FUNDAMENTAL PHYSICS ISSUES ON RADIATION BELTS AND REMEDIATION

Invited Presentation at the 16th Annual RF Ionospheric Interactions Workshop
April 20, 2010

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The MURI Team

- **Leadership**
  - **UMCP – Dennis Papadopoulos - Overall Direction**
  - **Stanford University – Umran Inan -Wave Particle Interactions (Theory, Modeling and Field Tests)**
  - **UCLA – Walter Gekelman - Laboratory Experiments**
  - **Va Tech – Wane Scales – USC- Joseph Wang**
    Particle and hybrid electromagnetic codes (Physics codes)
  - **Dartmouth – Anatoly Streltsov - Global numerical models (engineering codes)**

Acknowledge Major Contributions:

BAE Systems AT: C.L.Chang, I. Doxas, J. Lebinsky

UMCP: S. Sharma, X. Shao, B. Eliasson ,N. Gumerov,L. Rudakov, A. Karavaev

NRL: M. Lampe, G. Ganguli, J. Huba

Stanford: T. Bell

UCLA: G. Morales

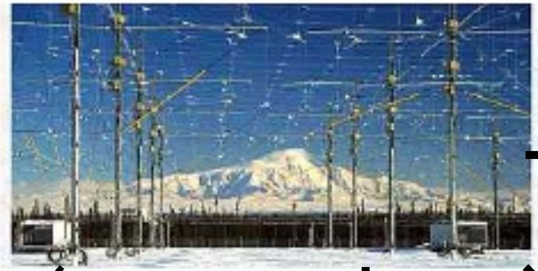
OVERARCHING OBJECTIVES

- TECHNICAL
  - DEVELOP QUANTITATIVE MODELS OF THE LOSS RATE OF ENERGETIC PARTICLES IN THE INNER RADIATION BELTS AND TEST AGAINST OBSERVATIONS
  - ASSES AND TEST CONCEPTS FOR CONTROLLED INJECTION OF VLF/ELF/ULF WAVES IN THE RB FROM GROUND AND SPACE PLATFORMS
  - PROVIDE THE PHYSICS UNDERPINNINGS THAT CAN LEAD TO ACTIVE CONTROL THE ENERGETIC PARTICLE FLUX TRAPPED IN THE RADIATION BELTS (RBR ; PRBR)
- EDUCATIONAL
  - DEVELOP THE SCIENTIFIC AND ENGINEERING MANPOWER WITH THE INTERDISCIPLINARY SKILLS REQUIRED TO ADDRESS FUTURE MAJOR TECHNICAL ISSUES OF NATIONAL SIGNIFICANCE

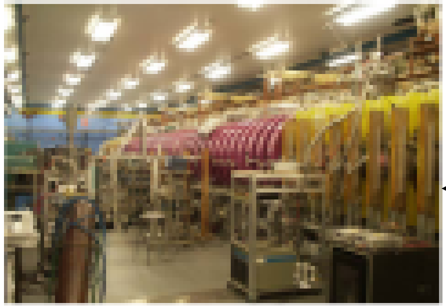
Methodology-Resources

TOPICS ADDRESSED BY *AN INTERPLAY* OF THEORY/COMPUTATION, LABORATORY EXPERIMENTS, FIELD EXPERIMENTS, SATELLITE MEASUREMENTS AND DATA ANALYSIS

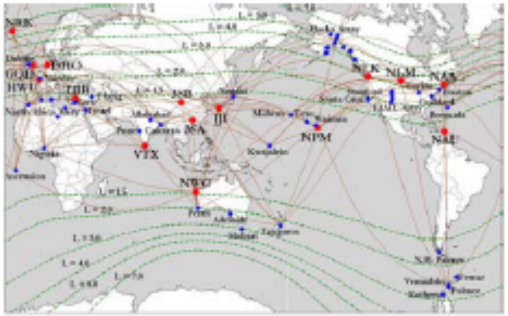
HAARP



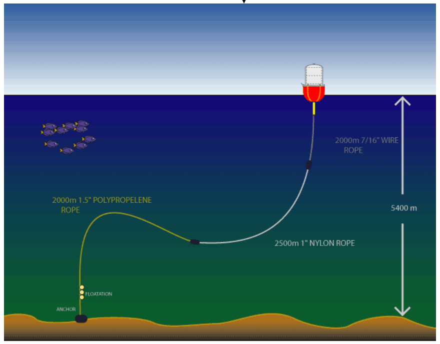
DEMETER



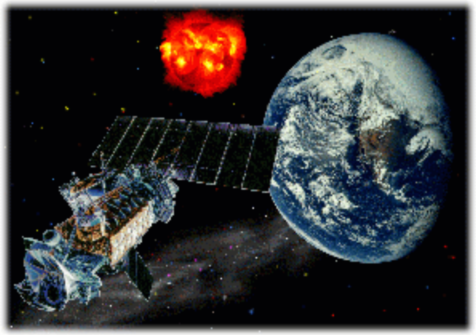
LAPD



Worldwide SU-Deployed VLF Receiver in support of IHY/UNBSS Program



CONJUGATE BUOYS



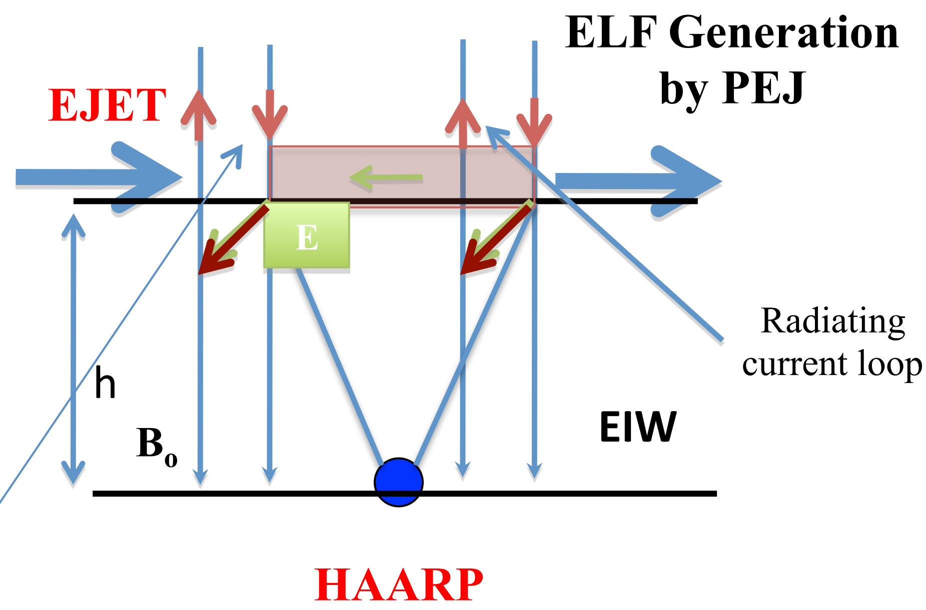
DMSP

PHYSICS AND TECHNOLOGY CHALLENGES

- **Radiate** - Inject efficiently from space or ground VLF/ELF/ULF waves in the RB
  - Performance of electric dipole antennas at VLF in plasmas (DSX - AF)
  - VLF generation in RB by injection of low ionization chemicals -
  - Innovative Injection Concepts – Rotating Magnetic Field (RMF), Ionospheric Current Drive (ICD), Sneak-Through (ST)
- **Propagate** – Guide waves to regions of enhanced RB
  - Injection to naturally occurring ducts
  - Generation of artificial ducts by ionospheric heaters (HAARP)
  - The missing 20 dB puzzle
- **Amplify** – Use the free energy stored in trapped energetic particles to amplify the VLF wave power
  - The physics of Artificially Stimulated Emissions
  - Optimizing conditions for ASE
- **Precipitate** – Physics of particle precipitation with Wave Particle Interactions (WPI)
  - The physics of slot formation
  - The physics of energetic proton loss
  - How to precipitate without requiring resonance

RADIATE

The Polar Electrojet (PEJ) Antenna

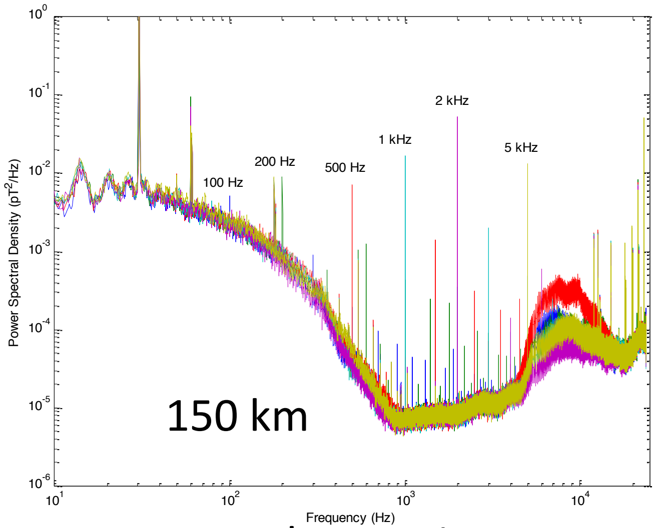


How it Works – What does it do

1. Find a region where natural currents flow in the lower ionosphere – Polar Electrojet
2. Use an ionospheric heater to modulate the electron temperature and conductivity at the D/E region (hall Region).
3. Create an HED at the modulation frequency – current closure by current carried by whistlers or shear Alfven waves in the magnetosphere.

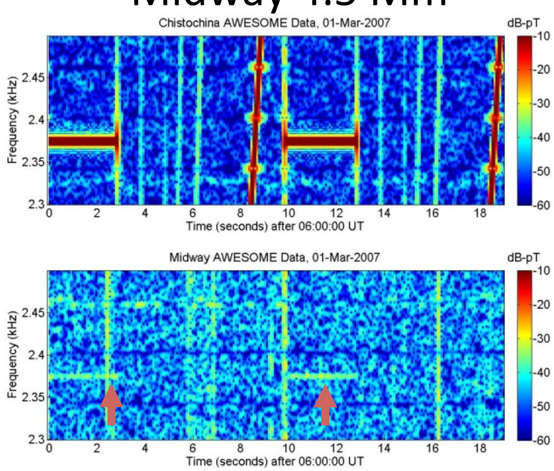
1. Injects waves of any frequency below 10-15 kHz in the EIW
2. Injects waves at any frequency below 10-15 kHz in the magnetosphere and the RB

PEJ Performance Examples

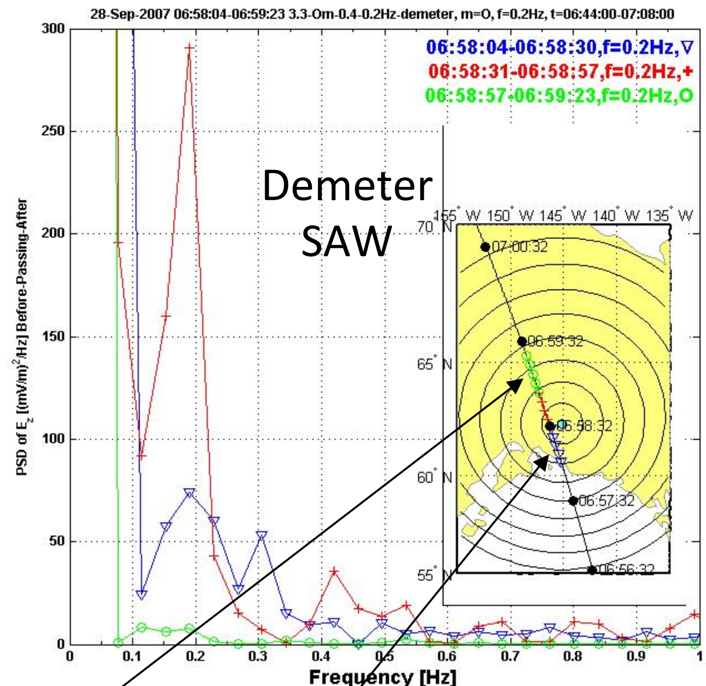


Local Detection

Midway 4.5 Mm



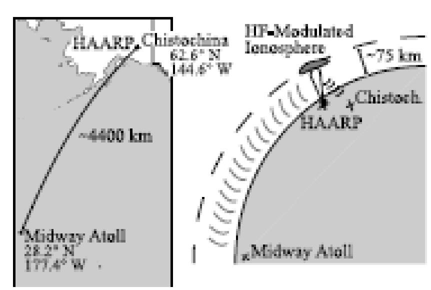
T_{det}< 1 sec



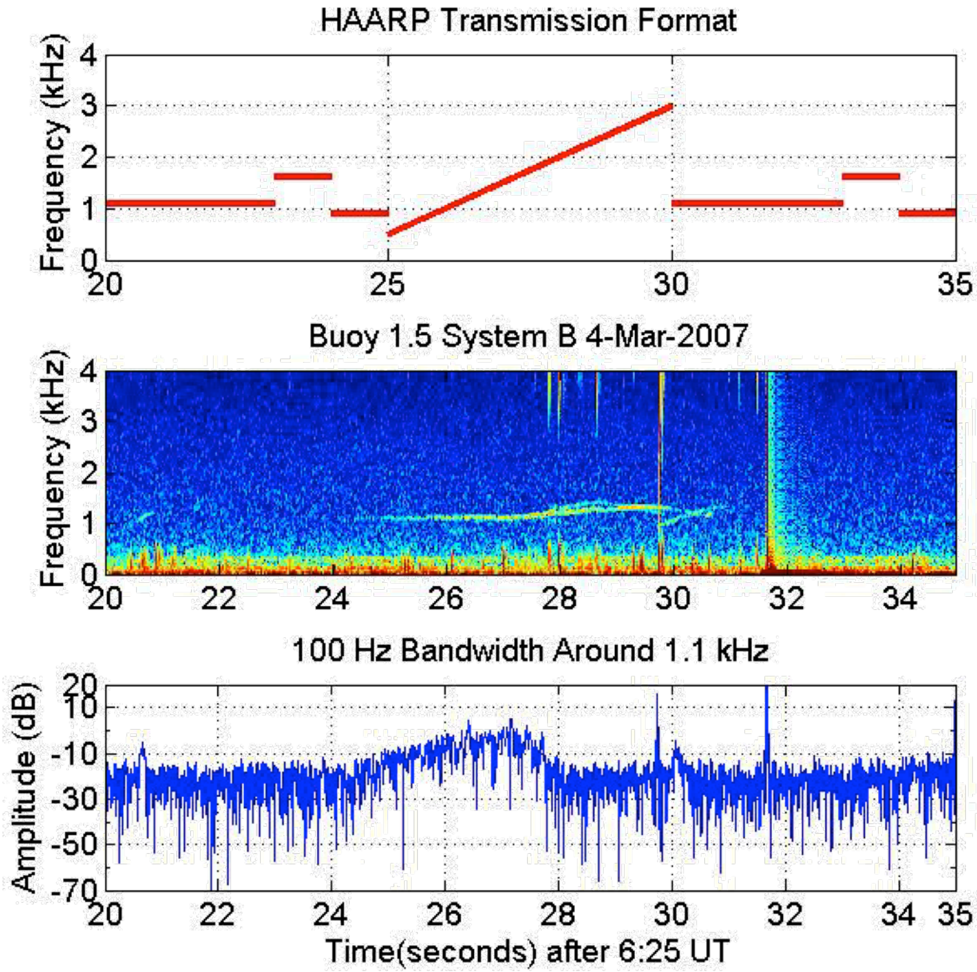
After

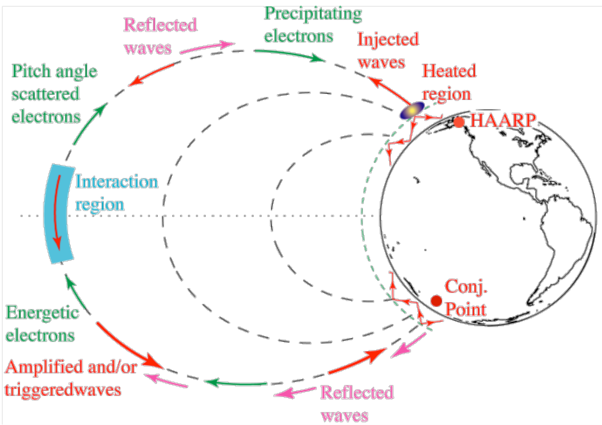
Before

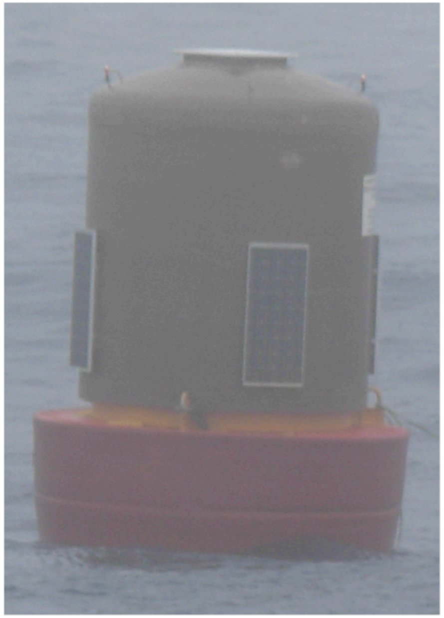
Injection to EIW Stanford



15 dB/s Amplification & Triggered Emissions







Only the pulse at 1100 Hz is amplified

Stanford

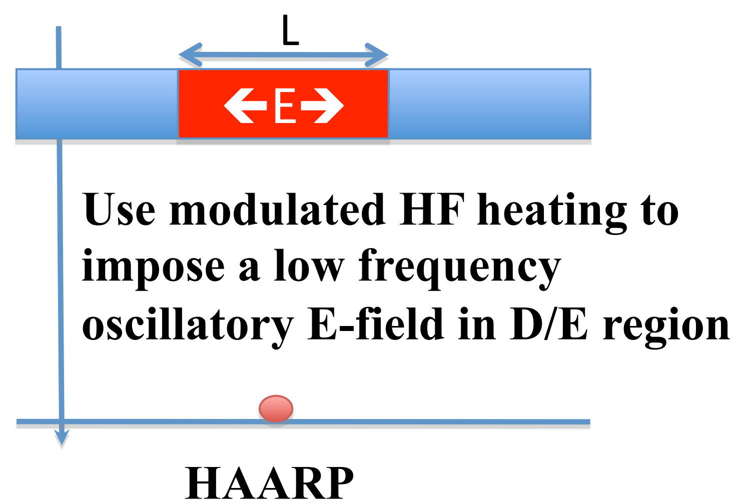
ASE theory UMCP-NRL- Dartmouth

PEJ Issues – ICD Desirability

PEJ Issues:

- Availability - EJ Unpredictable and often completely absent
- Location – EJ location far from desirable for applications for both communications and ASE

ICD: Use HF to drive oscillatory currents in the Hall (D/E) region. Virtual antenna.
Create your own current. No location and EJ availability constraints

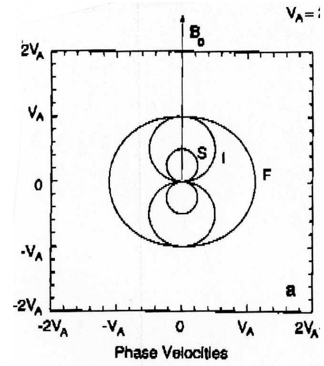


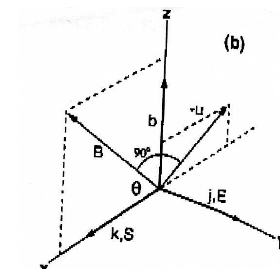
$$\vec{p} = (\overleftrightarrow{\Sigma}\vec{E}L)L$$

$$p_h \approx (\Sigma_h EL)L$$

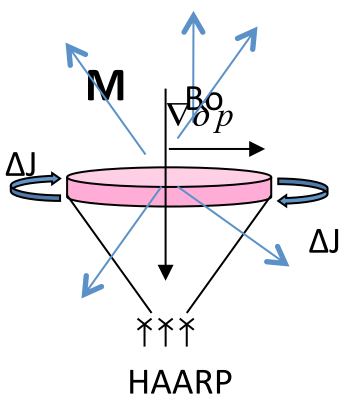
ICD Basics - F-region Heating – Diamagnetic Current

Step 1: Modulated F-region heating creates oscillatory diamagnetic current. Field aligned magnetic moment radiates Msonic waves isotropically in the plasma.

