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: $B_0 \approx 28 \times 10^{-6}$ T
- Plasma Pressure Versus Magnetic Pressure
  $\beta \approx nkT/(B^2/2\mu_0) = 10^{-8}$
- Ion Collisions Versus Ion Gyro Orbits
  $\Omega_i \sim v_i$ at 100 km Altitude
Past, Current and Future HF Ionospheric Modification Facilities

- HIPAS
  - HAARP
- Arecibo
- Platteville
- Jicamarca
- EISCAT
- SURA
- Arecibo Conjugate
Stimulated Electromagnetic Emissions, Radar Backscatter, Enhanced Plasma Waves and Artificial Aurora

HF Radar
HAARP Transmitter
UHF Radar

HF Receiver
HF Receiver
Camera
Plasma Physics of Ionospheric Modification with High Power Radio Waves

- Electron Temperature Elevation
- Plasma Pressure and Density Changes
- VLF Ducts and Conductivity Modification
- VLF Waveguides and VLF Generation
- Plasma Irregularity Formation
- Enhanced Radar Scatter
- Plasma Line
- Ion Line
- Electrostatic Wave Generation
- Low Frequency Waves
- Mode Conversion
- Stimulated Electromagnetic Emissions
- Parametric Decay and Strong Turbulence
- High Frequency Waves
- Electron Acceleration
- Artificial Aurora
- High Power Electromagnetic Wave Beam
- VLF Waveguides and VLF Generation
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

- **EM Pump Wave**
- **Optional Mode Conversion**
- **High Power EM or ES Wave**
- **Parametric Decay**
- **Low Frequency ES Wave**
- **Possible Mode Conversion?**
- **Low Frequency EM Wave**
- **Optional Mode Conversion**
- **Received EM Wave**

**Graph**

- **Relative Power (dB)**
- **Frequency (MHz)**
- **In Situ Source: Upper Hybrid Waves**
- **In Situ Source: Electron Bernstein Modes**

**Legend**

- **DM**
- **2D**
- **UM**
- **BU**

**Labels**

- **Loss**
- **4.10 - 4.15 - 4.20 - 4.25 - 4.30**
- **-10 -20 -30 -40 -50 -60**
HAARP HF Transmitter Array
2.6 to 10 MHz, Up to 3.6 GW Effective Radiated Power
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 $f_3$;
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

For O mode reflected at \( \omega_0 = \omega_p \)

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

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

EM1

IA1

EM2

SBS-1

θ = 0

Date 2008/10/24, Time 19:37:50

Power (dB)

SBS-1

SBS+1

SBS+2

-20

-40

-60

-80

-200

0

200

Frequency Offset (Hz) from 5.6 MHz

Date 2008/10/24, Time 19:37:50

Absolute Time Offset (s)

0

10

20

30

40

-200

-100

0

100

200

Frequency Offset (Hz) from 5.6 MHz

Pump

f_{IA1}
Brillouin Scattering of the 4.5 MHz HAARP Vertical Beam in the Ionosphere
SBS with EIC Generation Yields Ion Mass

\[ f_{EIC-1} = m_{[O^+]}. \]

\[ m_i = e B / f_{EIC} \]

Radio Beam Angel with B (\( \theta \))

Stimulated Brillouin Lines at 4.2 MHz

Ion Acoustic Frequencies

Ion Cyclotron Frequency
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 $f_1 = 10\sim12$ Hz is stronger close to the magnetic zenith
- The IA lines $f_2 = 24\sim26$ Hz appears for $ZA=28^\circ$, $AZ=202^\circ$
- The EIC lines $f_3 = 50\sim52$ Hz appears for $ZA=28^\circ$, $AZ=202^\circ$
- The newly observed $f_4 = 70\sim72$ Hz appears for $ZA=28^\circ$, $AZ=202^\circ$
Stimulated Ion Bernstein (SIB) Generation by Tuning to the Second Electron Gyro Frequency

![Diagram]

- **$EM_0$** \(\rightarrow\) **$EB_0$**
- **$IB_1$** \(\rightarrow\) **$IB_2$** \(\rightarrow\) **$IB_3$**
- **$EB_1$** \(\rightarrow\) **$EM_1$** \(\rightarrow\) **$SIB_1$**
- **$EB_2$** \(\rightarrow\) **$EM_2$** \(\rightarrow\) **$SIB_2$**
- **$EB_3$** \(\rightarrow\) **$EM_3$** \(\rightarrow\) **$SIB_3$**
Stimulated Ion Bernstein Waves with $f_0 = 2 f_{ce}$

- HF Tuned to 2$^{nd}$ 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 \( \mathbf{B} \)
  – 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

F-Region Ionosphere

HAARP Transmitter

ULF Receiver

HF Receiver
HAARP Array Generates a Hollow Beam

Antenna Gain (dB)
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
  - 4\textsuperscript{th} Harmonic Resonance
  - Cyclotron Resonance Theory
SEE Near the 4th Gyro Harmonic and Artificial Layers

Layer Produced for 4.5 Minutes

Mar 25 2011 00:48:00

Frequency Offset (kHz) From 5.78 MHz

25 March 2011 00:51:30 UT

25 March 2011 00:53:00 UT
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
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• Future Work – Plasma Science Instruments in Space
  – HF Receiver
  – Langmuir Probe
  – Magnetometer