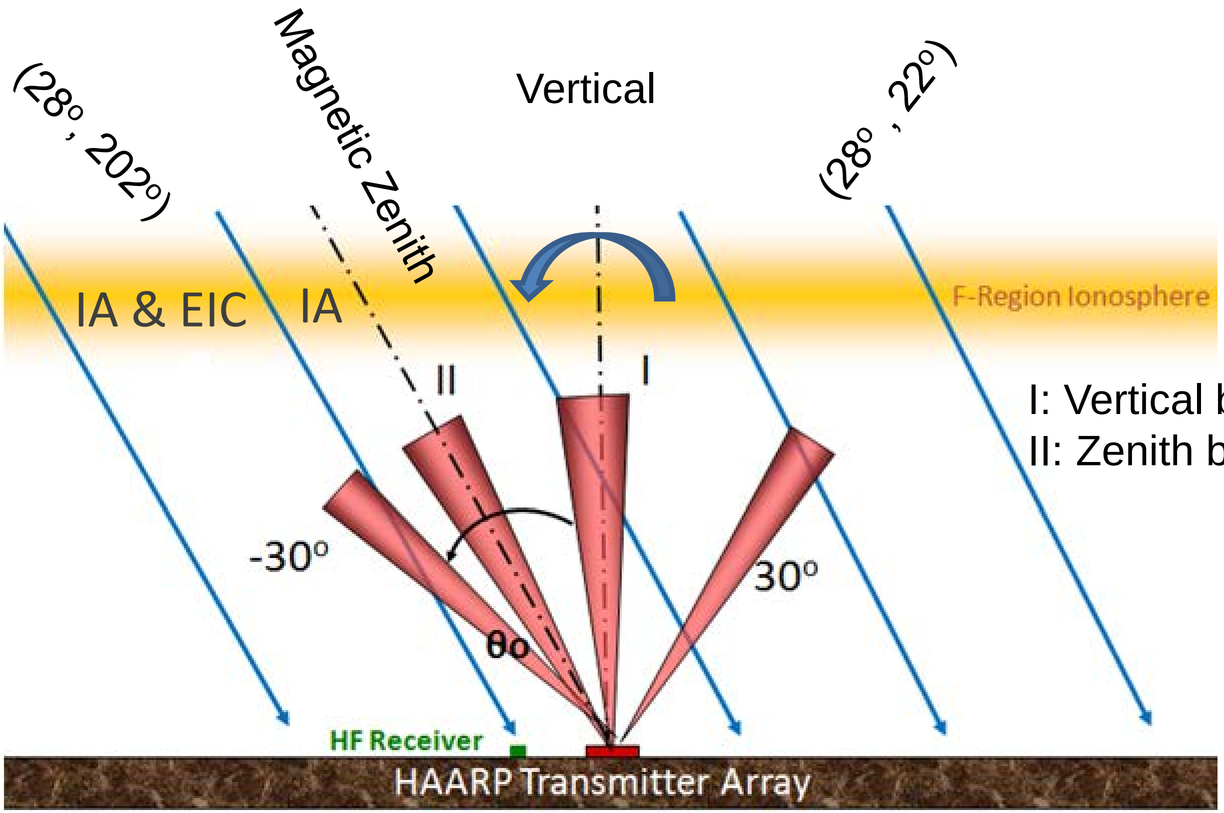


HAARP HF Transmitter Array

2.6 to 10 MHz, Up to 3.6 GW Effective Radiated Power



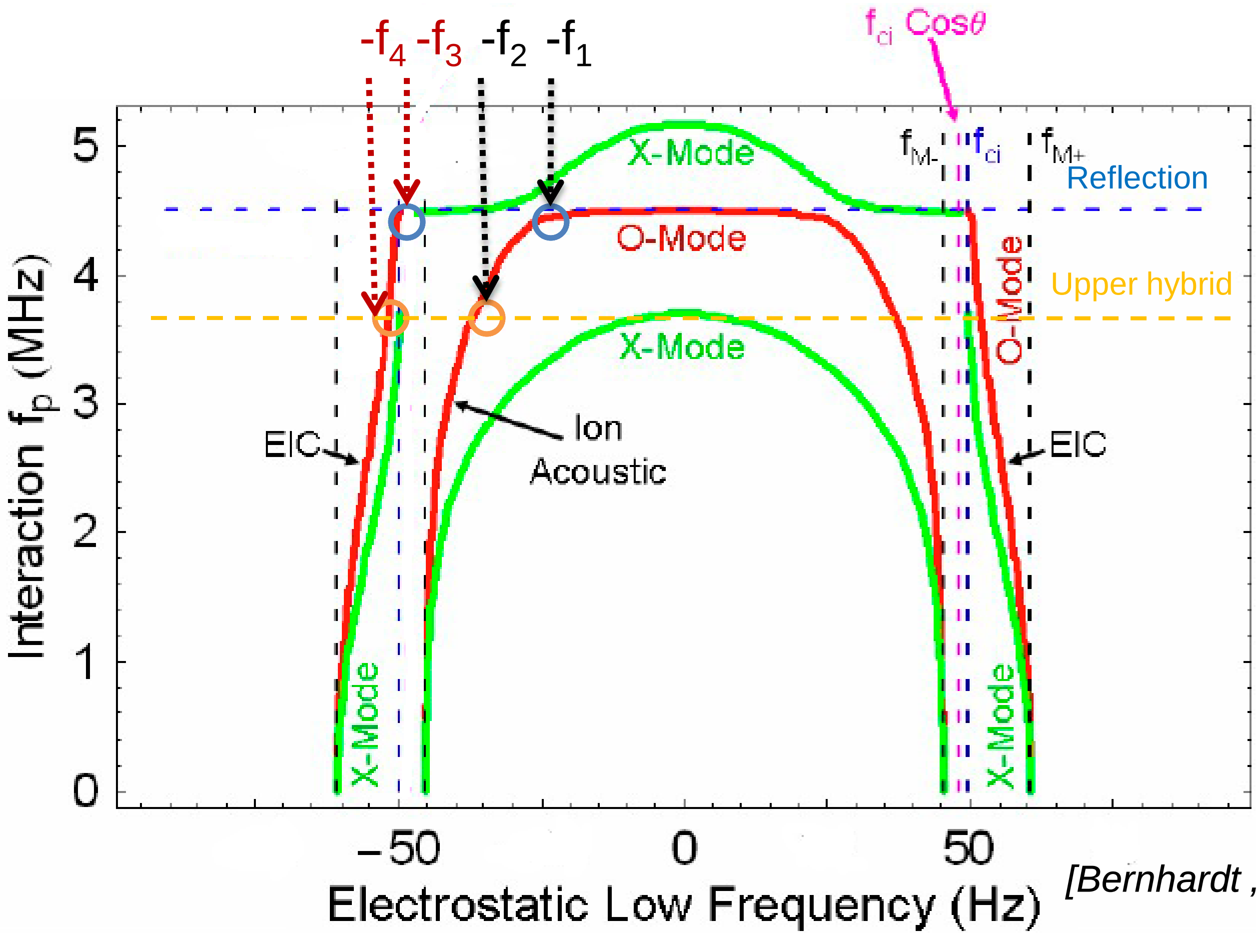
Heater Power Beam Angle Sweeping



I: Vertical beam (0°,0°)
II: Zenith beam (14° ,202°)

- *Norin et al., 2009* observed the IA emission lines f_1 and f_2 due to Simulated Brillouin Scatter;
- *Bernhardt et al.,2009* observed IA lines f_1 and 2010 observed IA line f_1 and EIC lines f_3 ;
- Bernhardt, P. A., C. A. Selcher, and S. Kowtha (2011), Electron and ion Bernstein waves excited in the ionosphere by high power EM waves at the second harmonic of the electron cyclotron frequency, *Geophys. Res. Lett.*, 38, L19107, doi:10.1029/2011GL049390.
- **The experiment conducted at HAARP in July, 2010 aims to look more thoroughly at a broader range of heater beam angle effects on IA and EIC waves generated by MSBS (Fu, Scales, Bernhardt 2011).**

Generalized MSBS matching conditions



[Bernhardt , 2009]

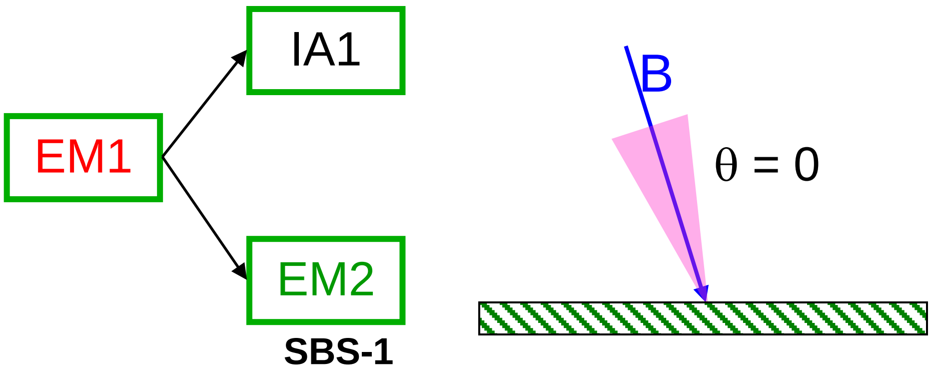
For O mode reflected at $\omega_0 = \omega_p$