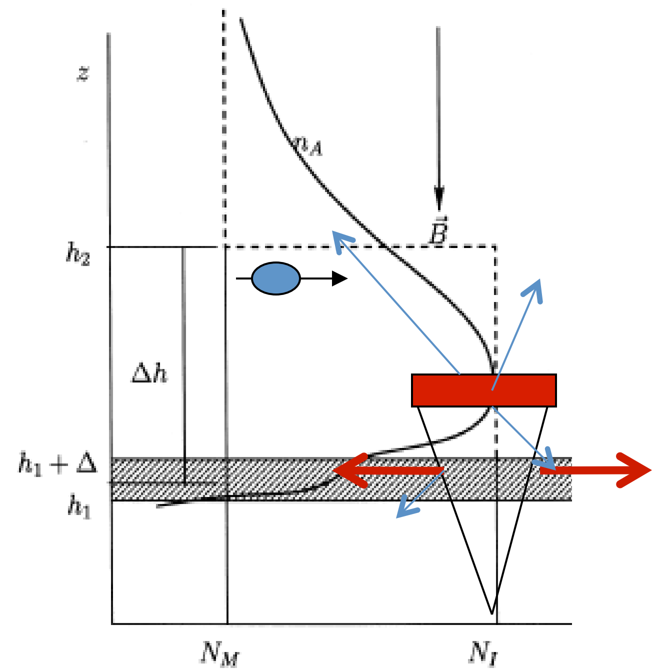




$$\Delta J = \frac{B \times \nabla \delta p}{B^2} \exp(i\omega t)$$

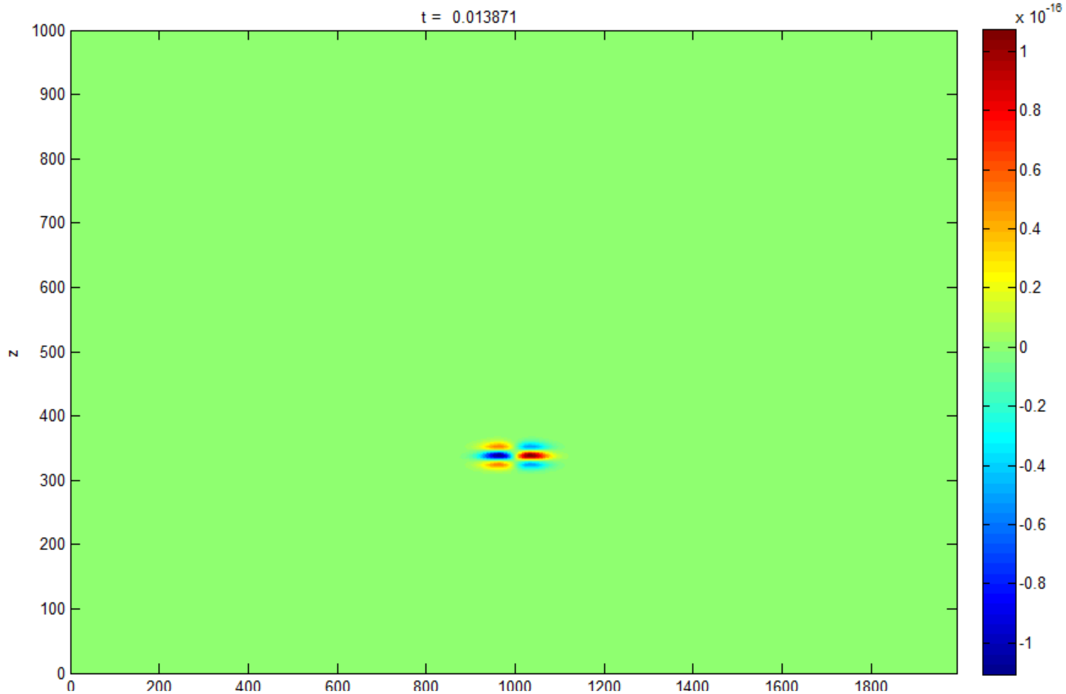


Step 2: E-field of msonic wave drives an oscillatory Hall current in the D/E region creating a virtual antenna. Injects waves in the EIW and SAW in the RB

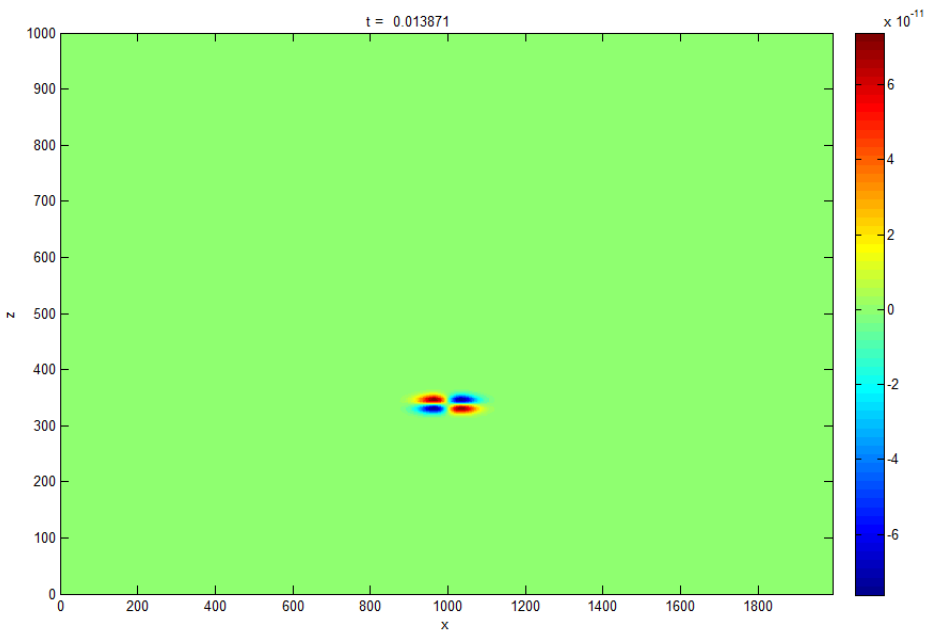


20 Hz ICD

J



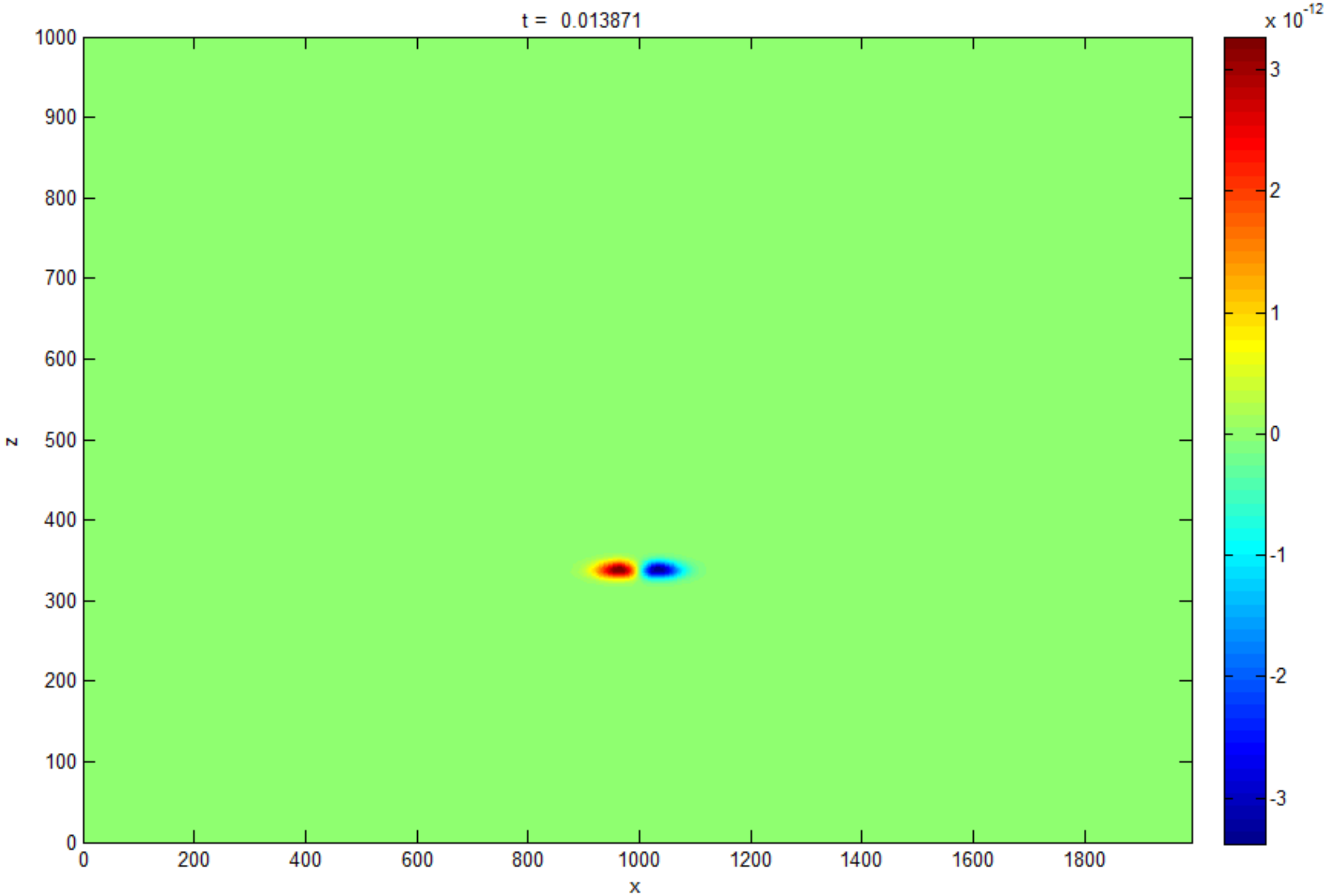
B_y



Code is modified version of Lysak Phys. & Chem. of the Earth (1997)

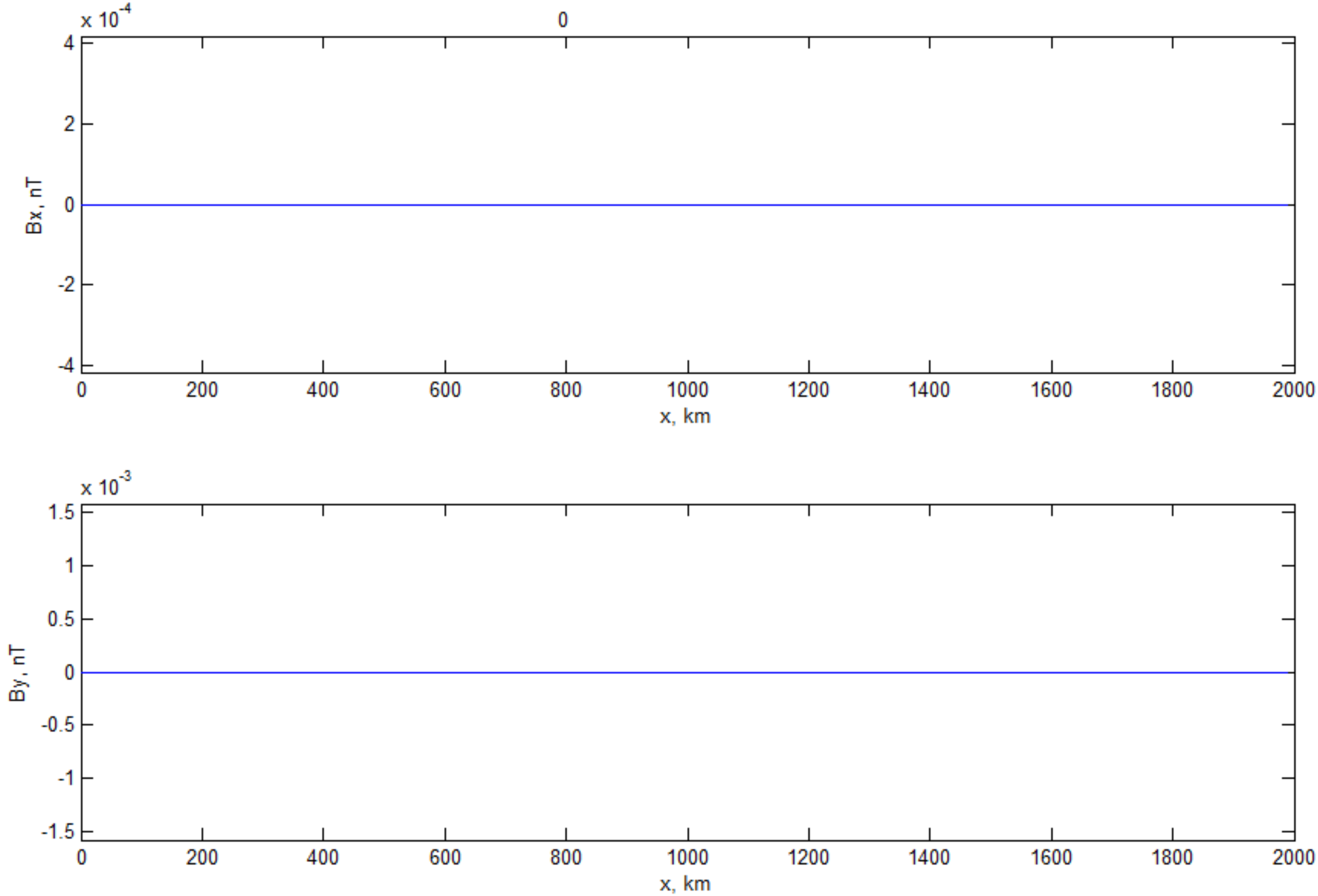
20 HZ

E FIELD



t = 0.013871
x 10^{-12}
3
2
1
0
-1
-2
-3
1000
900
800
700
600
500
400
300
200
100
0
z
0
200
400
600
800
1000
1200
1400
1600
1800
x

B field Ground Signature 20 Hz

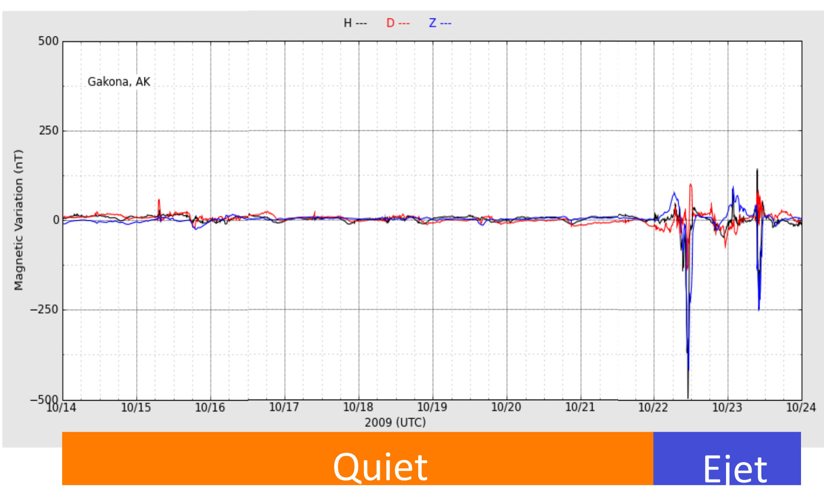


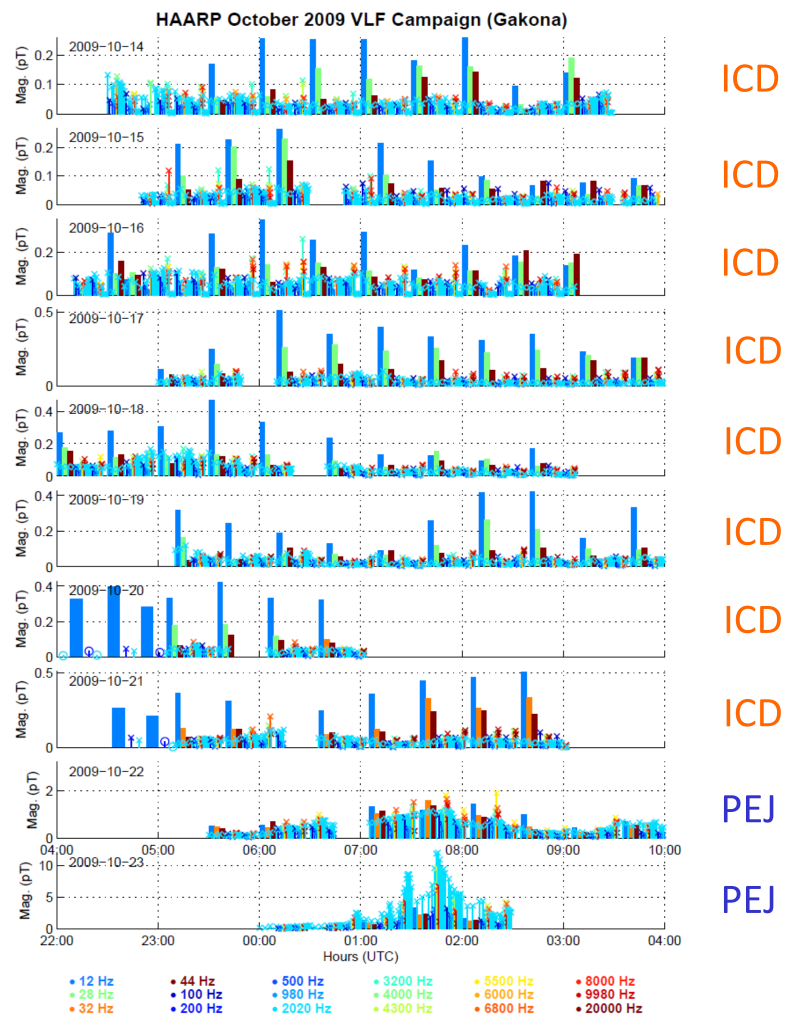
Theoretical Expectations

- **Ground B_w scaling**
  - **with frequency: Define $f_c \approx 1/\tau_c$ B_w** =const for $f<f_c$; $1/f$ for $f>f_c$
  - **With absorbed HF power $B_w \propto \alpha P_{HF}$**
  - **With distance from HAARP max. at 250-300 km, min Gakona**
- **Signal Optimum when f_{oE} low compared to f_{oF}**

ELF/VLF Generation - ICD vs. PEJ

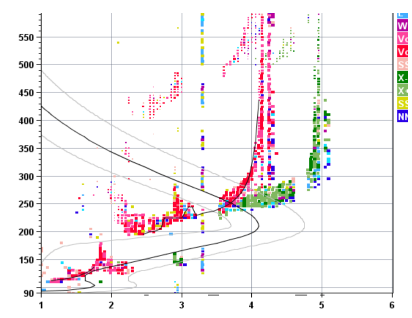
- **Oct.14-21, *ICD* was the source**
  - No electrojet, quiet ionosphere
  - Consistent daily ELF production, < 0.5 pT
- **Oct. 22-23, *PEJ* was the source**
  - Active electrojet
  - Spur of ELF/VLF production