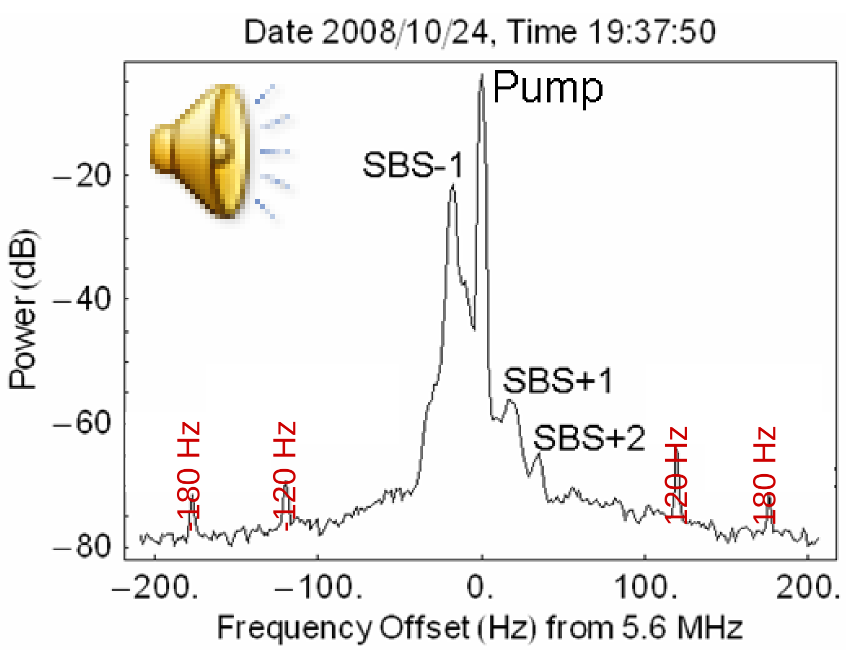
For X mode reflected at $\omega_0 = \frac{1}{2}[\pm\Omega_{ce} + (\Omega_{ce}^2 + 4\omega_{pe}^2)^{1/2}]$

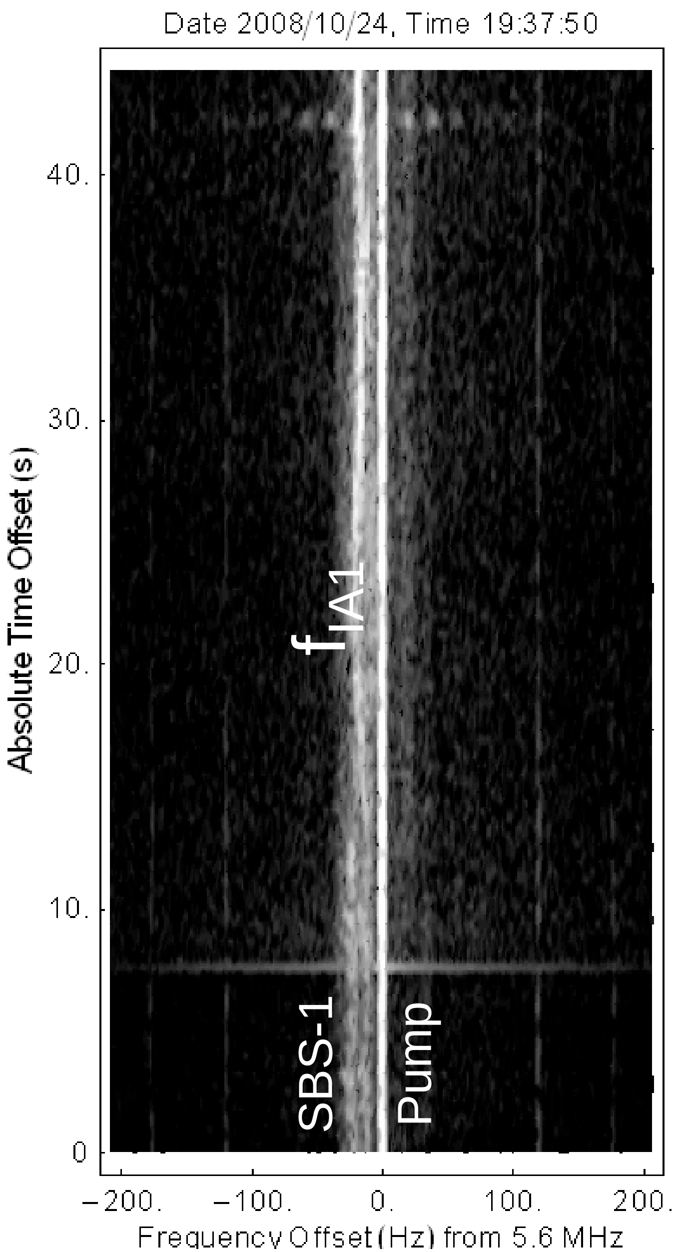
The upper hybrid resonance is $\omega_0 = \omega_{UH} = \sqrt{\Omega_{ce}^2 + \omega_{pe}^2}$

f_1- IA at reflection region;
f_2- IA at upper hybrid;
f_3- EIC at reflection region;
f_4- EIC at upper hybrid;

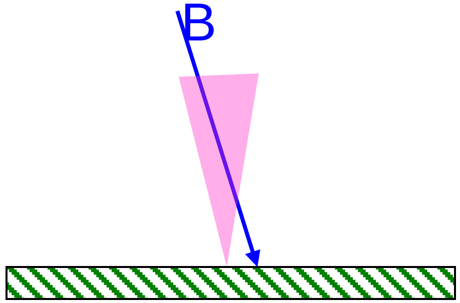
Stimulated Brillouin Scatter with Ion Acoustic Wave Generation is Simple

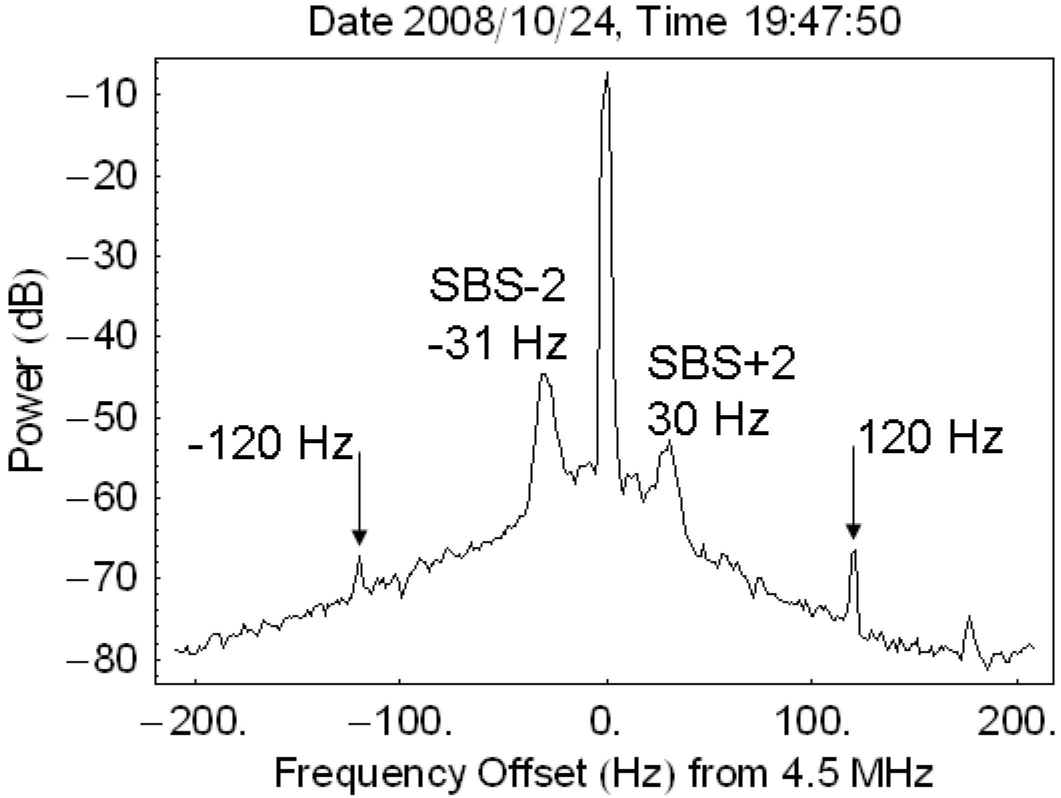


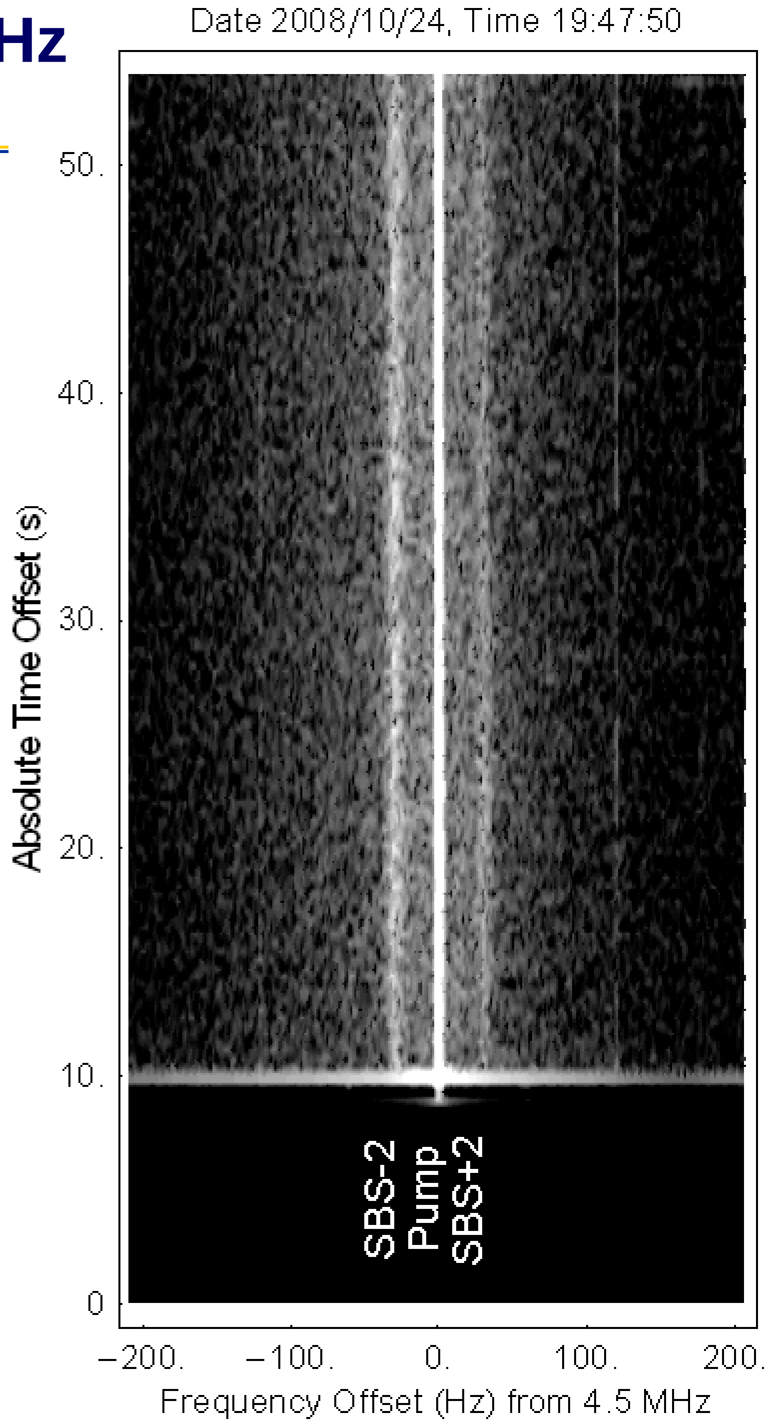




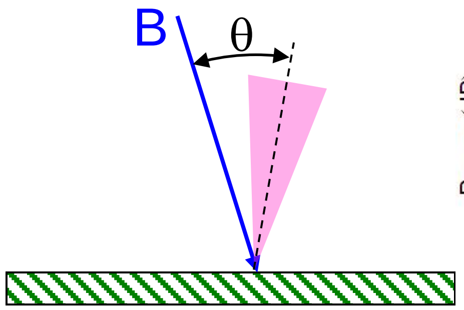
Brillouin Scattering of the 4.5 MHz HAARP Vertical Beam in the Ionosphere