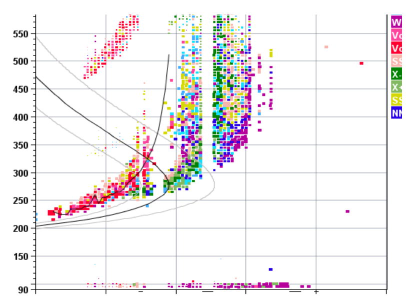


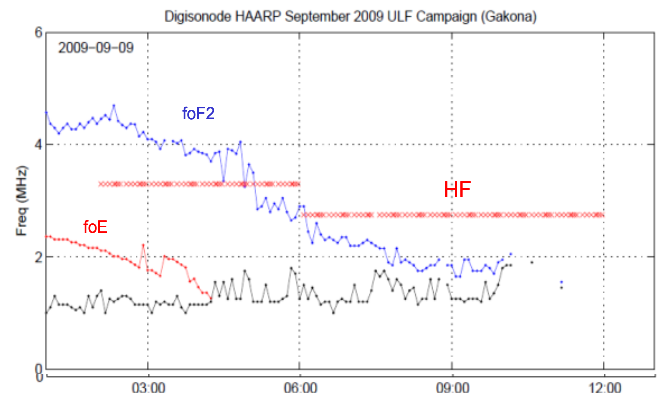


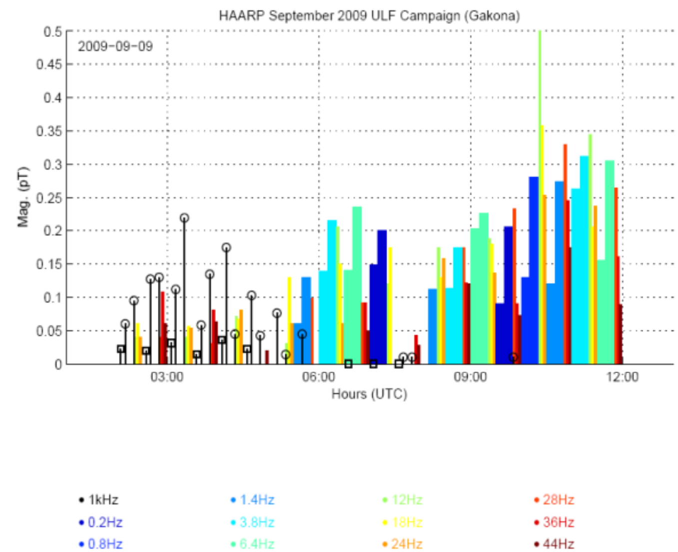
ELF Generation by F layer Modulation

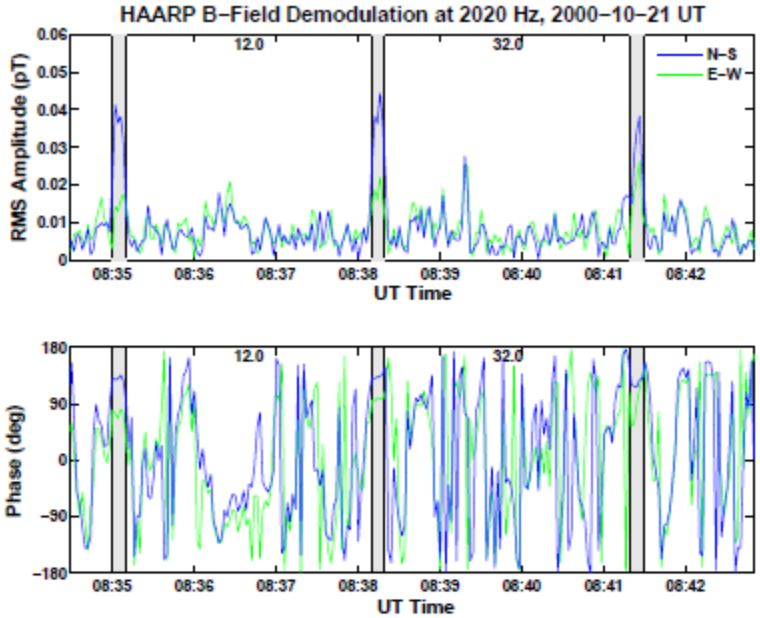
- September HAARP campaign
  - ULF: 0.2-6.4 Hz
  - ELF: 12-44 Hz & 1 kHz
- The ULF-ELF signals at Gakona:
  - Emerge on Sep. 9 after F is exposed
  - Generated up to 50 Hz
- The 1 kHz amp. is only significant when D/E layers were present

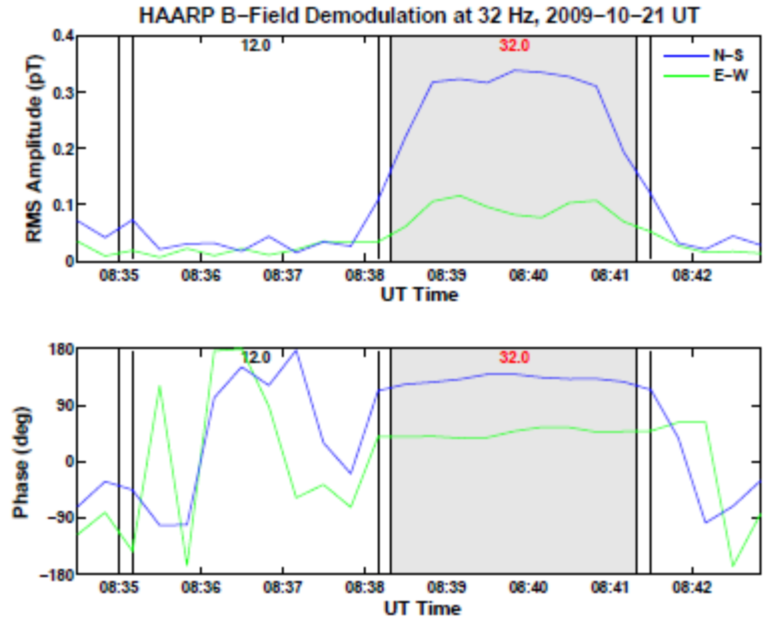


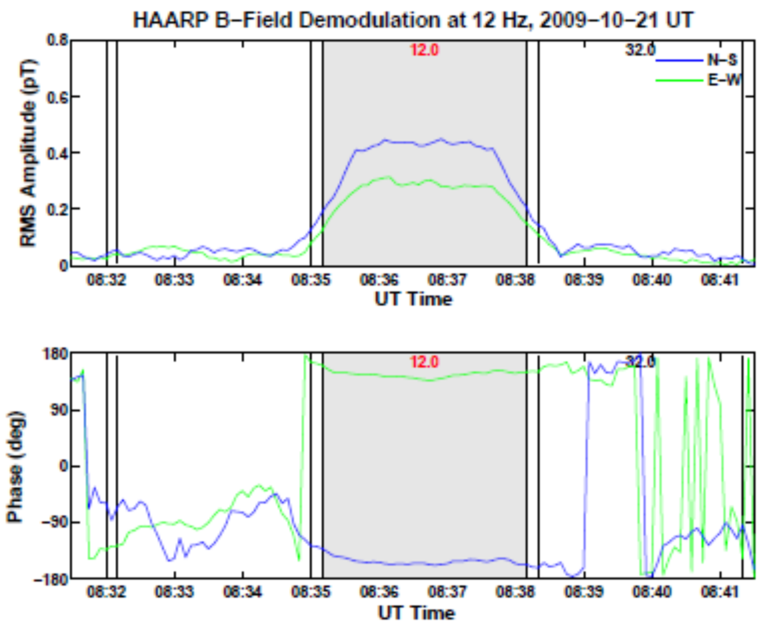


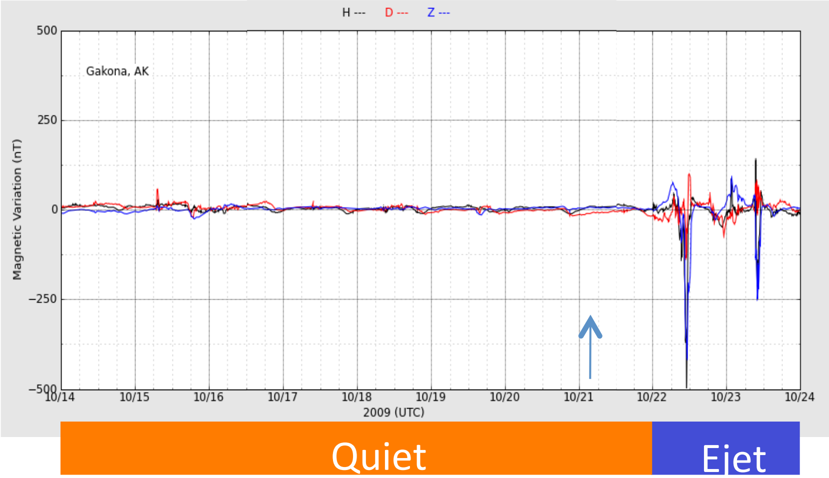


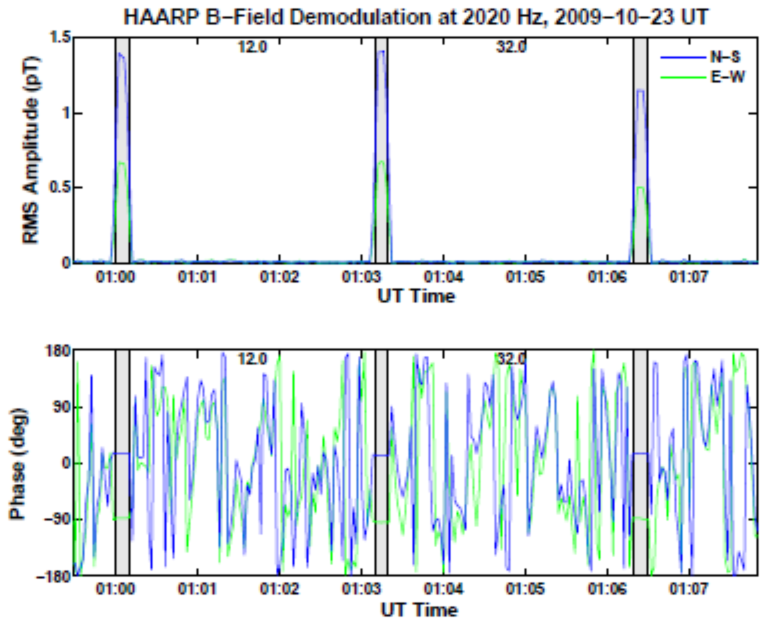


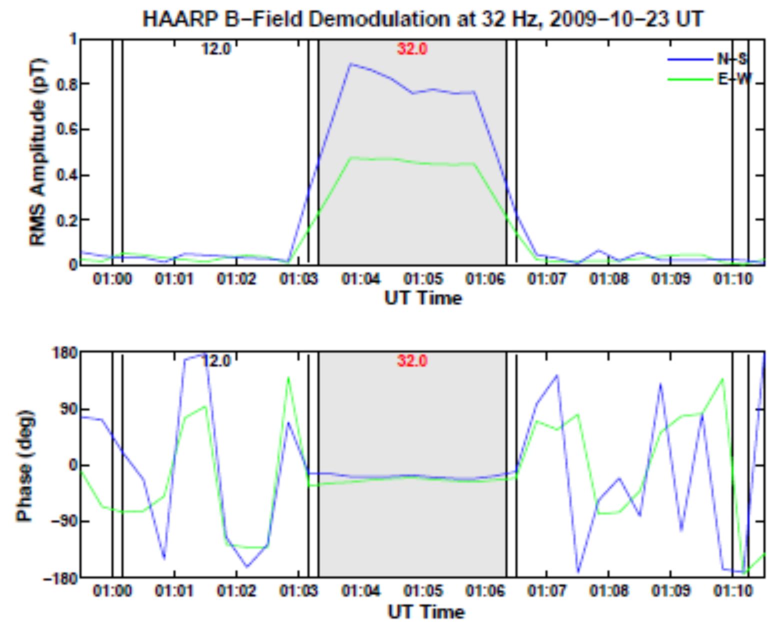

HAARP B–Field Demodulation at 2020 Hz, 2000–10–21 UT
RMS Amplitude (pT)
Phase (deg)
12.0
32.0
N–S
E–W
UT Time

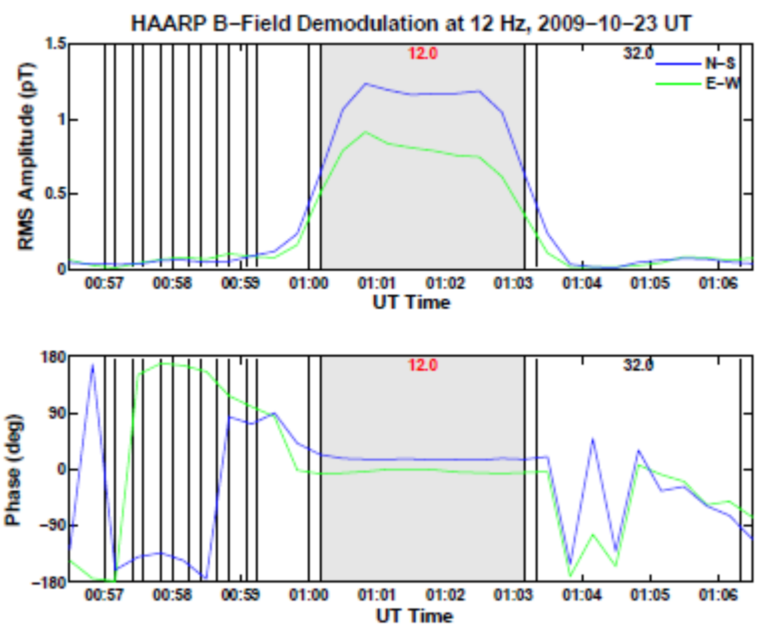

HAARP B–Field Demodulation at 32 Hz, 2009–10–21 UT
RMS Amplitude (pT)
Phase (deg)
12.0
32.0
N–S
E–W
UT Time

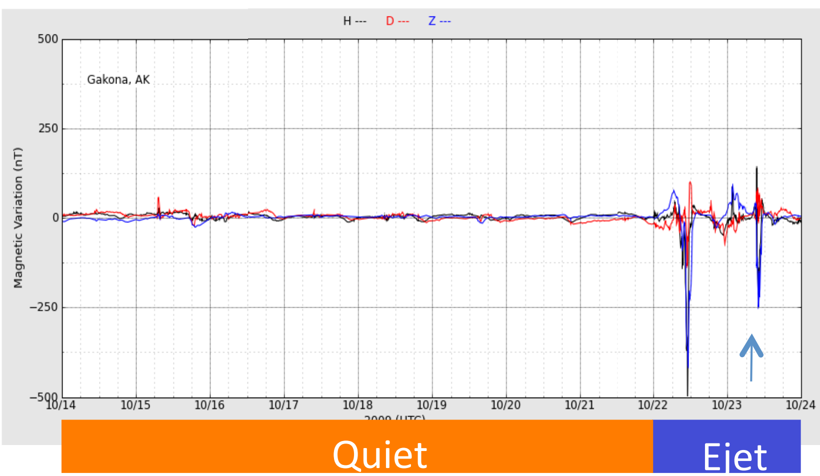

HAARP B–Field Demodulation at 12 Hz, 2009–10–21 UT
RMS Amplitude (pT)
Phase (deg)
12.0
32.0
N–S
E–W
UT Time


H --- D --- Z ---
Gakona, AK
Magnetic Variation (nT)
2009 (UTC)
Quiet
Ejet


HAARP B−Field Demodulation at 2020 Hz, 2009−10−23 UT
RMS Amplitude (pT)
Phase (deg)
UT Time
N−S
E−W
12.0
32.0
01:00
01:01
01:02
01:03
01:04
01:05
01:06
01:07

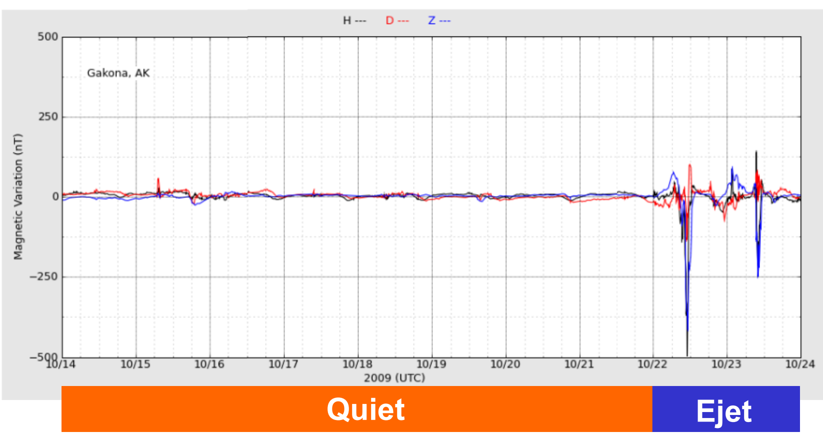

HAARP B−Field Demodulation at 32 Hz, 2009−10−23 UT
RMS Amplitude (pT)
Phase (deg)
UT Time
N−S
E−W
12.0
32.0
01:00
01:01
01:02
01:03
01:04
01:05
01:06
01:07
01:08
01:09
01:10

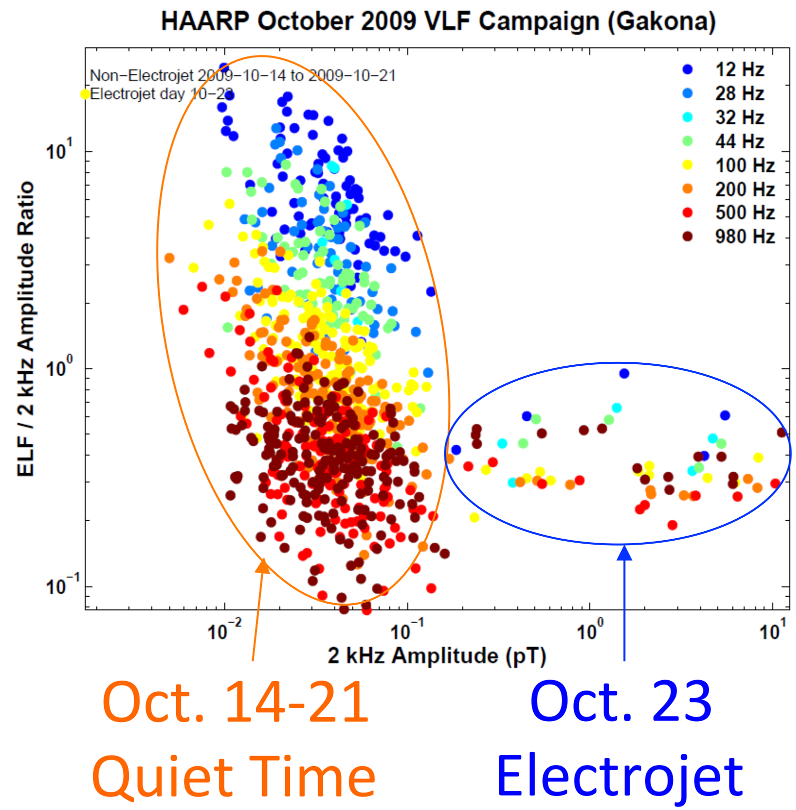

HAARP B−Field Demodulation at 12 Hz, 2009−10−23 UT
RMS Amplitude (pT)
Phase (deg)
UT Time
N−S
E−W
12.0
32.0
00:57
00:58
00:59
01:00
01:01
01:02
01:03
01:04
01:05
01:06