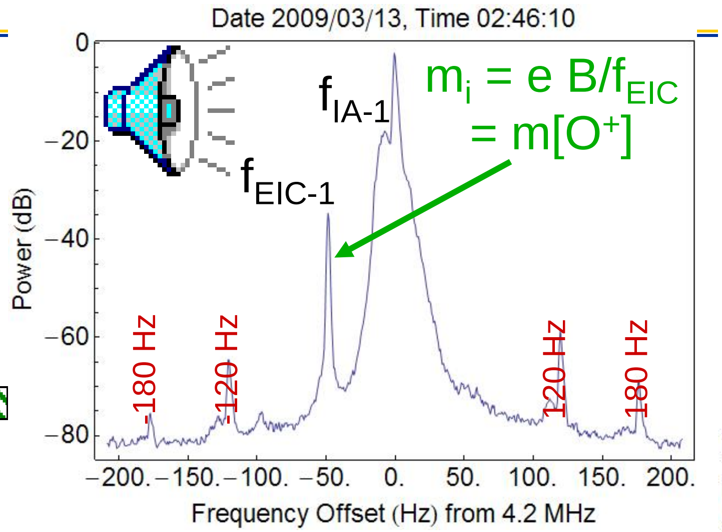


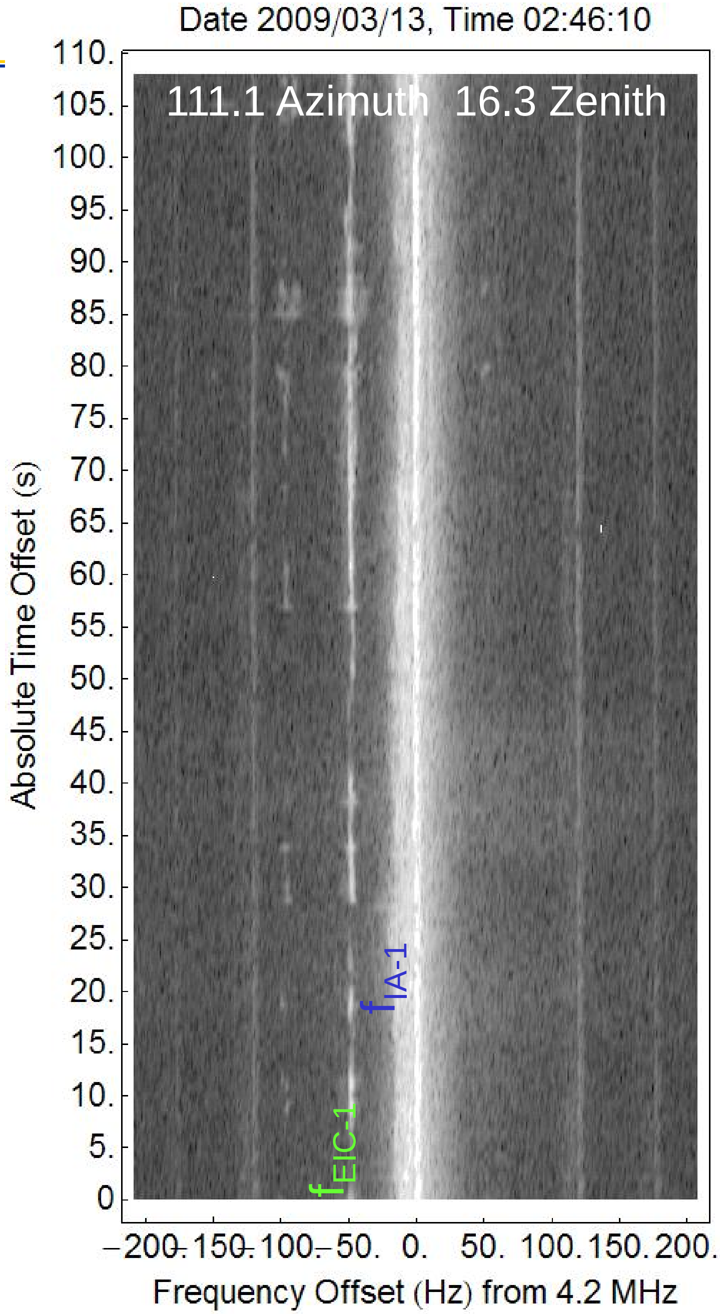


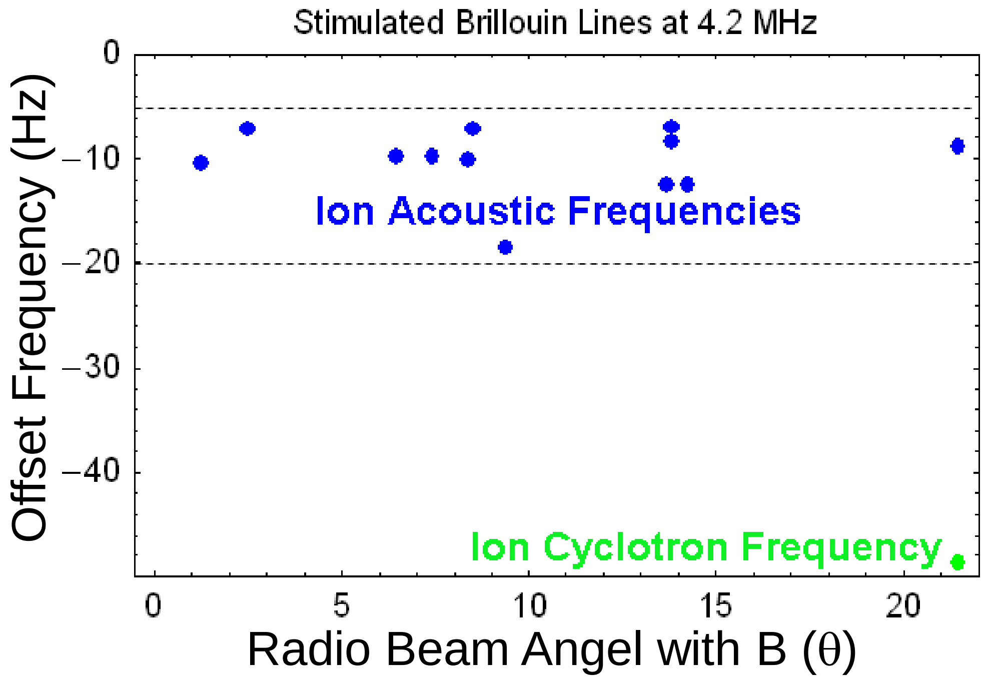


SBS with EIC Generation Yields Ion Mass



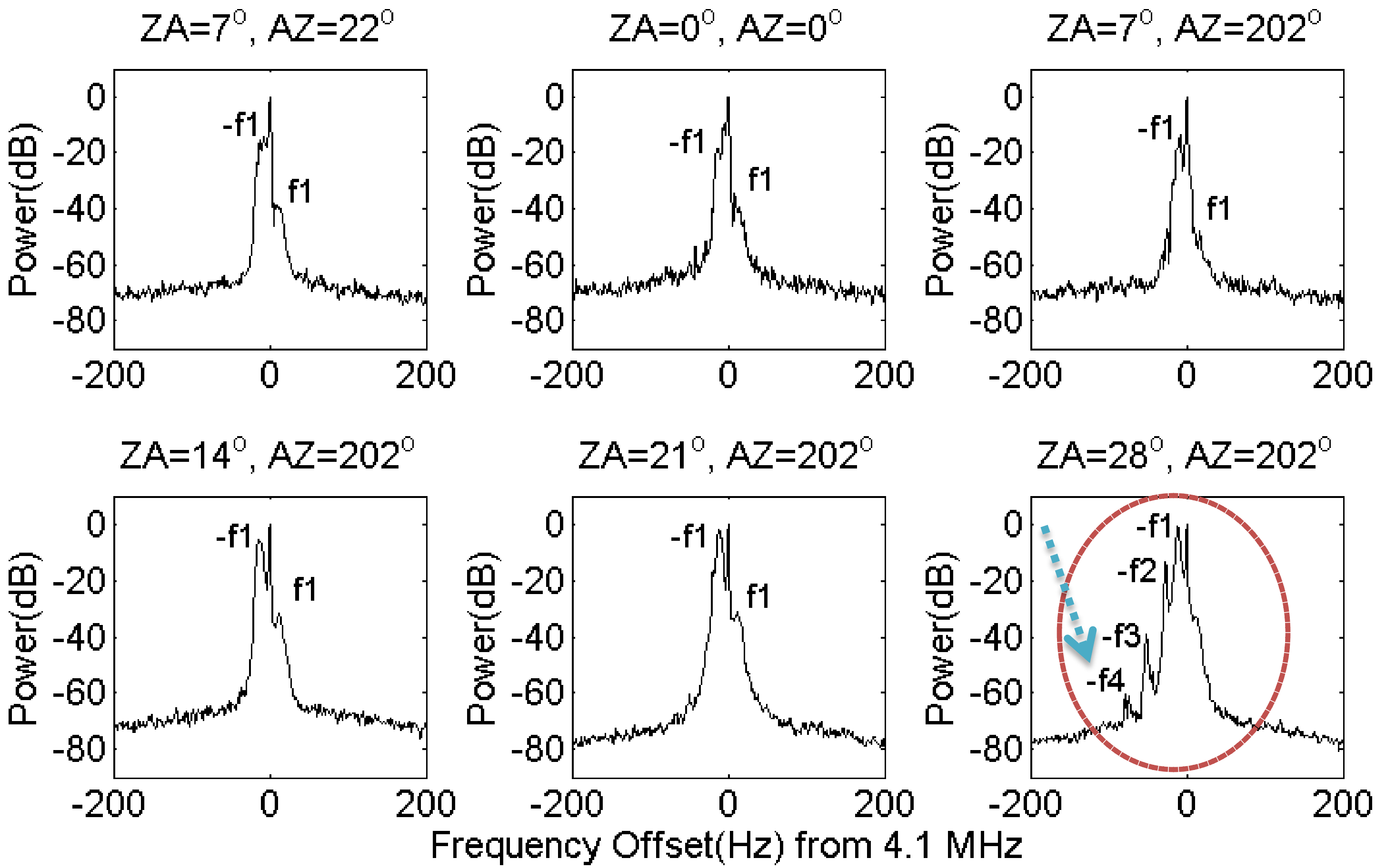






Set II : Experimental Results for 4.1 MHz, O-mode Full Power, UT 04:15:00-04:60:00,07/22/2010

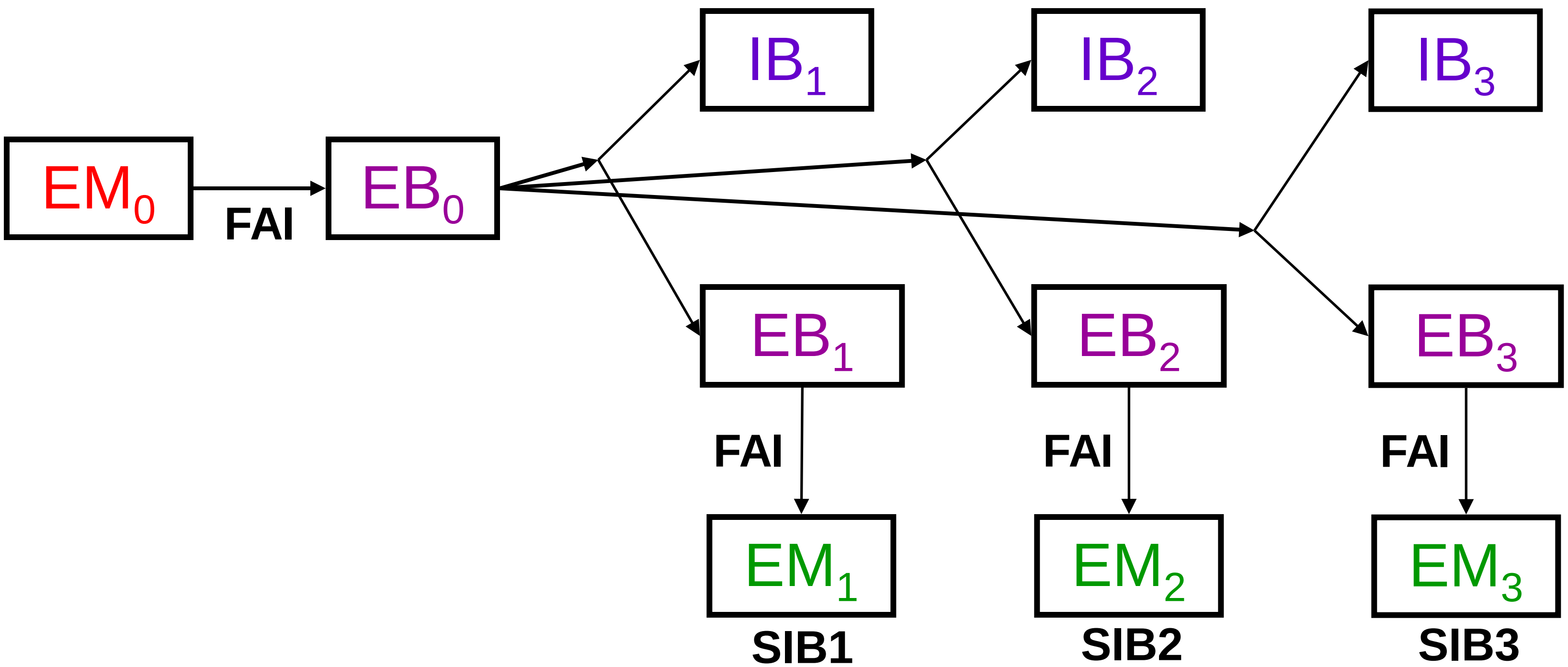
(Haiyang Fu, Virginia Tech)