H ---
D ---
Z ---
Gakona, AK
Magnetic Variation (nT)
10/14
10/15
10/16
10/17
10/18
10/19
10/20
10/21
10/22
10/23
10/24
Quiet
Ejet

Overall ELF/VLF Results

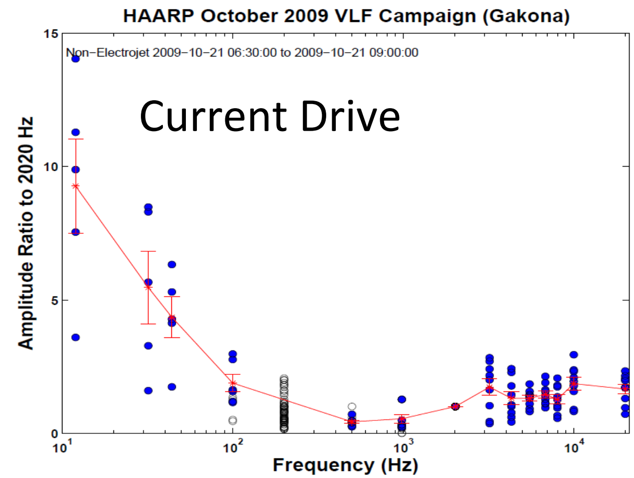
- 10 Hz – 1 kHz Gakona results
  - Normalized to 2 kHz amp.
- Two distinct groups of data
  - Quiet time
  - During Electrojet

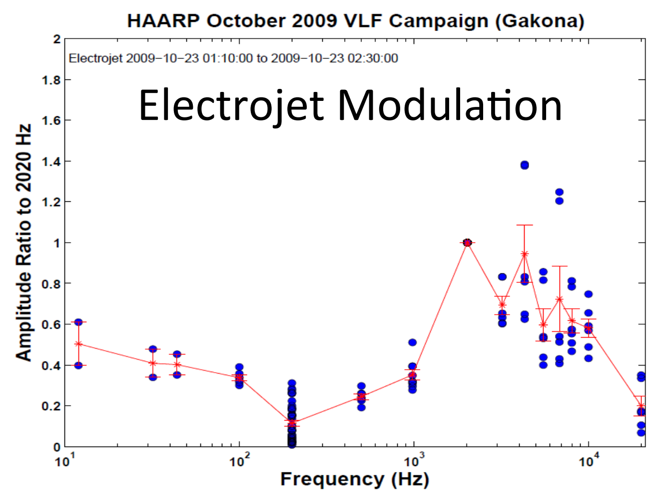




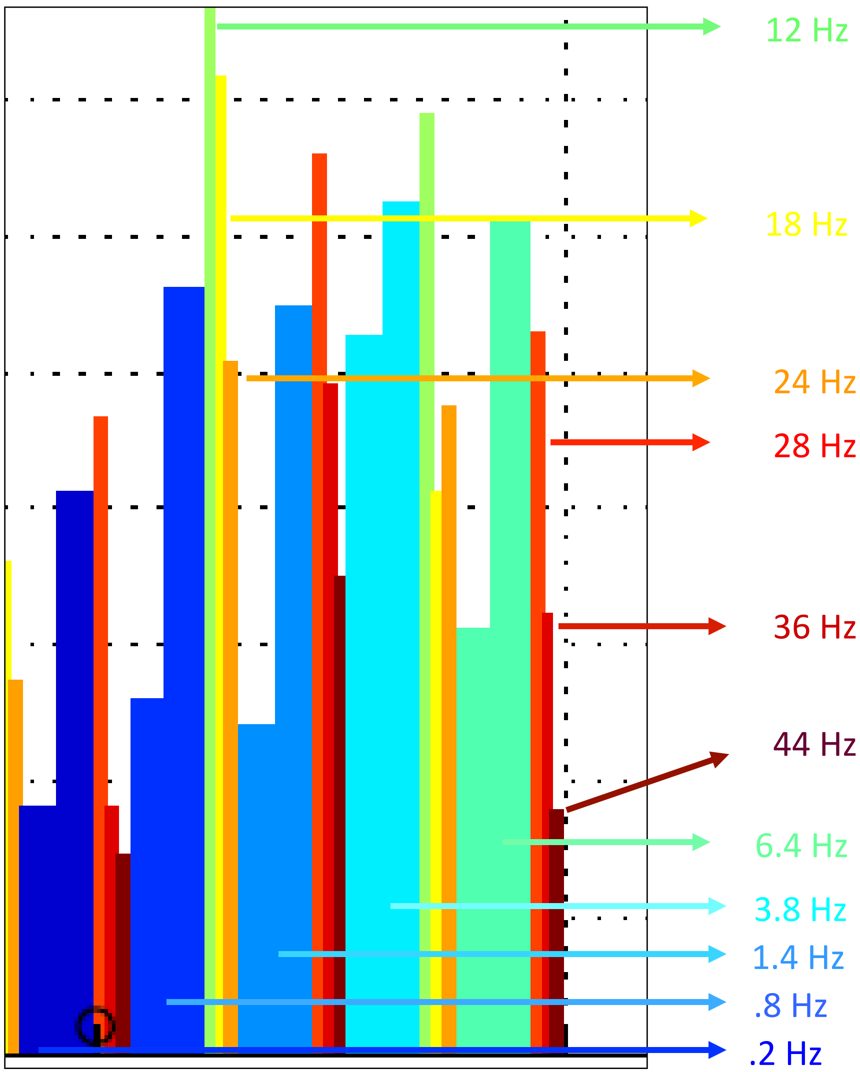
ELF/VLF Generation Efficiency - ICD vs. PEJ

- Ionospheric current drive produced ELF waves up to 50 Hz (F layer)
  - < 50 Hz, $1/f^{\alpha}$ dependence
    - Consistent ELF source suitable for mid/low latitude regions
    - Upper freq. is defined by pressure relaxation time scale in the F layer
  - 200-400 Hz under background
  - > 1 kHz, small signals at Gakona
    - Low background
    - Possible ICD in D/E layer?





ICD Scaling with HF Power and ELF Frequency



$$B \sim (pressure)Volume \approx E_{absorbed}$$

$$\frac{dE_a}{dt} = \alpha P_{HF} - \frac{E_a}{\tau}$$

$$E_a = \alpha P_{HF} \tau (1 - e^{-t/\tau})$$

$$f \sim 1/2t, f_o = 1/2\tau$$

$$B \sim (\alpha P_{HF} / f_o)[1 - e^{-(f_o/f)}]$$

$$f >> f_o, B \sim 1/f$$

$$P_{ULF} \sim P_{HF}^2$$

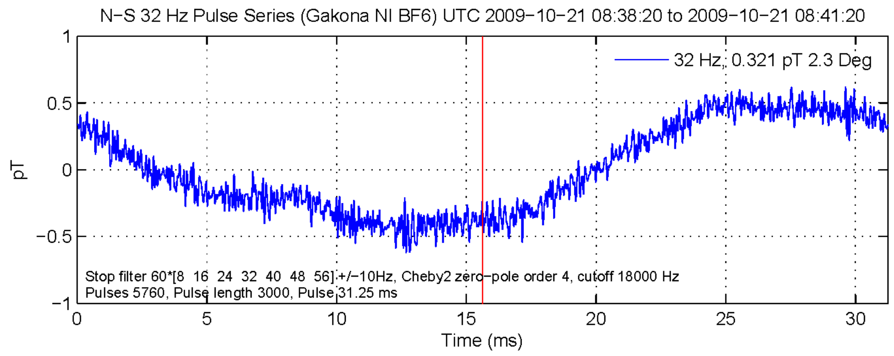
$\tau \approx .1$ sec , $f_o \approx$ 4-6 Hz,

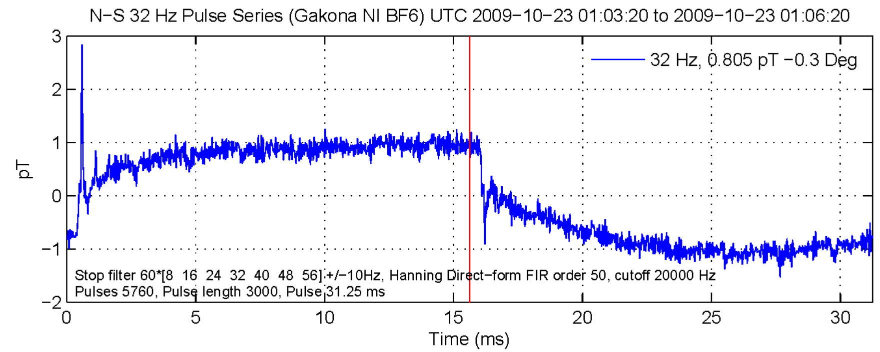
$\alpha \approx .2$-.3(X), $\alpha \approx .1$-.2 (O)

ELF Temporal Waveform – ICD vs. PEJ

- Use 32 Hz as an example
- ICD in the F layer does not have sharp peaks – time scale for pressure relax. Is long
- PEJ in D/E layers has initial sharp peak at ON and OFF due to current surge – time scale for HF heating is short ~ 0.1 ms. It also has other peaks due to wave bounce between ionosphere & ground