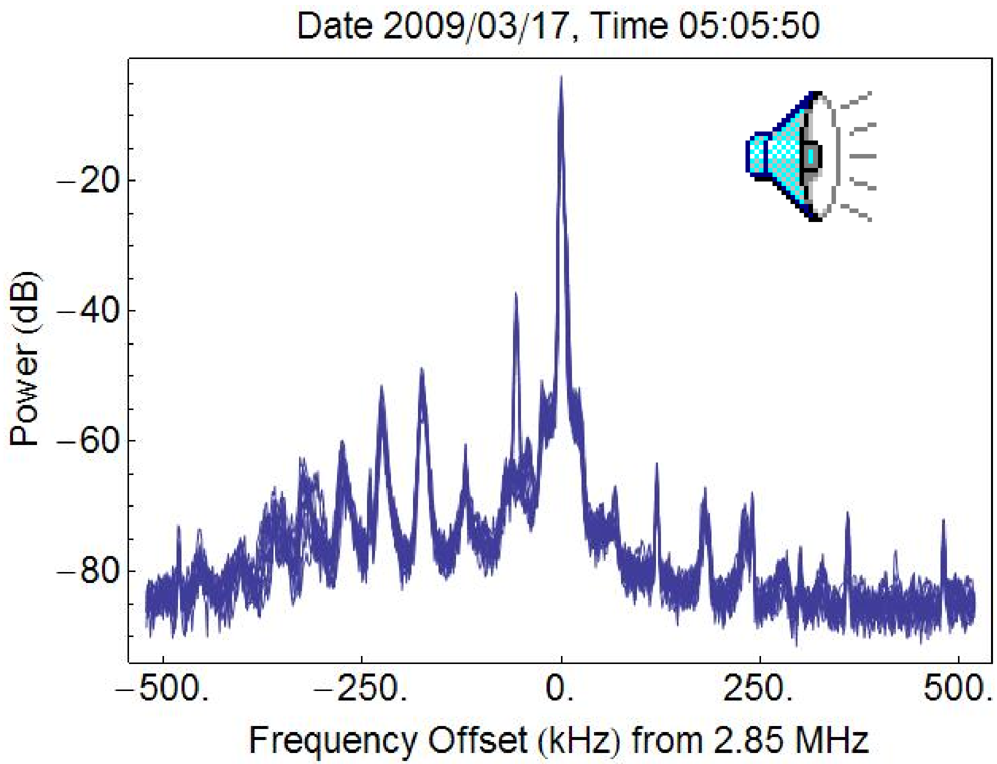
- The IA lines f_1=10~12 Hz is stronger close to the magnetic zenith
- The IA lines f_2=24~26 Hz appears for ZA=28°, AZ=202°
- The EIC lines f_3=50~52 appears for ZA=28°, AZ=202°
- The newly observed f_4=70~72 appears for ZA=28°, AZ=202°

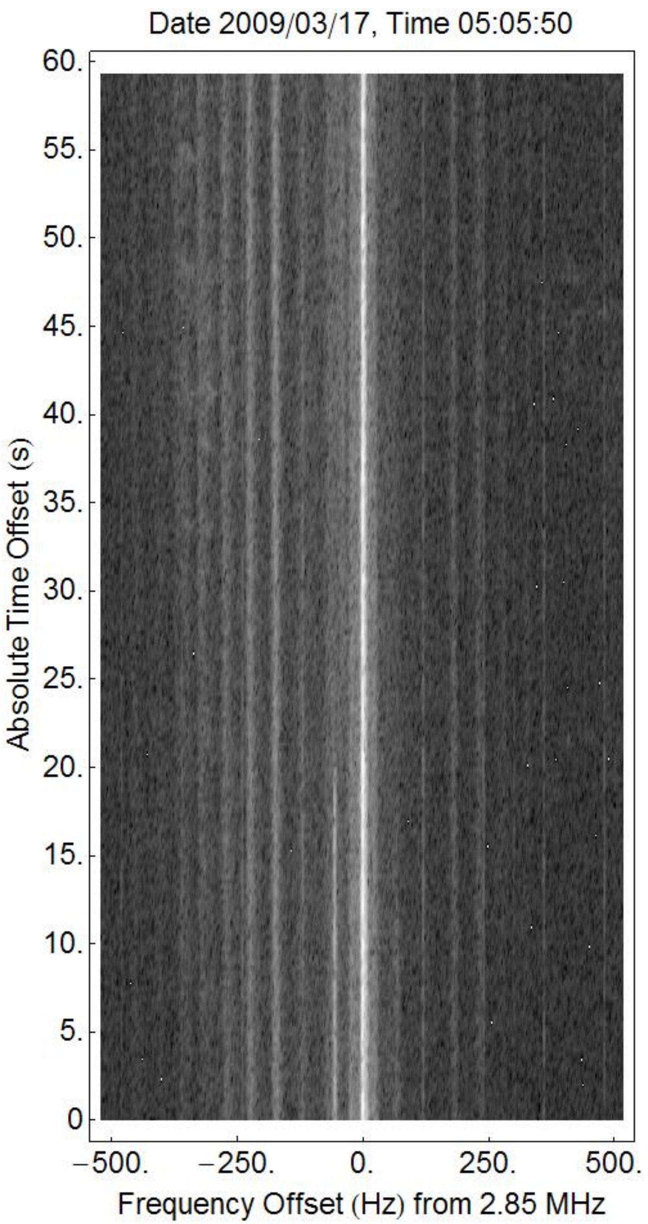
f_1=10~12 Hz;
f_2=24~26 Hz;
f_3=50~52 Hz;
f_4=70~72 Hz;

Stimulated Ion Bernstein (SIB) Generation by Tuning to the Second Electron Gyro Frequency



Stimulated Ion Bernstein Waves with $f_0 = 2\ f_{ce}$



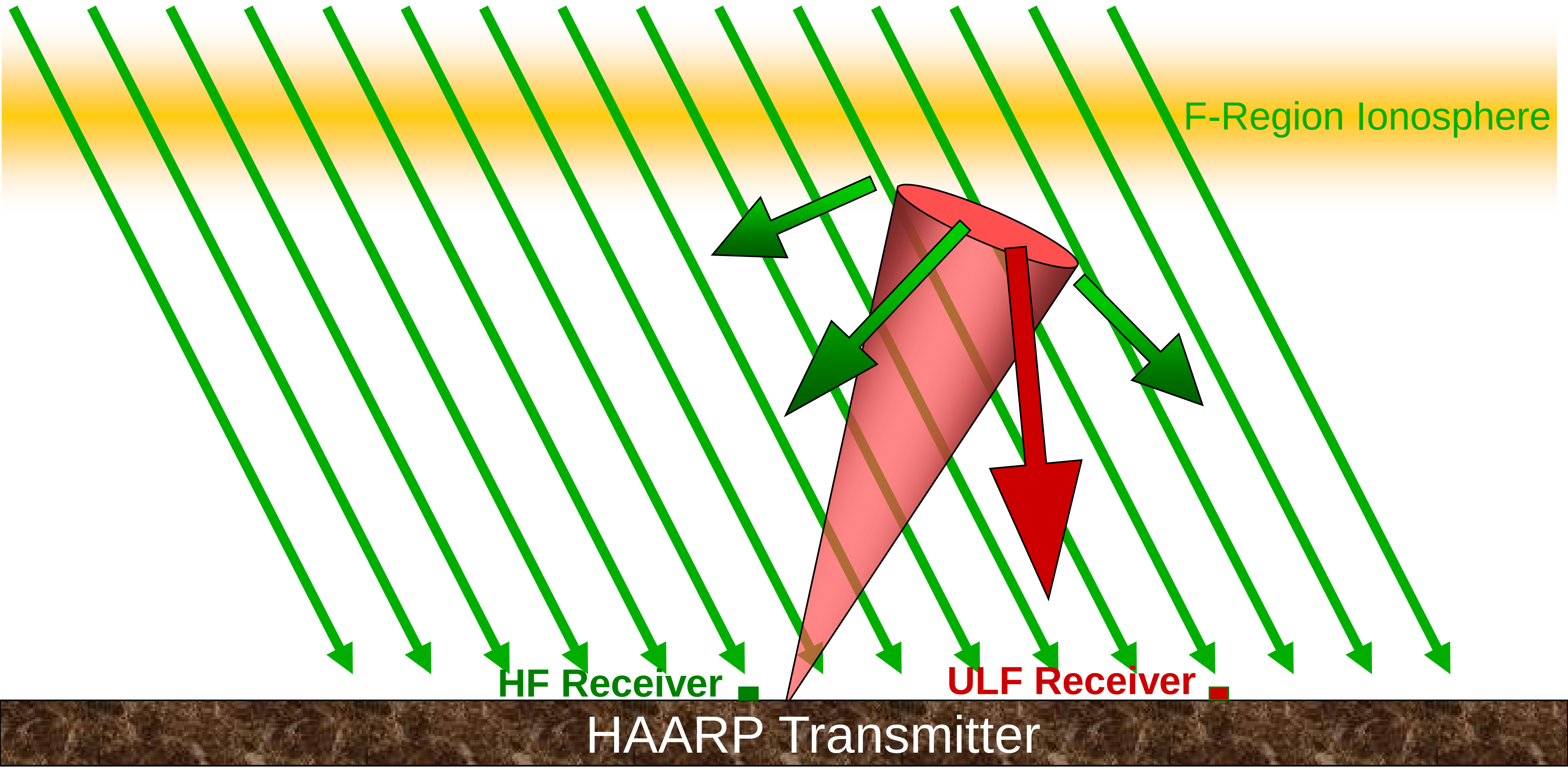


- HF Tuned to 2nd Electron Cyclotron Harmonic
- Ion Cyclotron Frequency = 55 Hz
- Dropout of Ion Cyclotron Mode
- Constant Amplitudes for Ion Bernstein Modes
- Observed at All Pointing Angles
- Search for Narrowband Ground ELF Signal

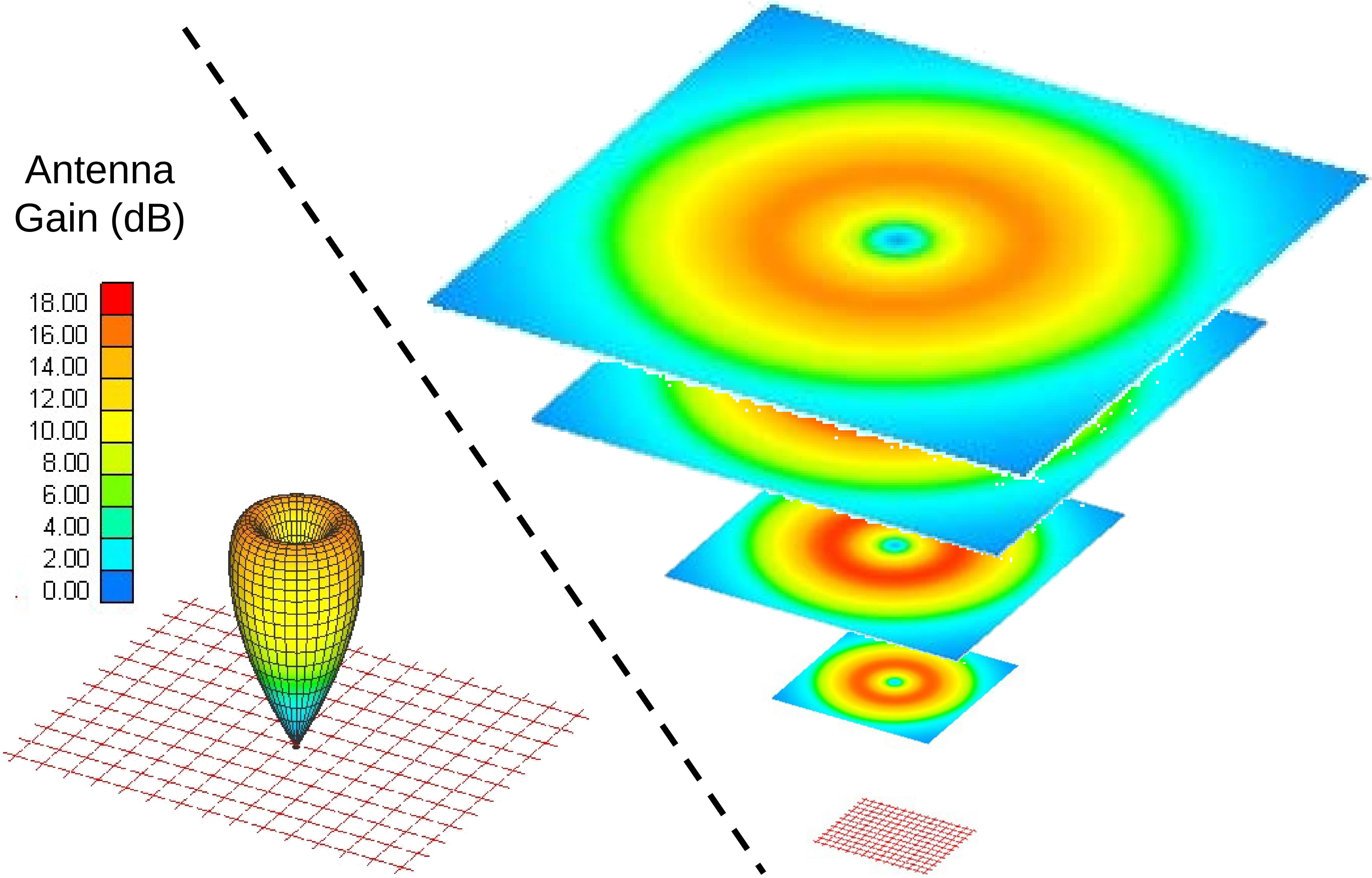
Direct ULF Generation

- Process
  - HAARP 3.6 MW HF transmitter
  - High Gain Phased Array Antenna
    - 12 x 15 Dipoles Each Excited by 20 kW
    - Phased to Tilt HF Beam Greater than 20 Degrees from **B**
  - Frequency Tuned Away from Gyro Harmonic (4.2 MHz)
    - Decay of Pump Wave
      - Electrostatic Ion Cyclotron Wave
      - Downshifted EM Wave
    - Coupling of EIC wave to ULF EM Mode on Field Aligned Irregularities
  - Detection with Ground Receivers
    - UFL Receiver Tuned to About 48 Hz
    - HF Receiver Tuned to 4.2 MHz with 250 kHz BW
- Results
  - EIC Mode Second Strongest Produced
  - Strong Dependence of HF Beam Orientation

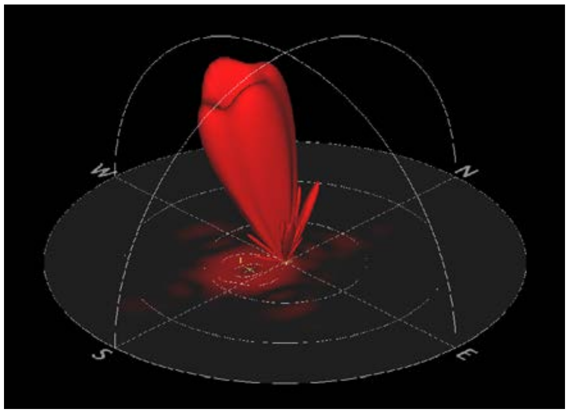
Stimulated ULF and HF Electromagnetic Emissions with HAARP