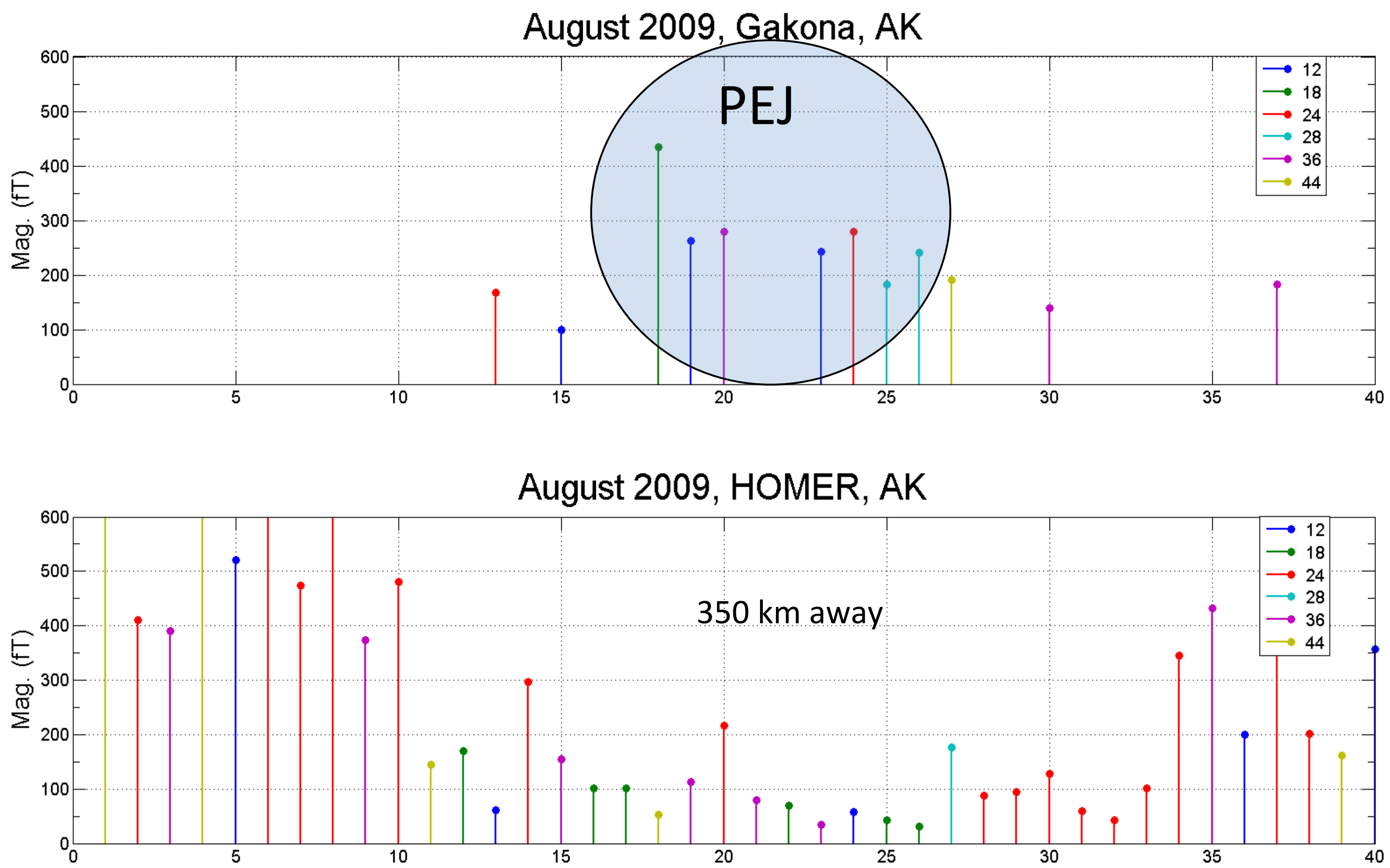
F Layer ICD

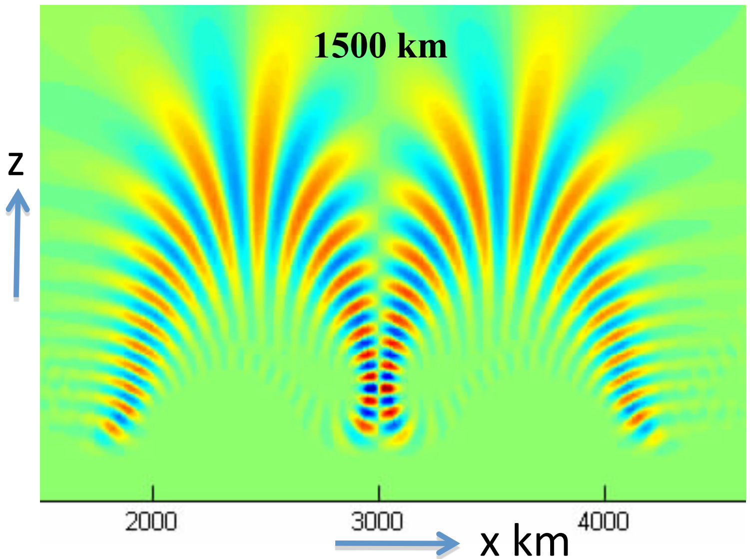


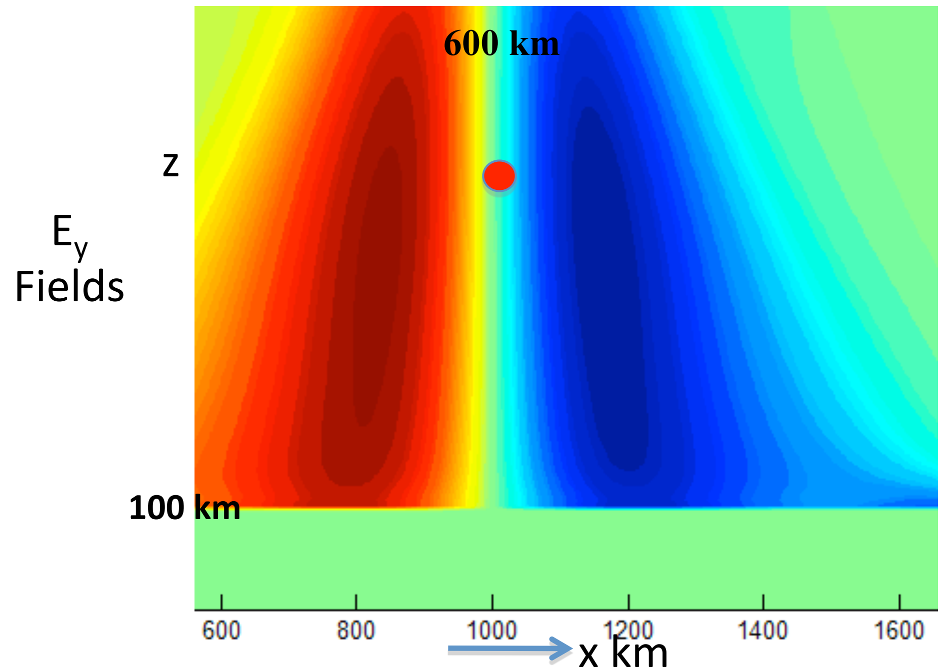


D/E Layer PEJ

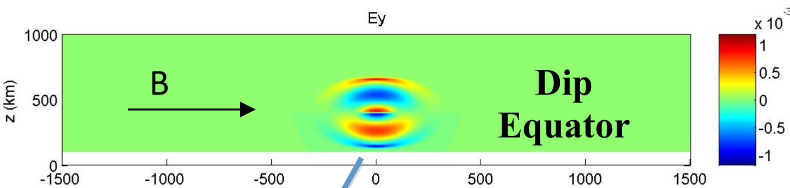
Two site measurements - ICD vs. PEJ

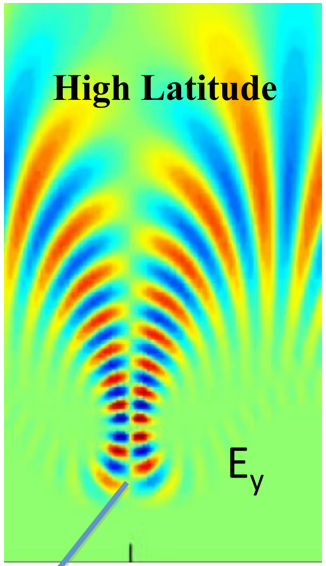


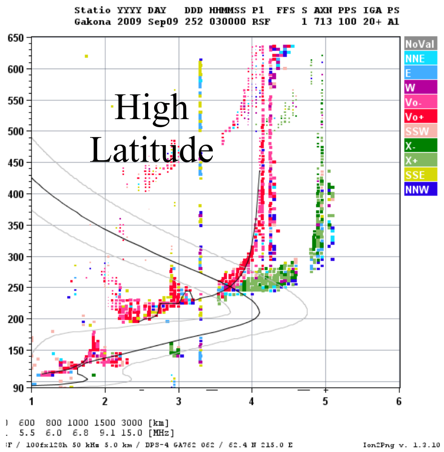

1500 km
z
2000
3000
4000
x km


600 km
z
E_y
Fields
100 km
600
800
1000
1200
1400
1600
x km

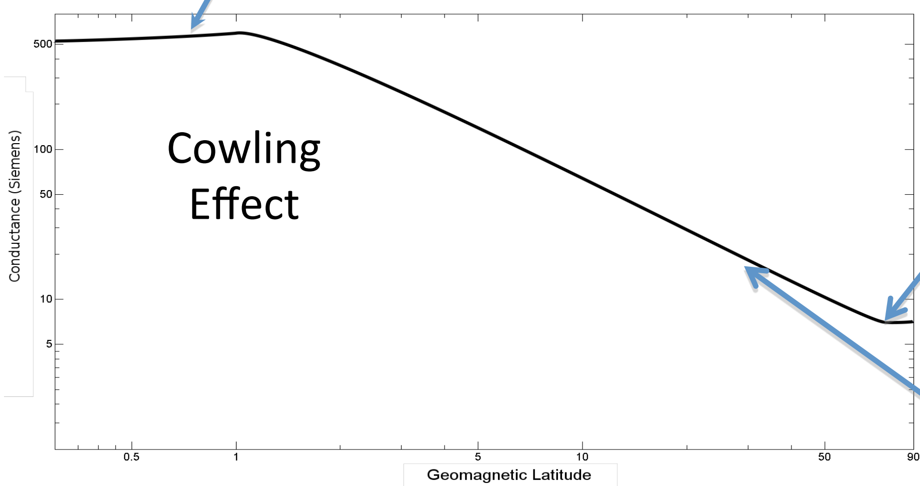
ICD Latitude Dependence

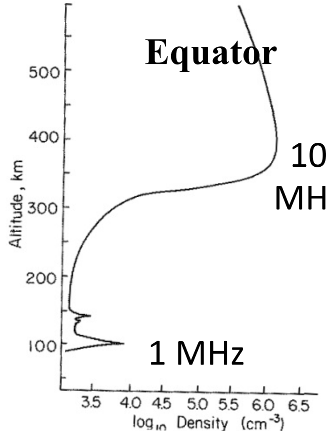


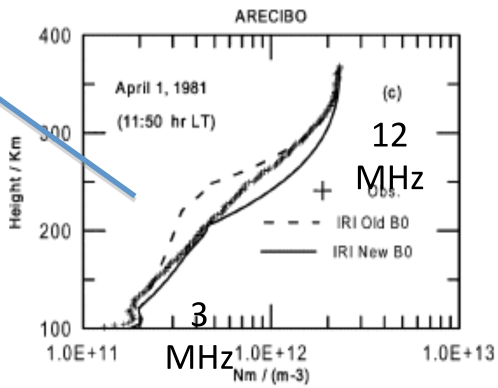




$$P=(\Sigma EL)L$$







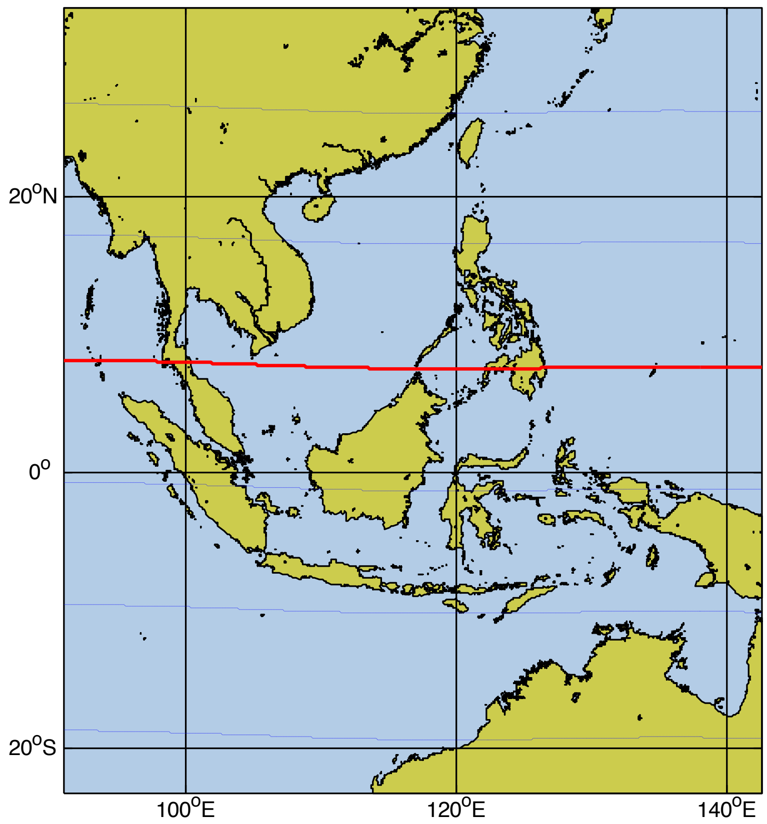
1. Conduction 100 times better
2. Msonic E field at Hall region unidirectional
3. Weak D/E region self absorption self absorption

Inject to inner belt

Summary of equatorial location advantages

- **Equatorial ionosphere much more reliable than auroral**
- **Equatorial electron density profiles better suited to heating at high altitudes (improving heating efficiency and reducing absorption)**
- **Cowling current provides a factor of 400 more power than aurora for similar VMD moment**
- **Equatorial heating creates significant vertical electric dipole moment providing isotropic coverage**
- **Equatorial and sea based facilities can provide global ULF/ELF coverage for all frequencies up to 50 Hz**
- **Required HF frequency 6-10 MHz. Facility smaller and relatively inexpensive**

Potential sites



Potential land sites:

- Jicamarca, Peru
- Thumba, India
- Koror, Palau
- Phuket Area, Thailand
- Mindanao, Philippines

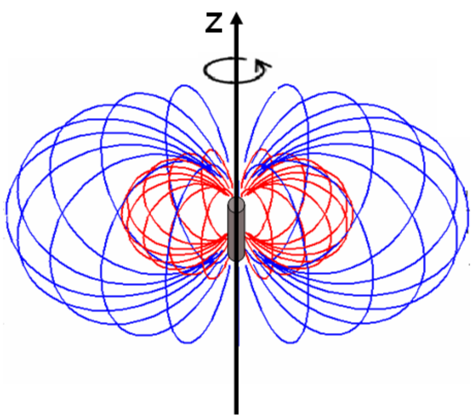
Sea basing offers additional flexibility

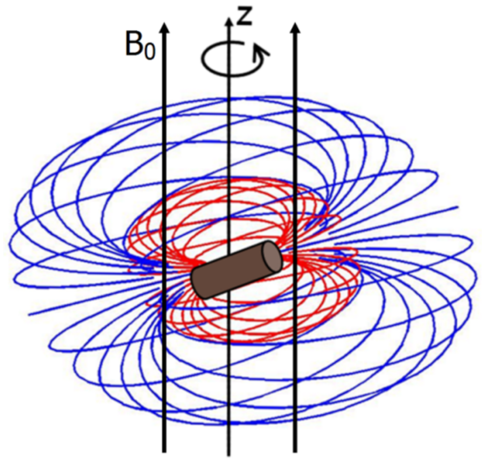
Self-propelled drilling platforms have the deck area and electrical power necessary for an ionospheric heater the size of the current HAARP IRI

Radiate – New Concepts
Rotating Magnetic Fields (RMF)

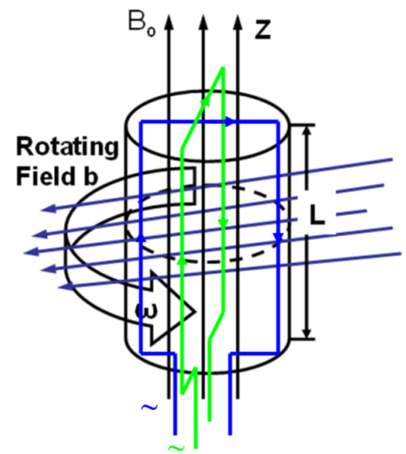
UCLA –UMCP Collaboration – Proof of Principle Exps – Gigliotti -Karavaev

Rotating permanent or superconducting magnets

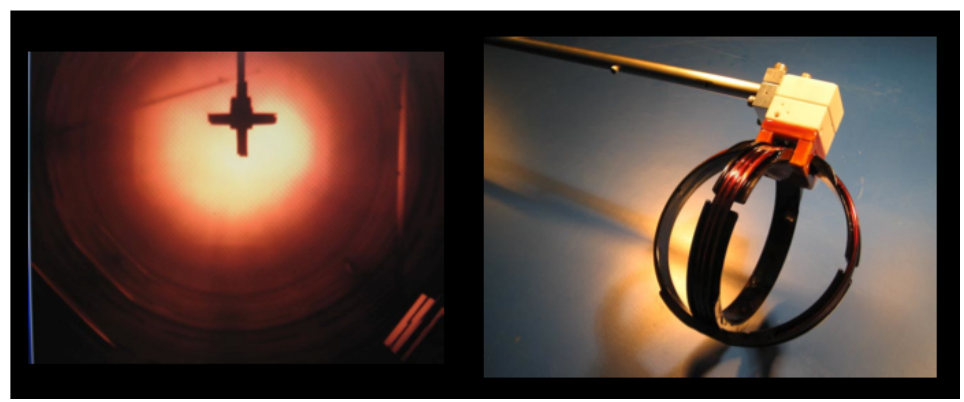




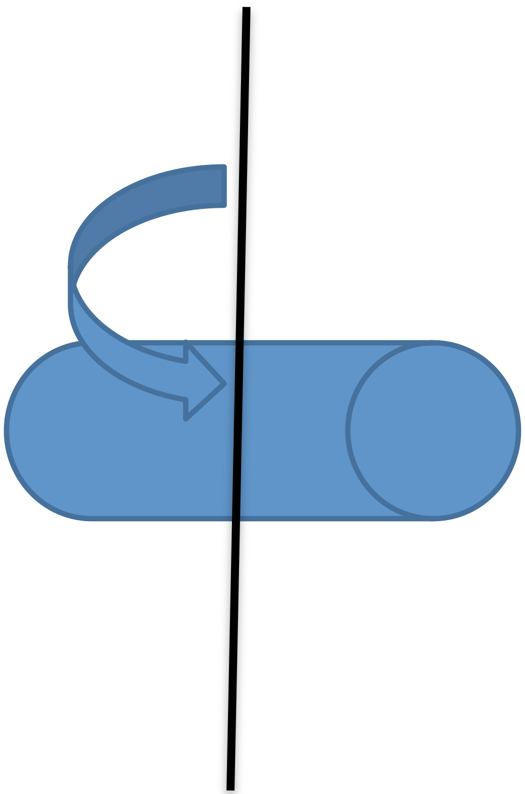
Polyphase current loops



RMF Antenna Efficiency, Properties, Codes
Compare LAPD experiments with simulations. Impact of results on VLF/ELF/ULF radiation from space based platforms and relevance to RBR and PRBR.



Superconducting RMF with 1 m length, .1 m^2 area, 1.5 x 10^4 turns gives 10^5-10^6 A-m^2 nT at 1 km



Spinning satellite with magnetic structure can act as as antenna – Cube sats

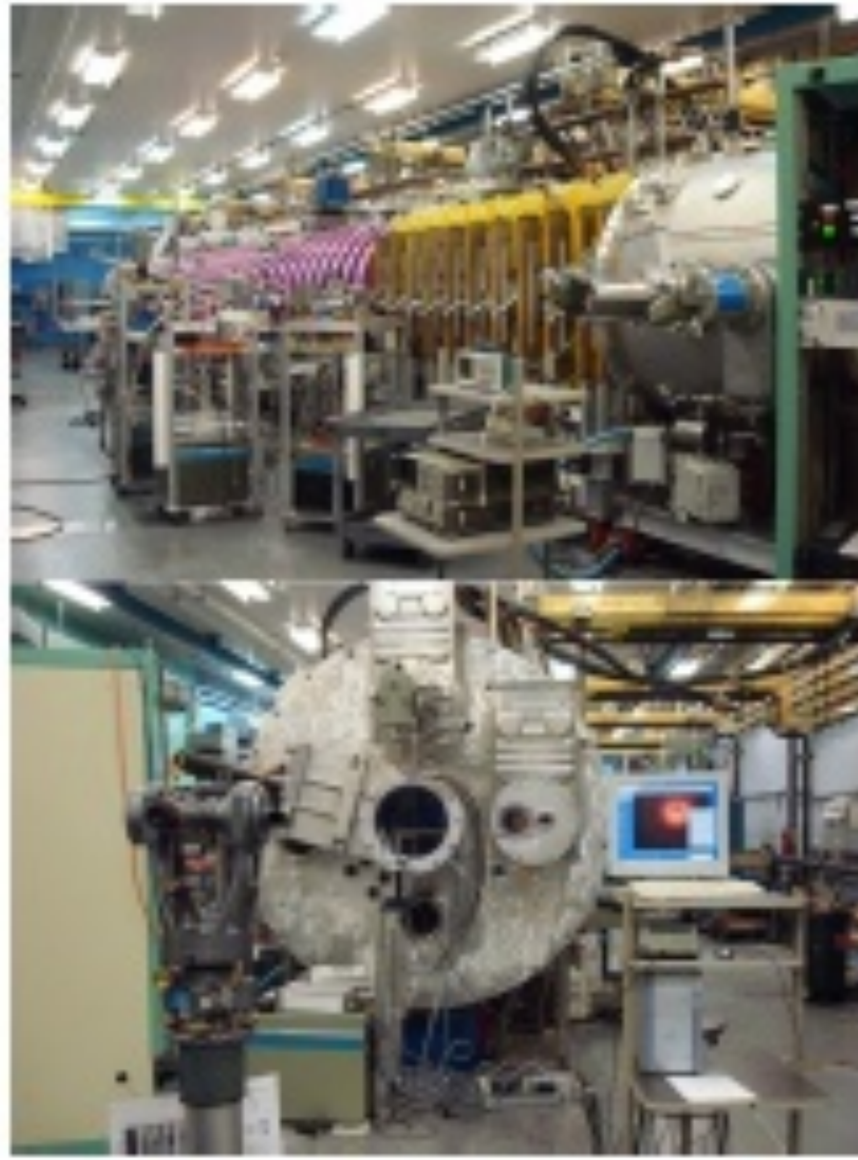
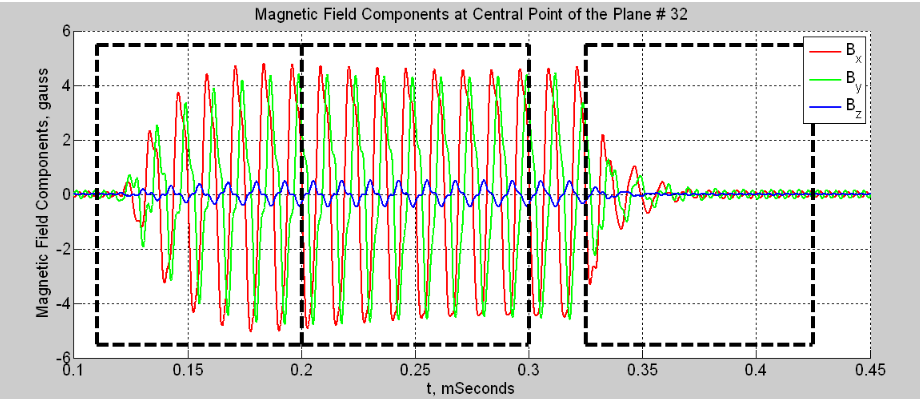
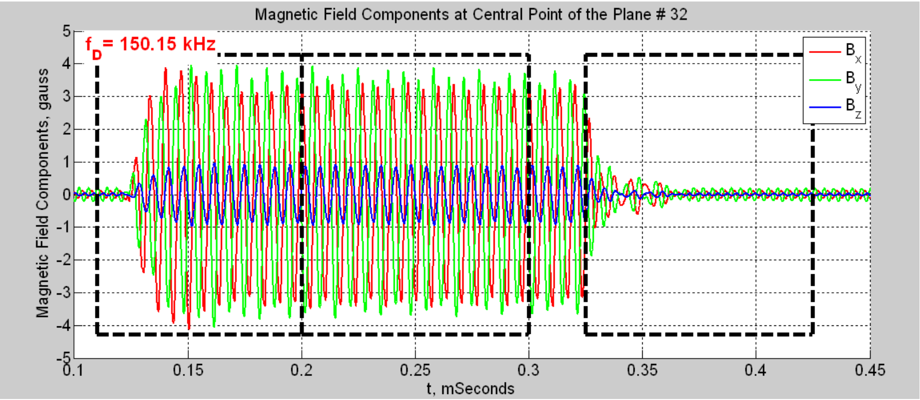
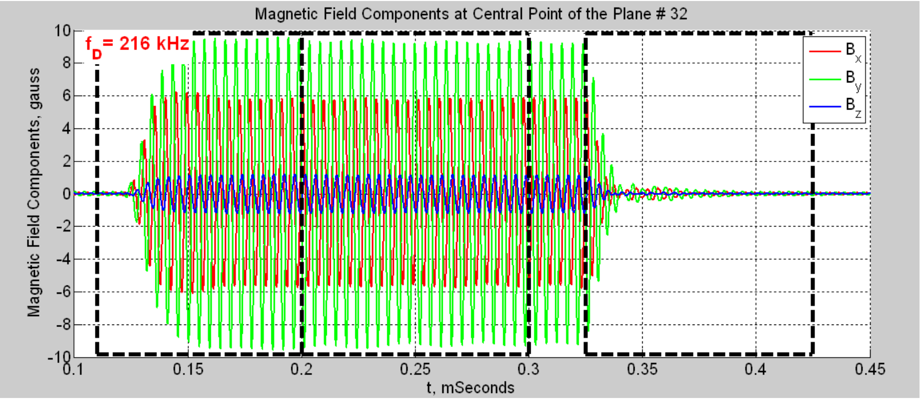


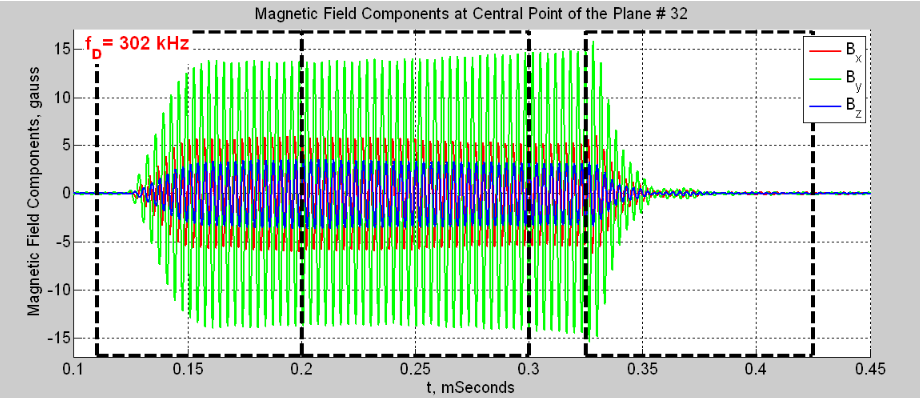
Figure 2.2: General view of the IAPD machine . 18 m long and 1 m in diameter stainless steel cylindrical vacuum chamber surrounded by 36 pancake electromagnets with DC current placed at 32 cm interval, which provide stationary ambient magnetic field of arbitrary profile along the device.