HAARP Array Generates a Hollow Beam

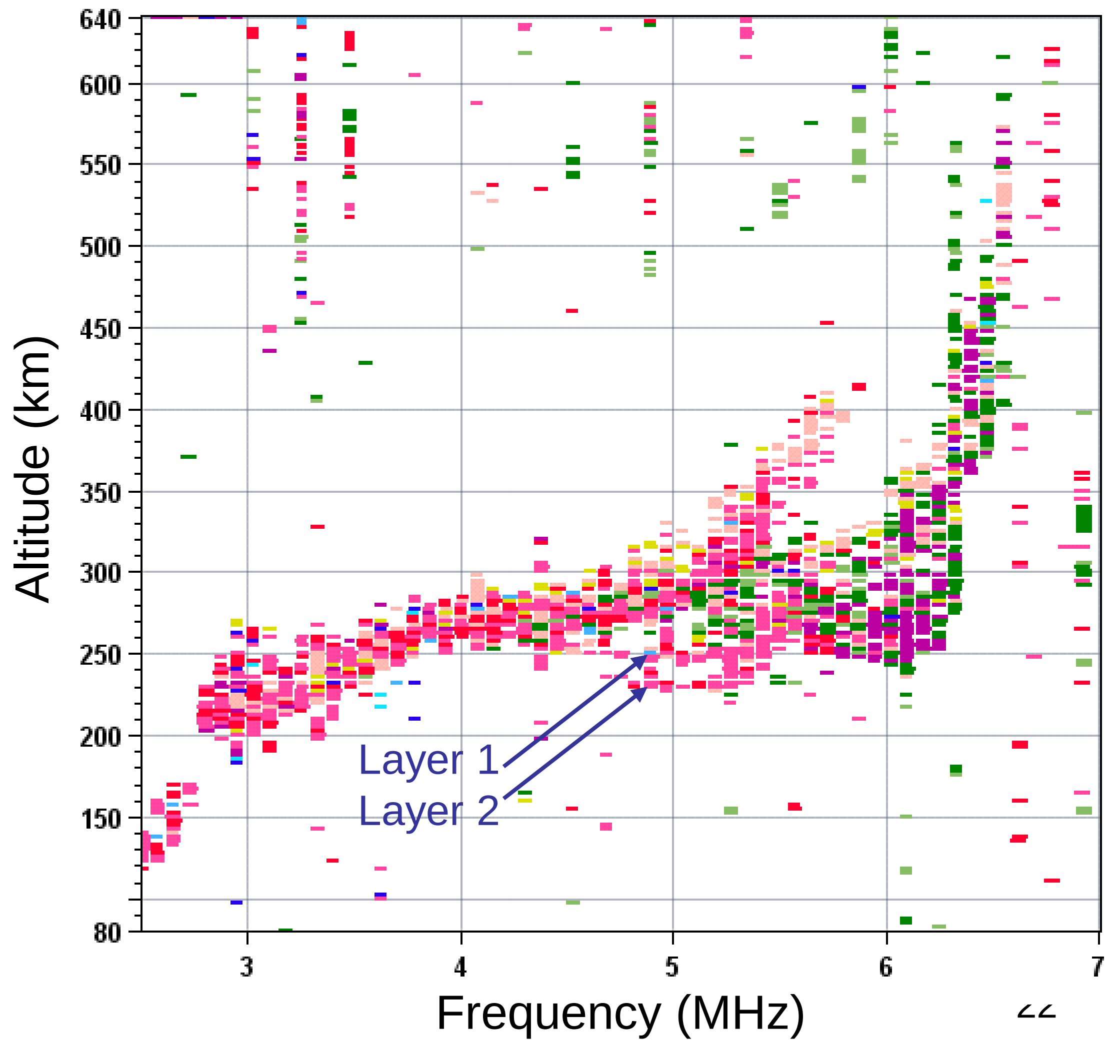


Artificial Ionospheric Layers Created by the HAARP Transmitter

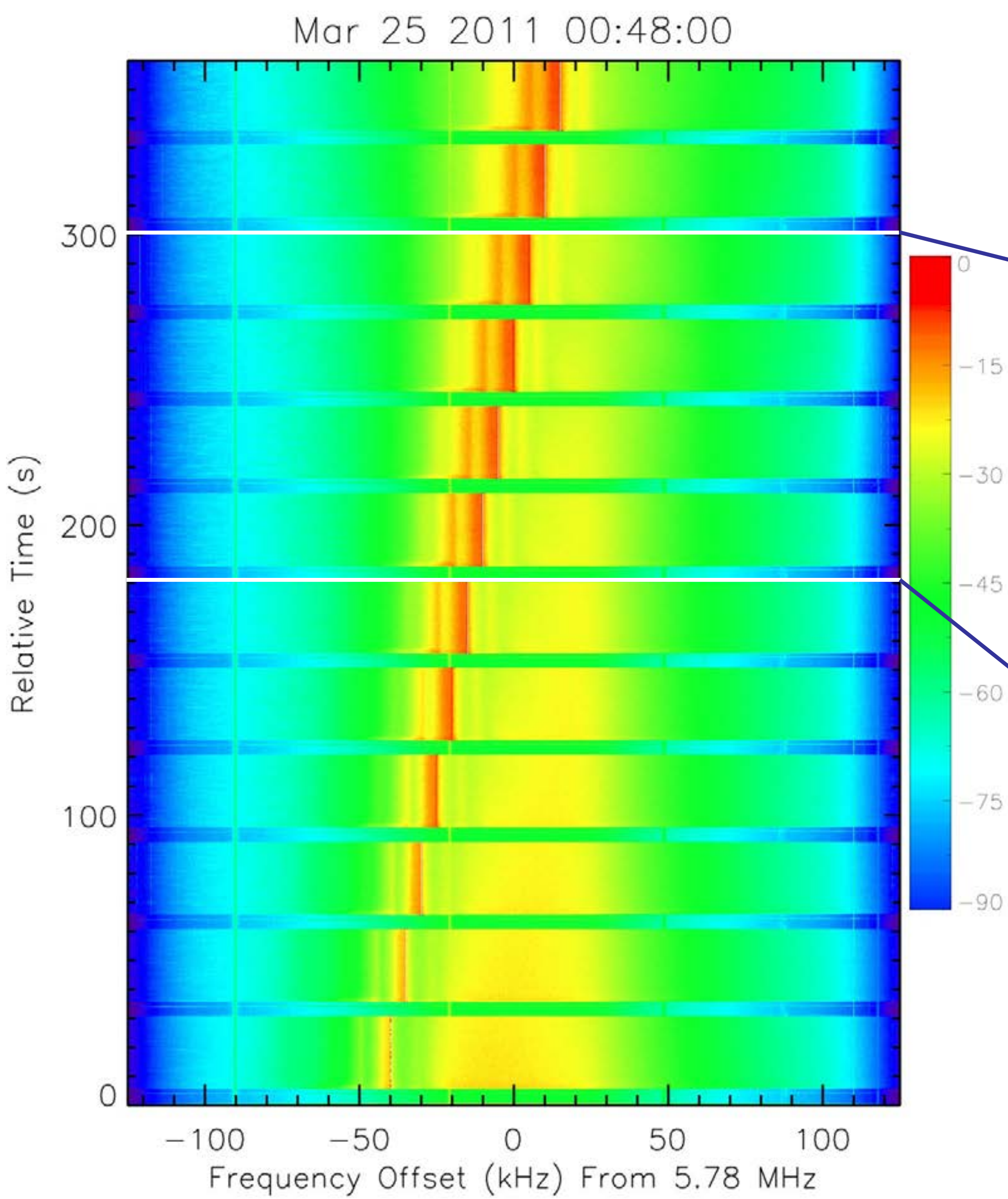


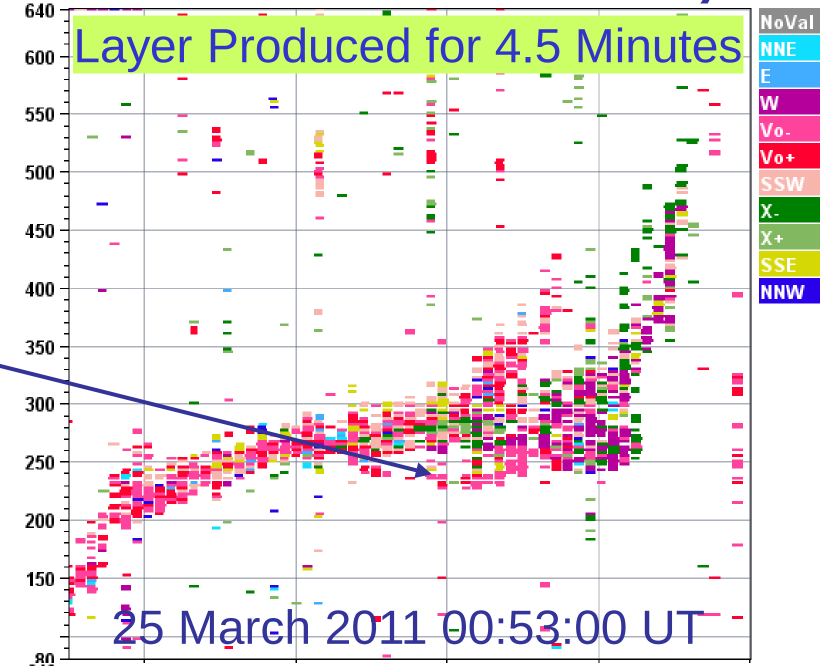
HF Twisted Beam

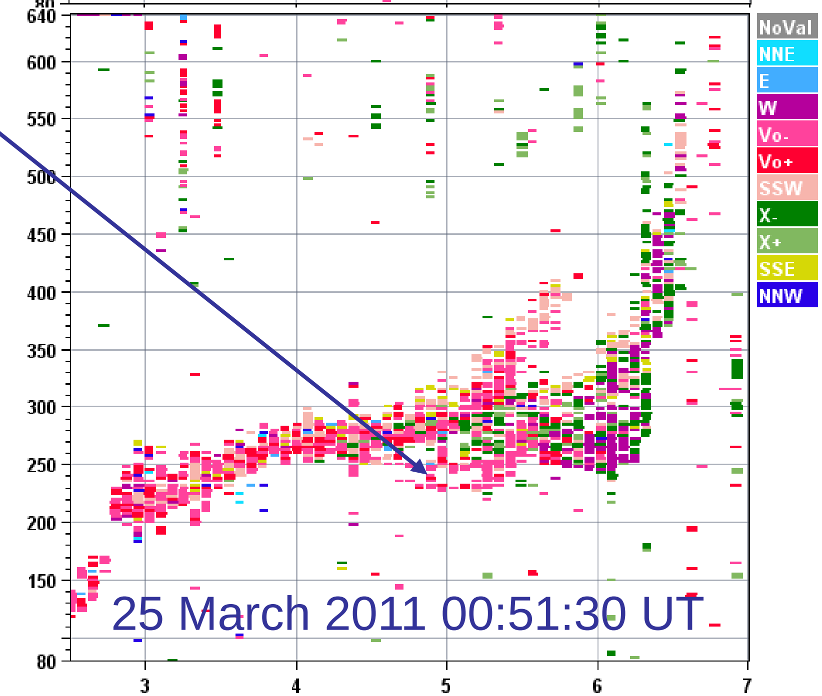
- Objectives
  - Form Stable Plasma Layer
  - Open Artificial Propagation Path
- Progress
  - Demonstrated Twisted Beam
  - Formed Layer Lasting 5 Minutes
  - 4th Harmonic Resonance
  - Cyclotron Resonance Theory