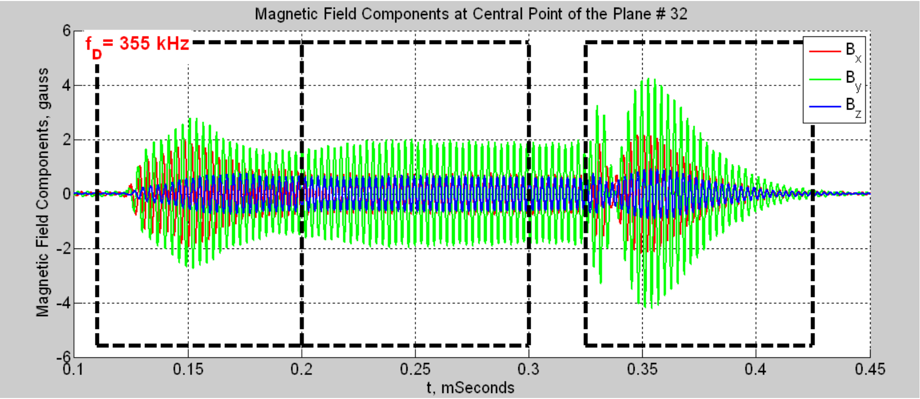
SAW Generation by RMF

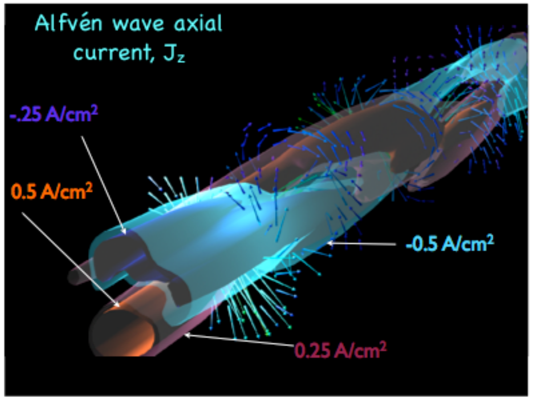








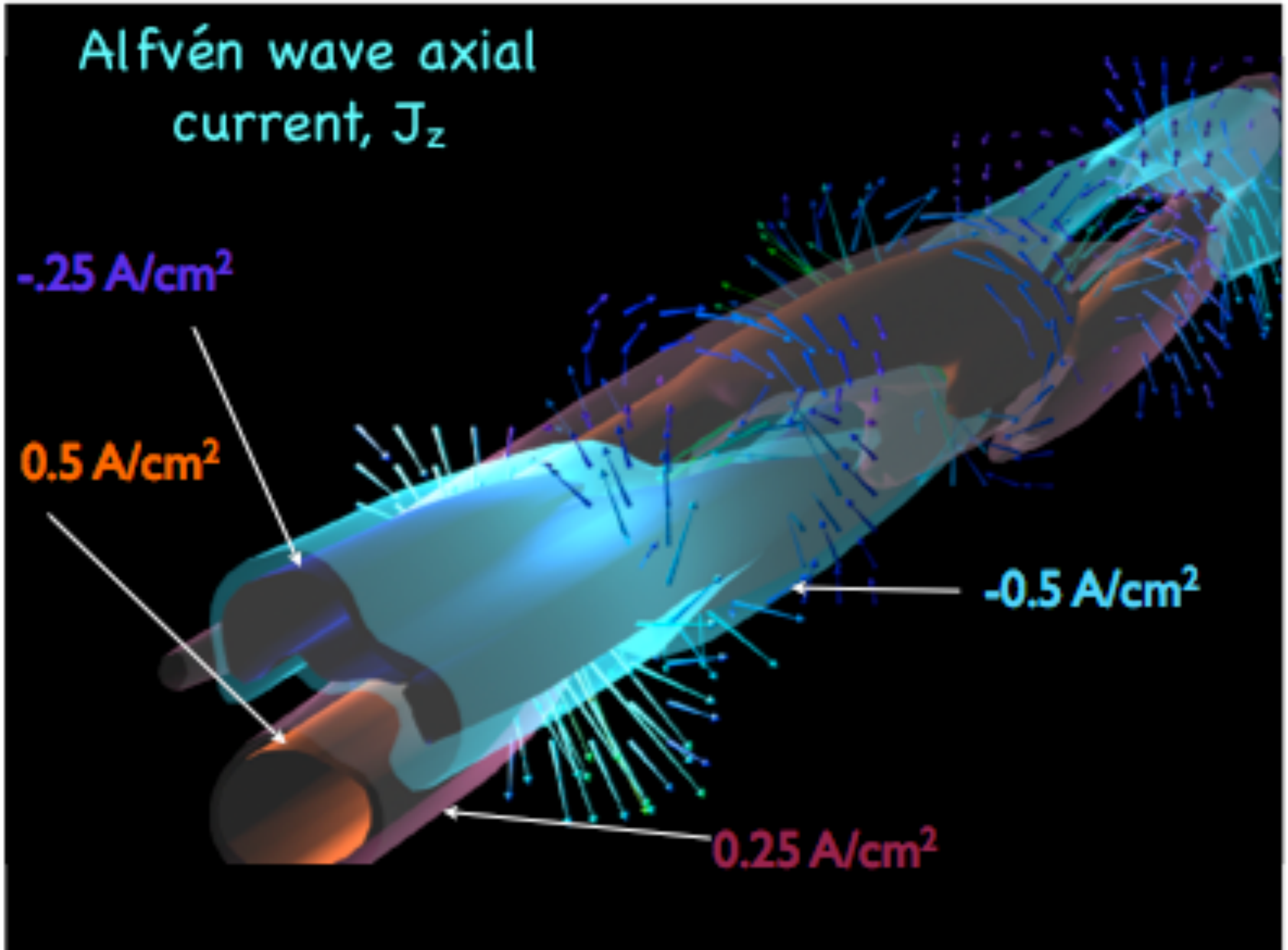




SAW generation by RMF in the 5-15 Hz Hz range could be an important space component of PRBR

SAW Current Structure - LAPD

Used for code validation Gigliotti et al. Phys. Pl, 2009



Code Validation

Karavaev et al. 2010

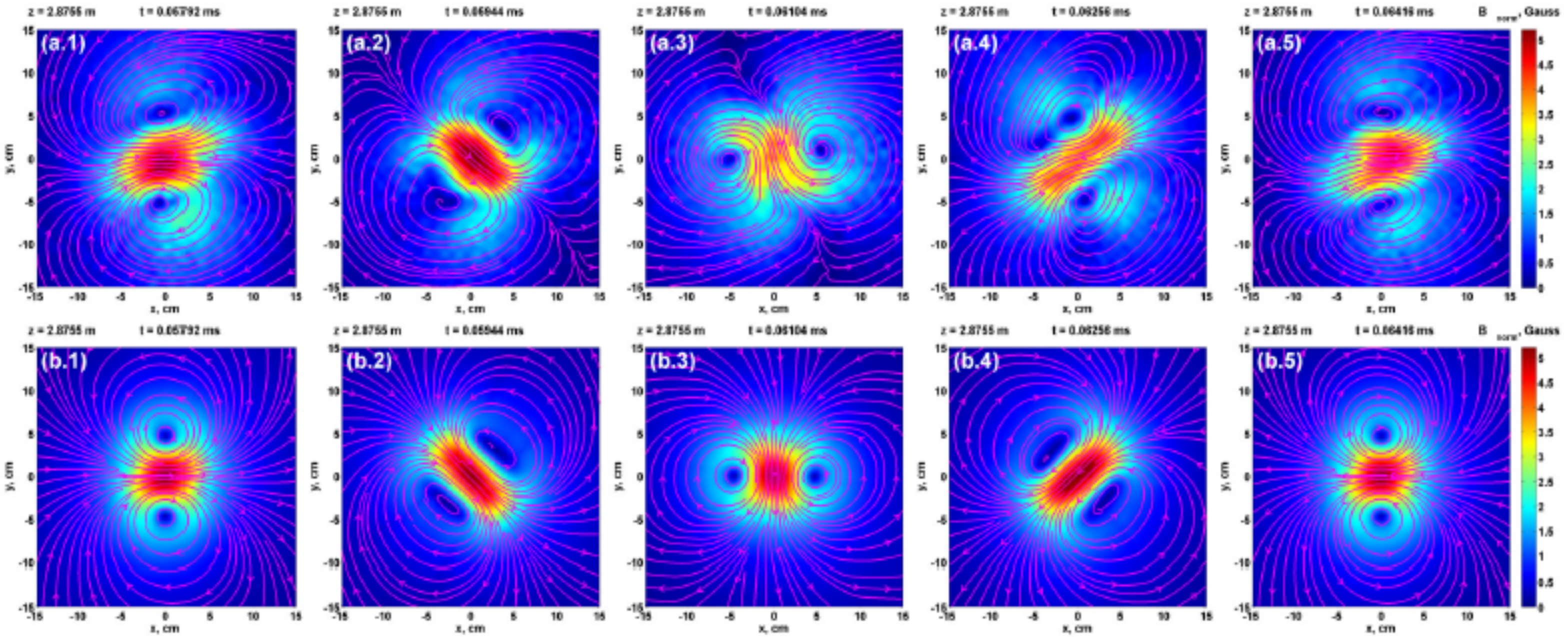
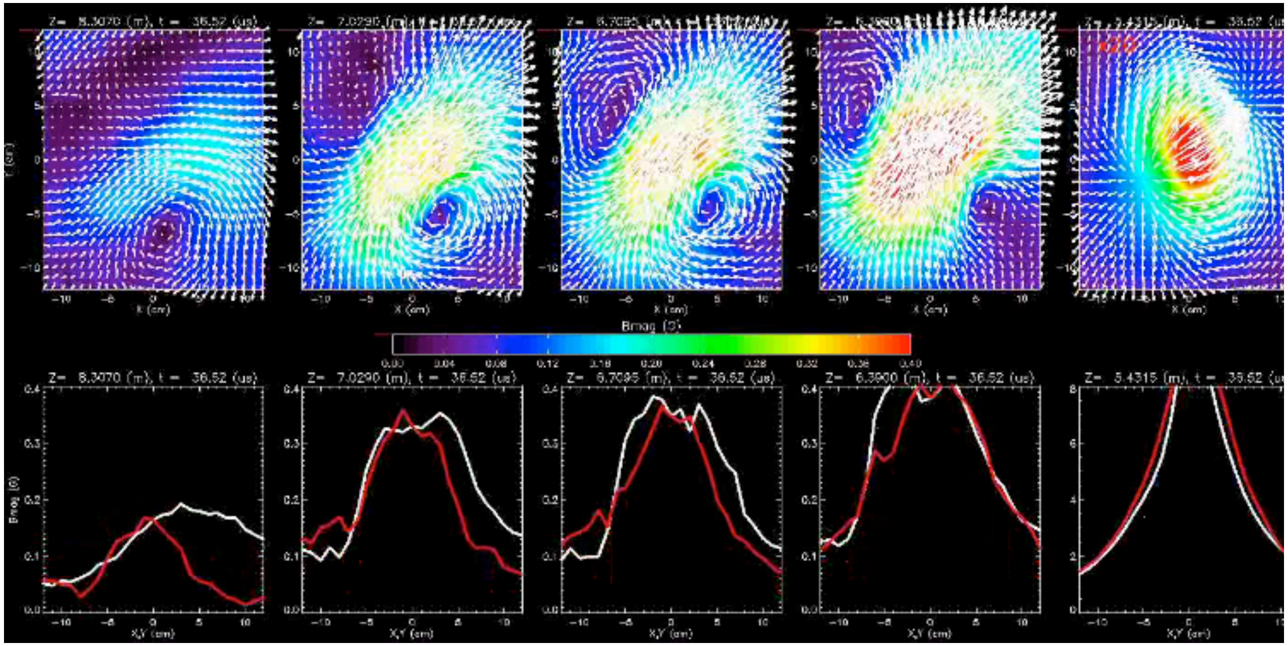


FIG. 1: (Color online) Comparison of the magnetic field structure in the plane $z = 2.88\ m$ away from the radiating antenna for five instants of time ($t_1 = 0.05792\ ms$, $t_2 = 0.05944\ ms$, $t_3 = 0.06104\ ms$, $t_4 = 0.06256\ ms$, and $t_5 = 0.06416\ ms$) separated by 1/8 of the wave period (driving frequency $f_d = 80\ kHz$) measured in the experiment (Experiment set 2) ((a.1) - (a.5)) and calculated using 3D model ((b.1) - (b.5)) for the left-handed polarization case. The ambient magnetic field $B_0 = 1000\ Gauss$ points outward of the plane of the picture.

Whistler Generation by RMF

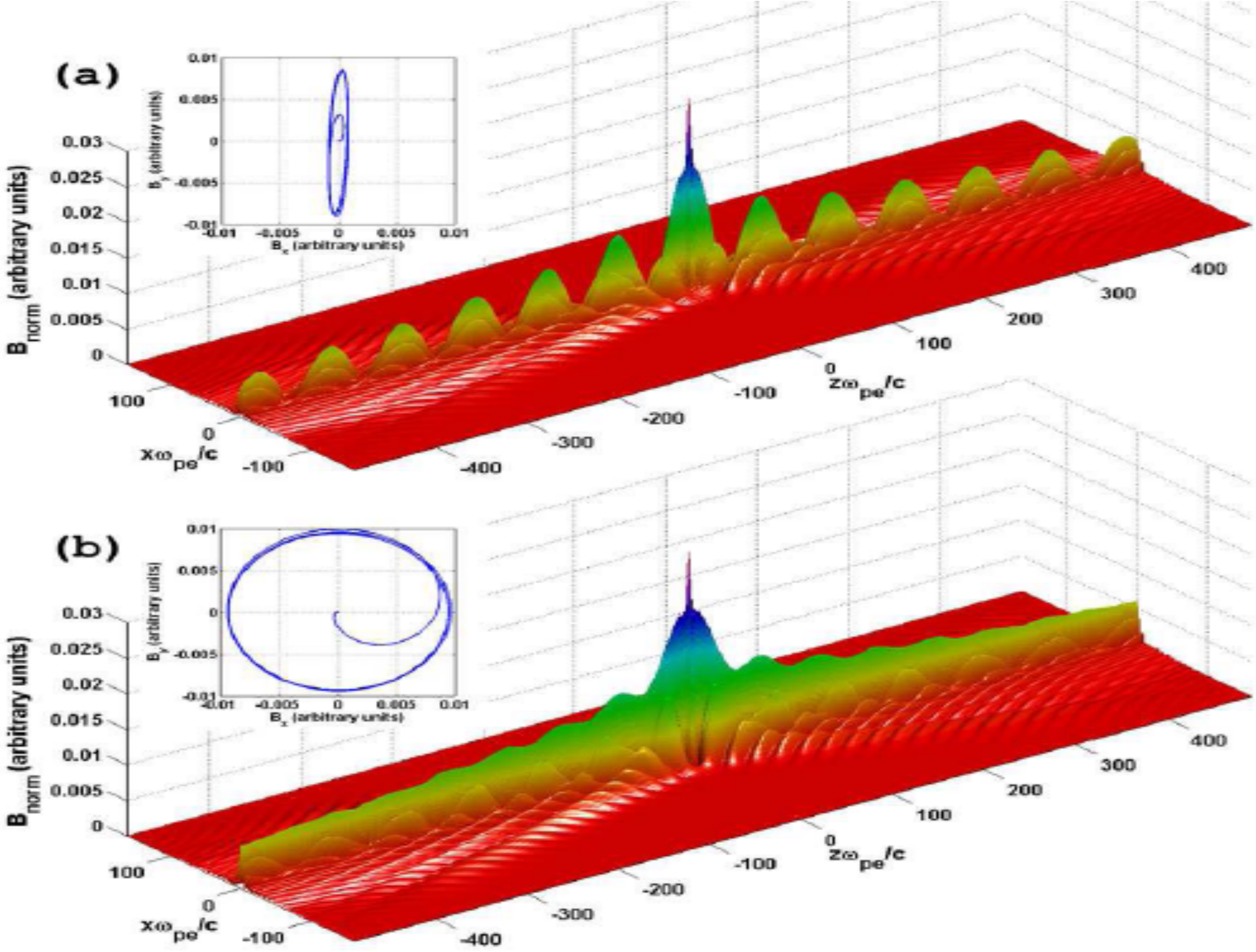


- Gradient generation requires frequencies above the ion cyclotron frequency (≈60 Hz at L=2)
- Breaks the adiabatic invariance of relativistic electrons for gradient lengths shorter than the electron gyroradius – no need for resonance
- Will require superconducting RMF with rotation speed in excess of 60 Hz and Tesla level B

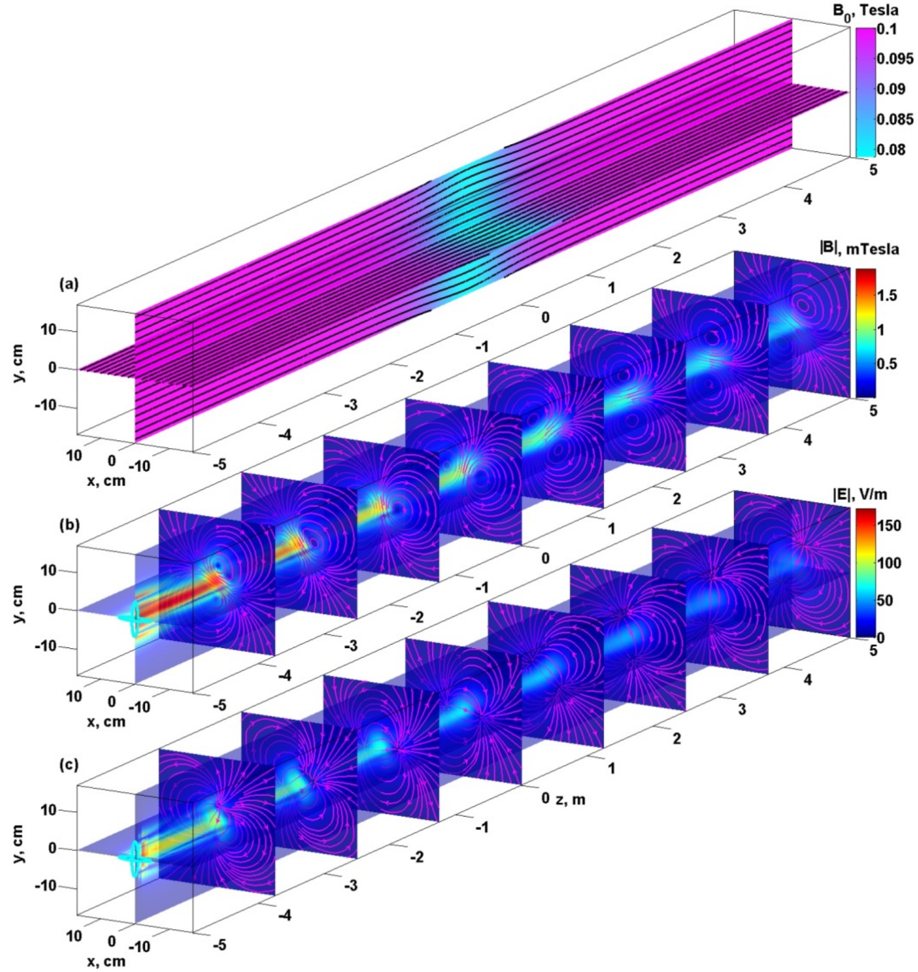
RMF Generated B field Gradient

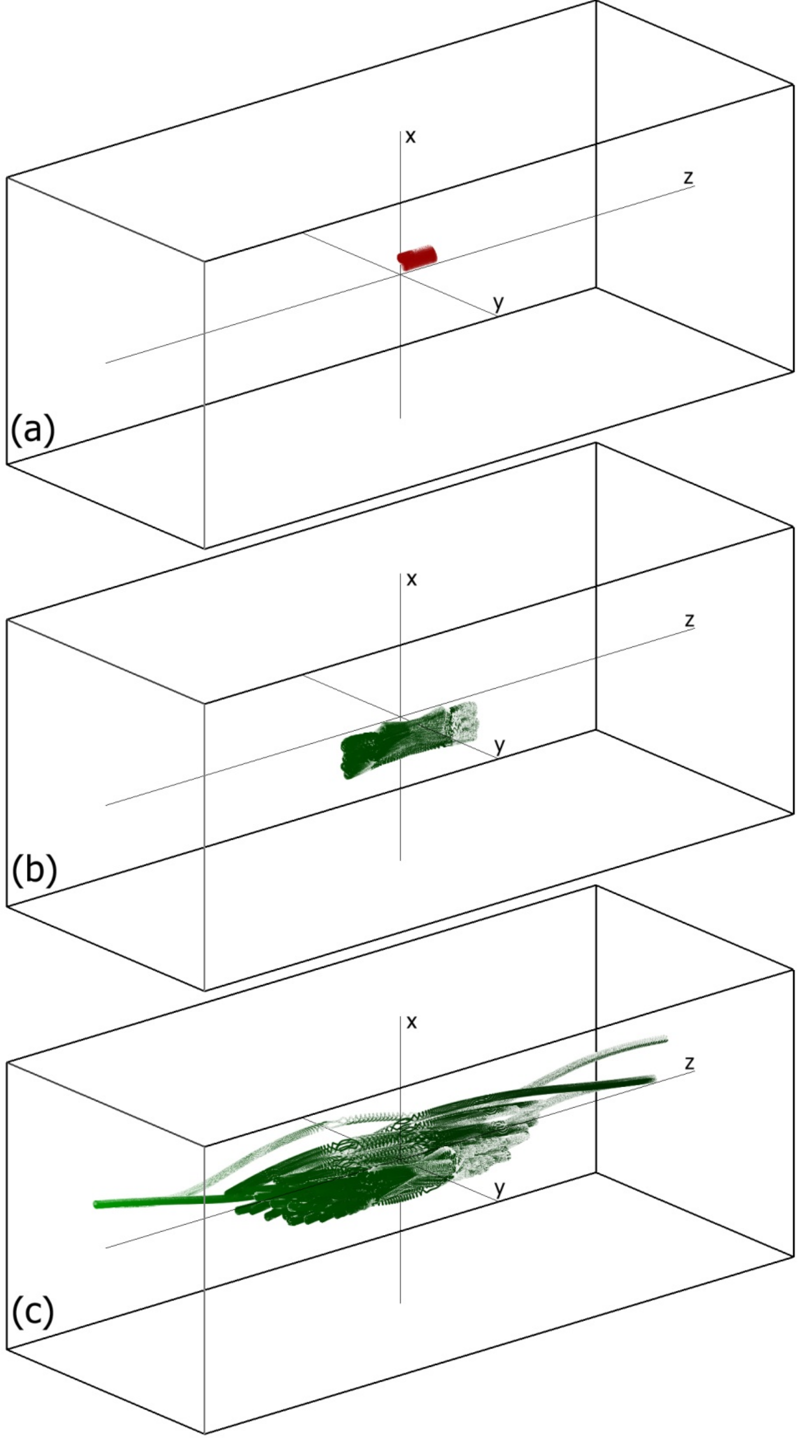
1 loop

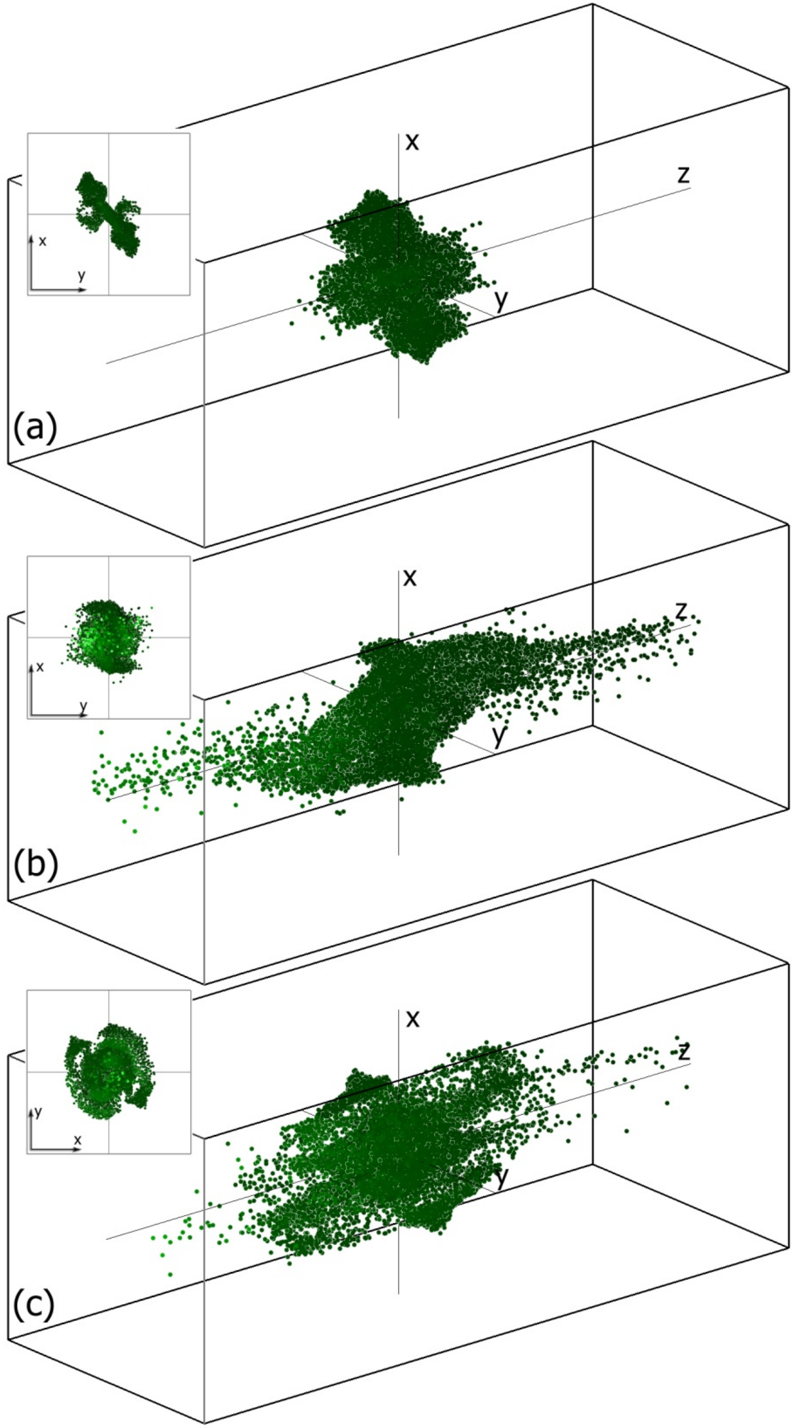
2 loop



Non Resonant Breakdown of the Electron Adiabatic Invariant




x
z
y
(a)
x
z
y
(b)
x
z
y
(c)



x
y
x
z
y
(a)
x
y
x
z
y
(b)
y
x
x
z
y
(c)

First multi-ionic lab tests – EMIC waves

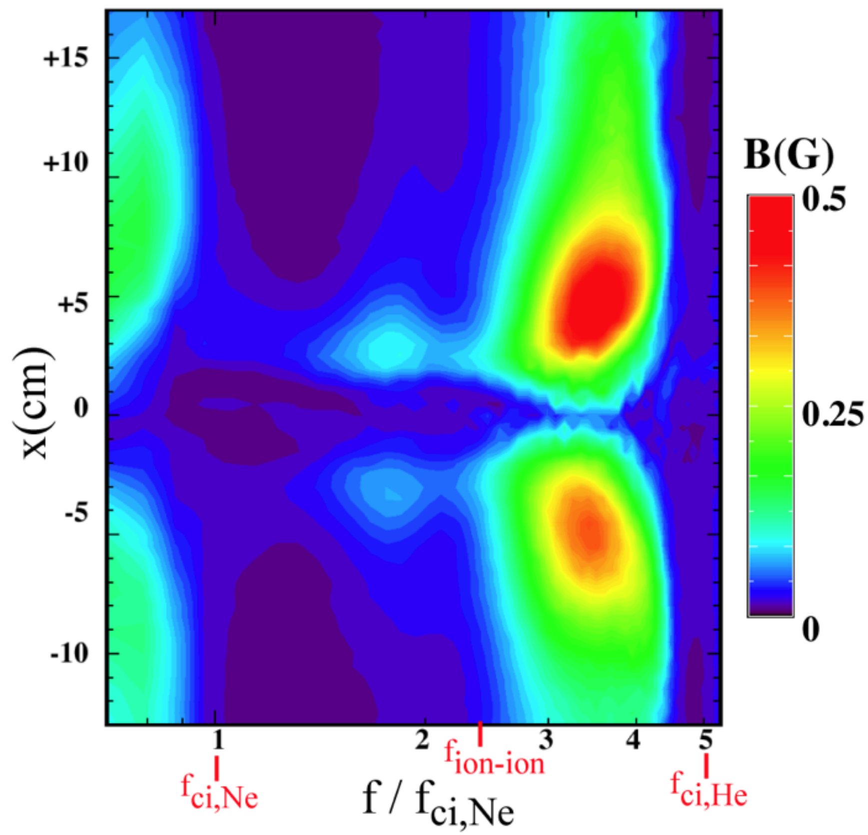
Shear Alfven wave propagation in a helium-neon plasma of equal ion concentrations.

SAW vs. frequency and distance across B

Source (RFM) 4.8 m away

Two broad propagation bands: one below the neon gyro-frequency and the other between the ion-ion hybrid resonance at 2.4 the neon and the helium gyro-frequency.

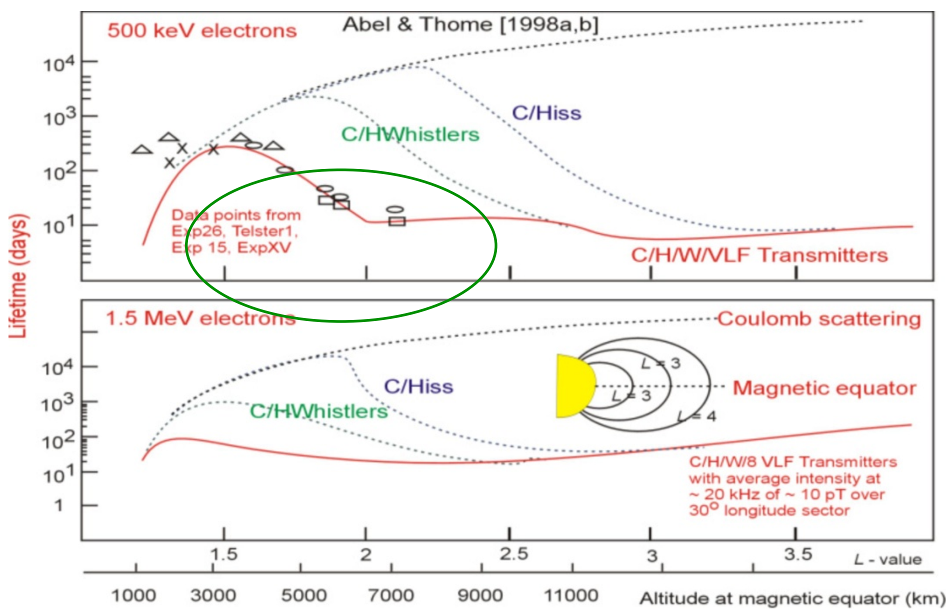
A third, short perpendicular wavelength mode is observed in the gap, just below the first harmonic of neon.



Propagation

THE 20 dB PUZZLE

Abel & Thorne (1998)



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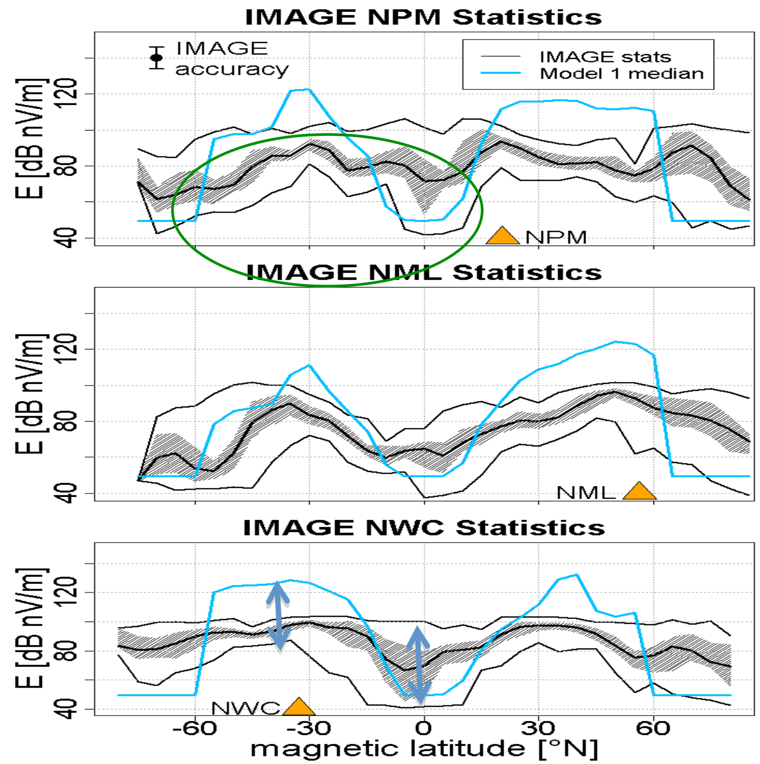
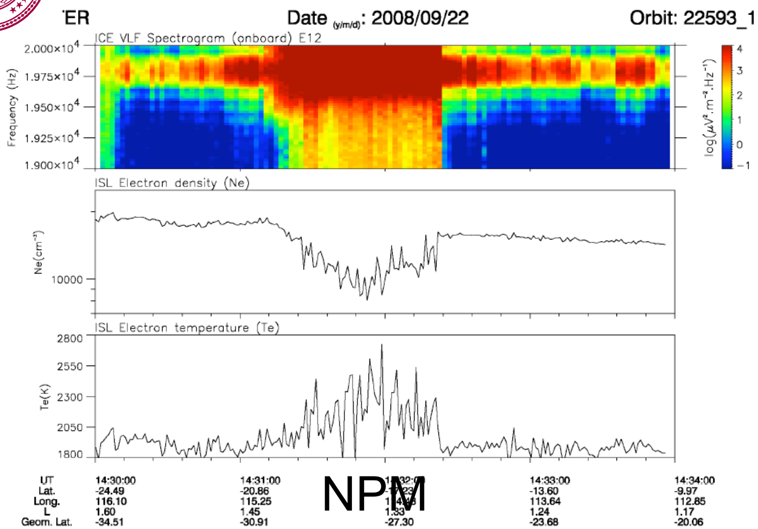


Starks, et al. (2008)

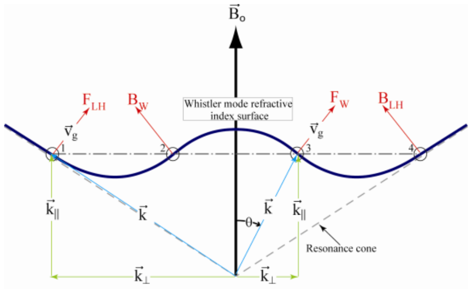
" Models systematically overestimate median field strength by 20 dB at night and more than 10 dB during day. Important physics not modeled"

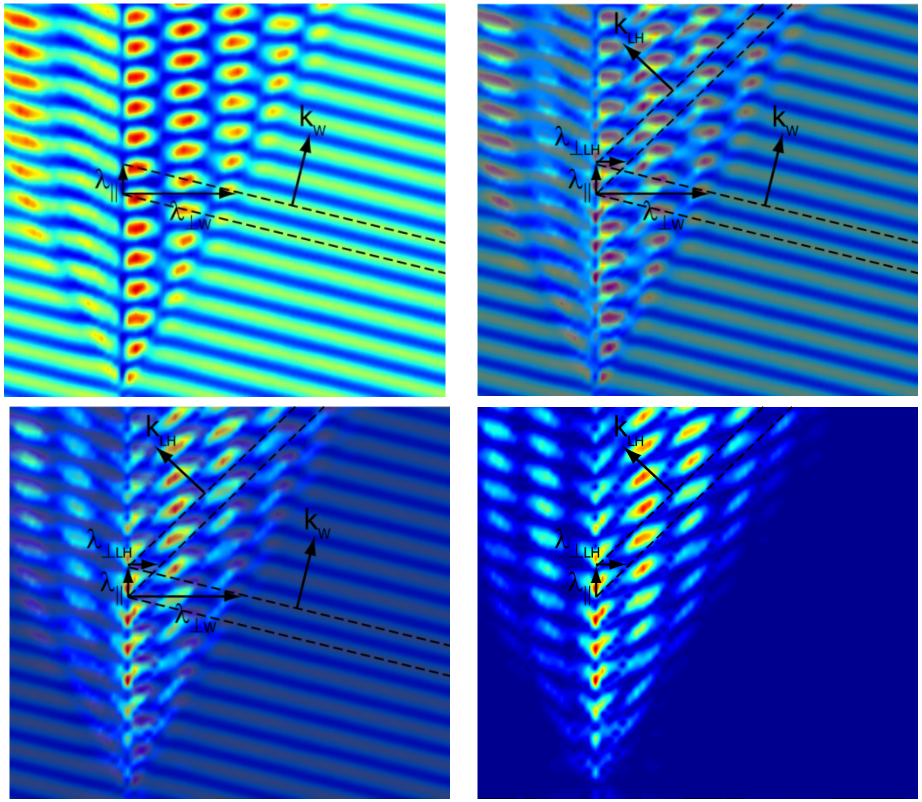
Anomalous absorption

Linear Mode Conversion 2D Static



Bell et al. (2008)

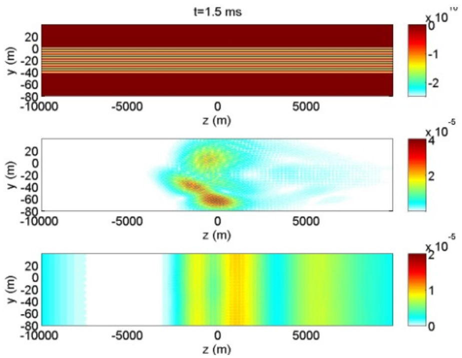




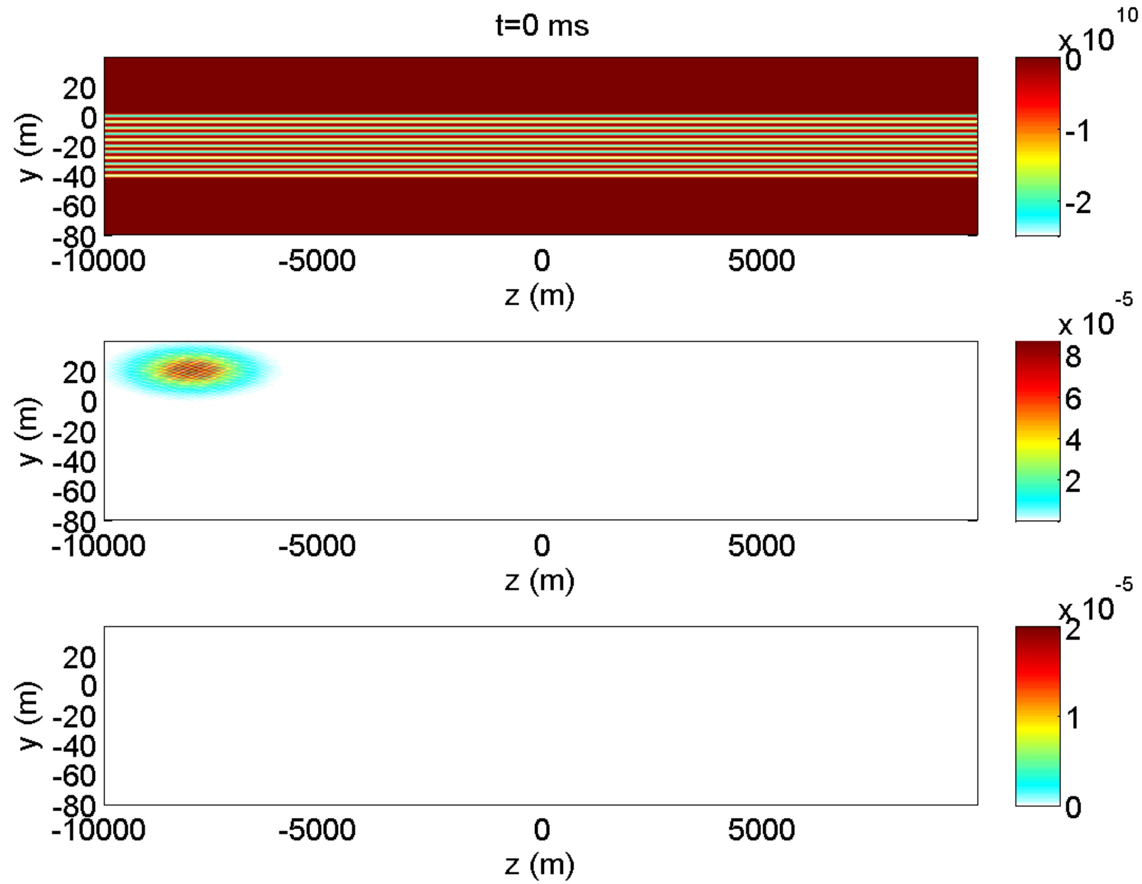
1. Total field clearly showing whistler mode.
2. Appearance of LH mode sharing parallel wave number as overlay of total field is removed.
3. LH mode is more evident in the scattered field plot as the total field has almost completely disappeared .
4. Scattered fields clearly show lower hybrid wave with perpendicular wave number in opposite direction as that of whistler mode.