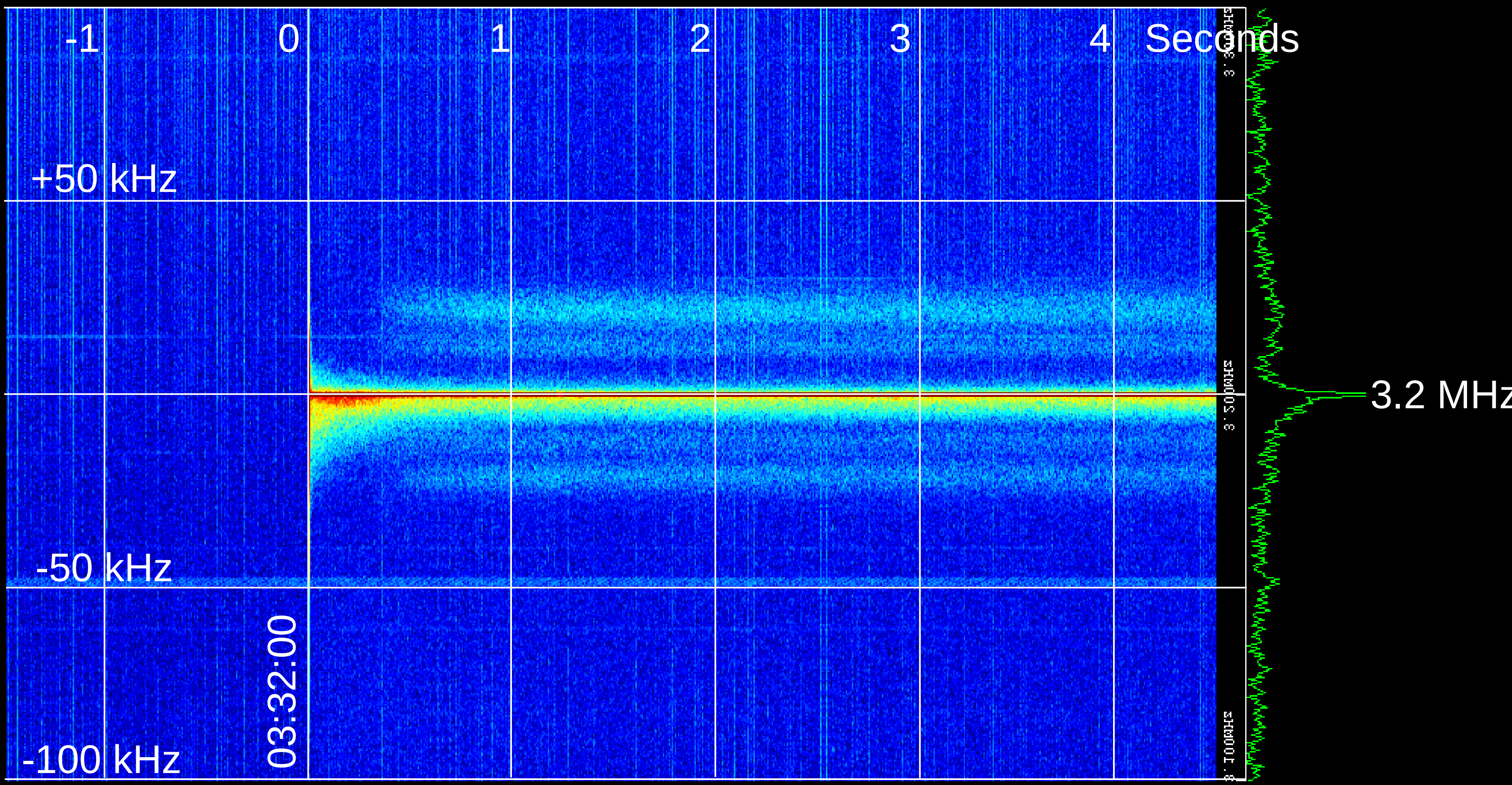
SEE Near the 4th Gyro Harmonic and Artificial Layers



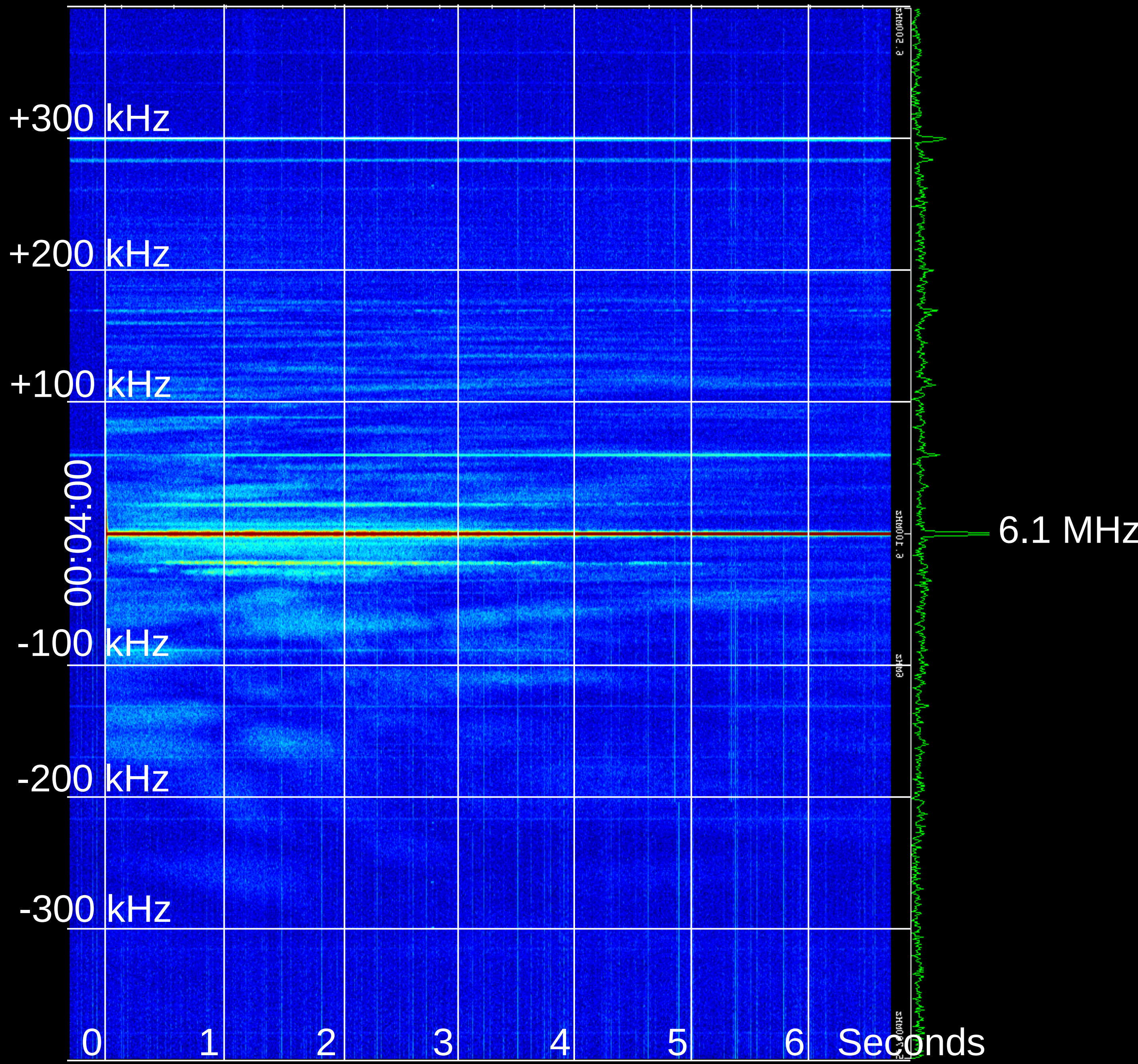




26 August 2011 SEE 03:32 UT



27
August
2011
SEE
00:04
UT



HF SEE Receiver Use Conclusions

- Simple New Experiments for HAARP
- 4th Gyro Harmonic Heating with Twisted Beam
  - Broad Upshifted Maximum and Ion Bernstein Waves in SEE Obtained with the Mark II-D Receivers
  - Long Lasting Artificial Plasma Layers at Fixed Altitude
- Coordinated Receiver Observations
  - HF SEE Modes Measured with the Mark II-D Receivers
  - ULF Ground Modes
- Acknowledgments

  - NRL Support by Geoff San Antonio and Serafin Rodriquez
  - MIT Lincoln Support by Scott Coutts and Matthew Morris

- Future Work – Plasma Science Instruments in Space
  - HF Receiver
  - Langmuir Probe
  - Magnetometer