Whistler to LH and LH to Whistler 2D Dynamic

Eliasson and Papadopoulos (2008)



Coupling by density irregularities converts long-wavelength whistler waves to quasi-es lower hybrid waves and vice versa



3D Effects – Whistler Turbulence

NRL-MURI collaboration

Ganguli – Rudakov noted that proper calculation of whistler turbulence evolution requires the presence of terms of the form

[illegible]

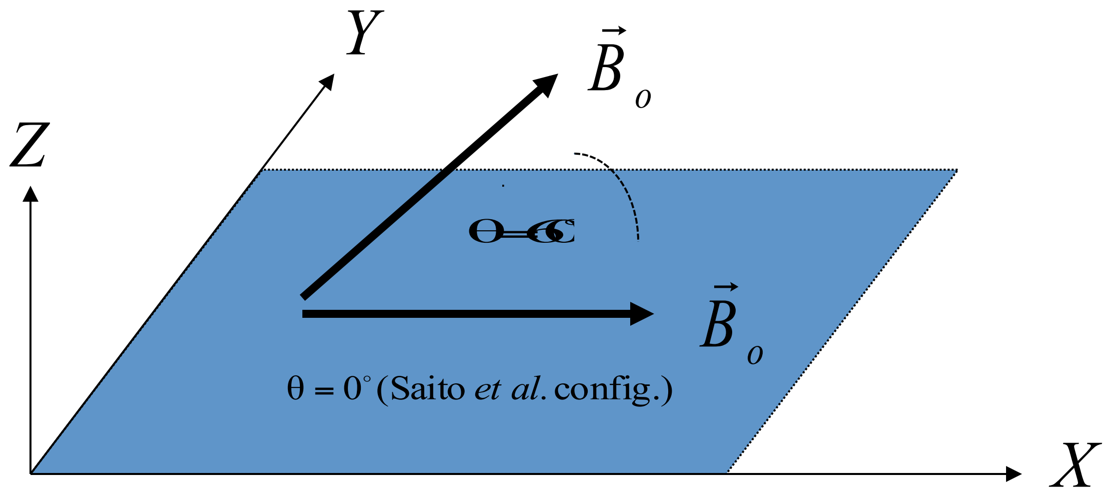
This term is zero if the analysis and simulations are conducted in a plane that contains the magnetic field. This can be seen by referring to NLS of whistlers

[illegible]

In 2D $$(\vec{k}_1 \times \vec{k}_2) \cdot \vec{b} = 0$$

Explore 3D physics using VA Tech particle codes Scale-Wong + NRL and UMCP

Simulation Domain



- **The simulation domain (*X*-*Y*) is 51.2 and 25.6 electron inertial lengths.**

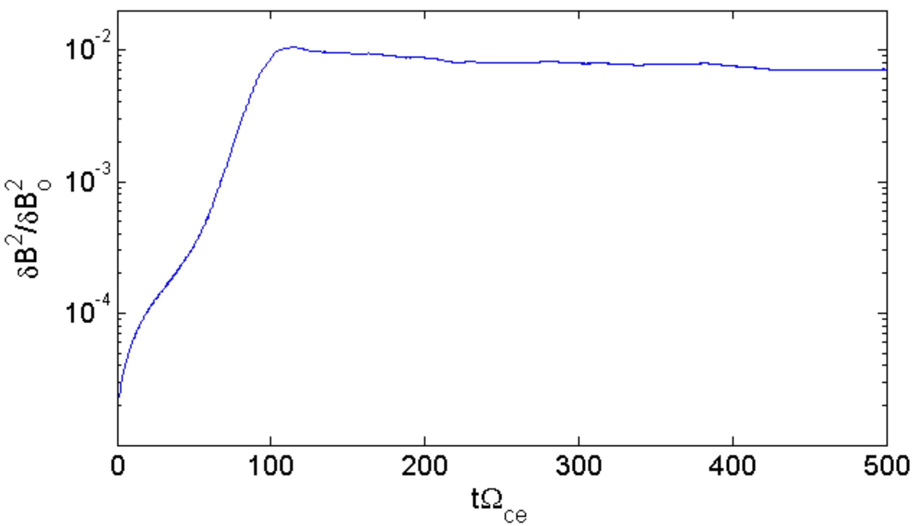
- **Two Cases:**

1. $\theta = 0^\circ$
2. $\theta = 60^\circ$

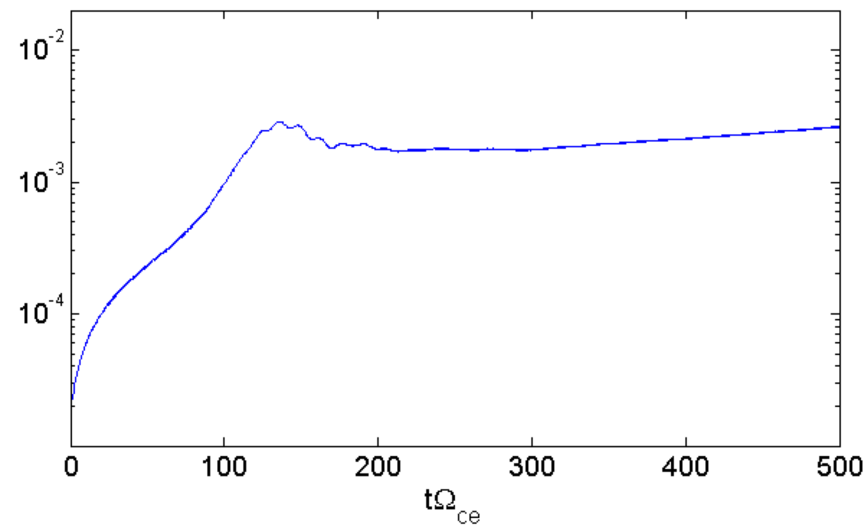
where θ is the angle between B_o and *X* direction.

Magnetic Field Energy

$\theta = 0^\circ$



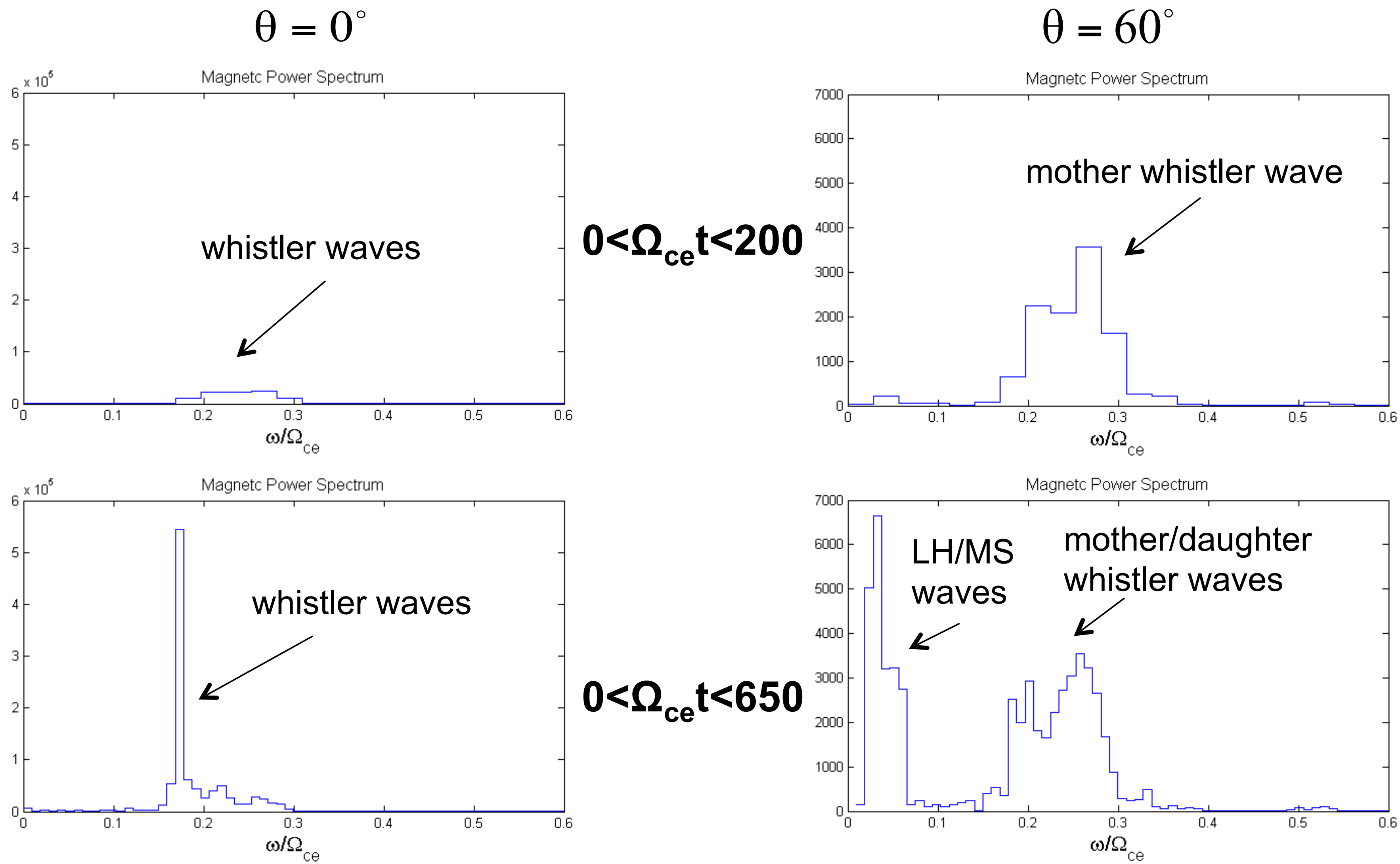
θ=6C



- Whistler waves linearly grow from the free energy in the perturbation in both configurations

- The nonlinear evolution is quite different

Frequency Power Spectrum

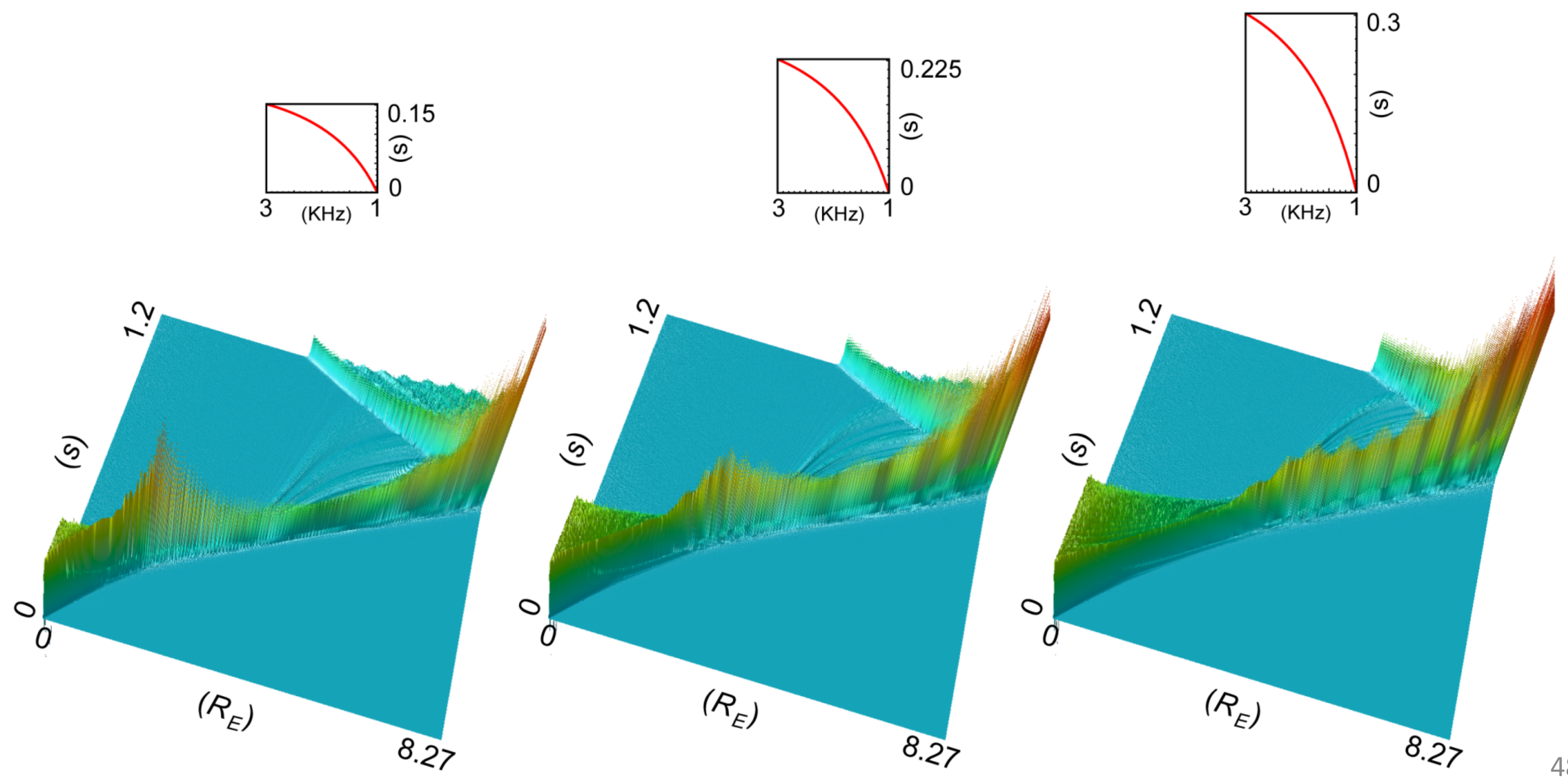


- For the case with inclination, whistler waves decay into lower hybrid/magnetosonic waves as predicted by weak turbulence theory.
- Without inclination, this decay is not apparent.

AMPLIFY

Optimize Probability for Triggering ASE

Strletsov et al. (2009) – Use full field line code to study frequency and chirp rate required to maximize trigger whistler amplitude at the equator – Collaborated with Stanford in conducting HAARP test

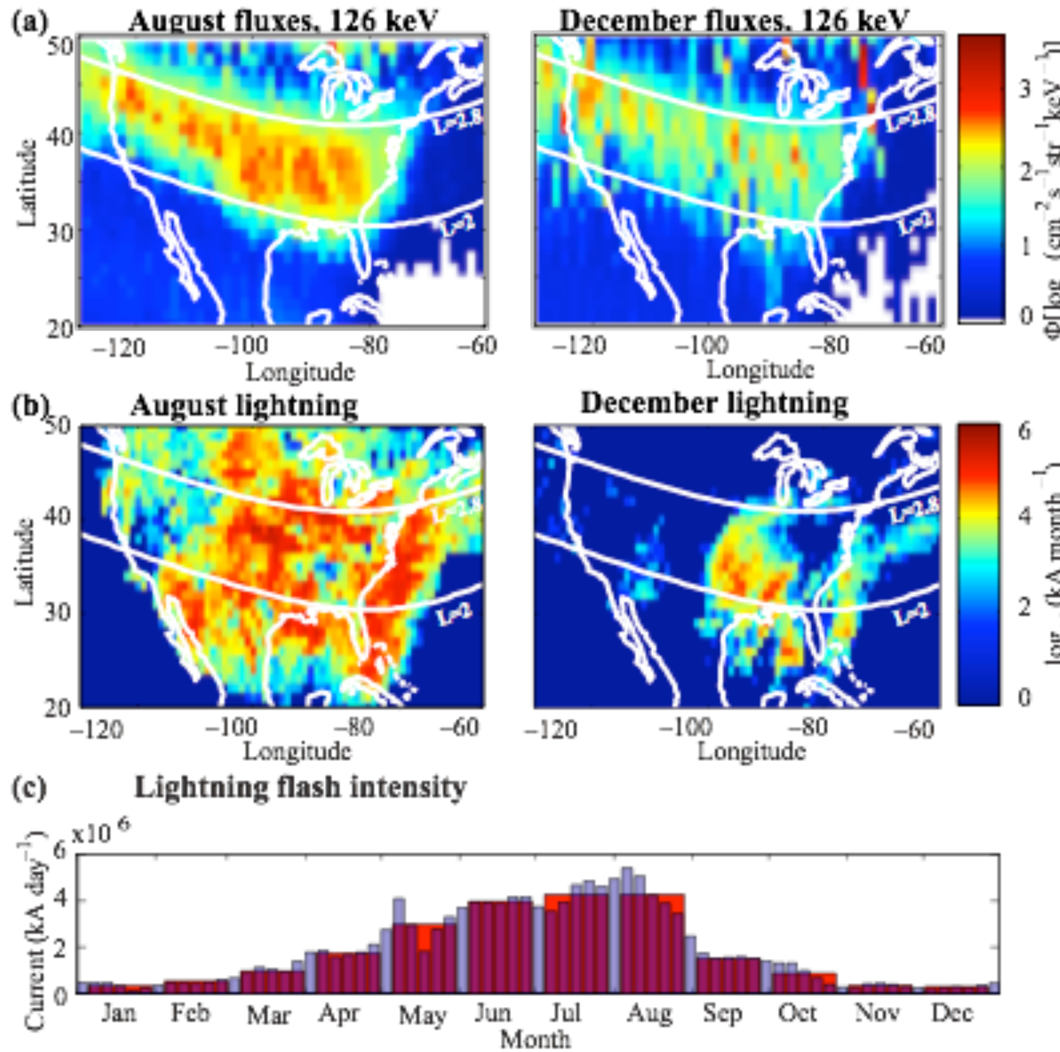


PRECIPITATE

Given the 20 dB deficit what creates the slot? LEP revisited Gemelos et al. 2009

DEMETER
Median of 2006-2008
monthly 128 flux

Fluxes over US are in the drift loss cone of the SAA. Seasonal dependence of drift loss cone flux correlates with measured flash intensity. Results indicate that LEP is the dominant cause of the slot. 5-10 kHz wave intensity at DEMETER shows similar variation



Three year monthly average

LEP as Benchmark for RBR Assessments

- Lightning-induced precipitation is a significant contributor to radiation belt loss in the inner-belt and slot regions
- Individual LEP bursts have been detected on satellites and on the ground
- Quantification of wave-induced precipitation requires that individual LEP bursts be measured together with whistler-mode waves
- Powerful lightning discharges illuminate the belts with waves of intensities of ~10 to 200 pT
- Waves generated for RBR must compete with lightning to significantly affect electron lifetimes

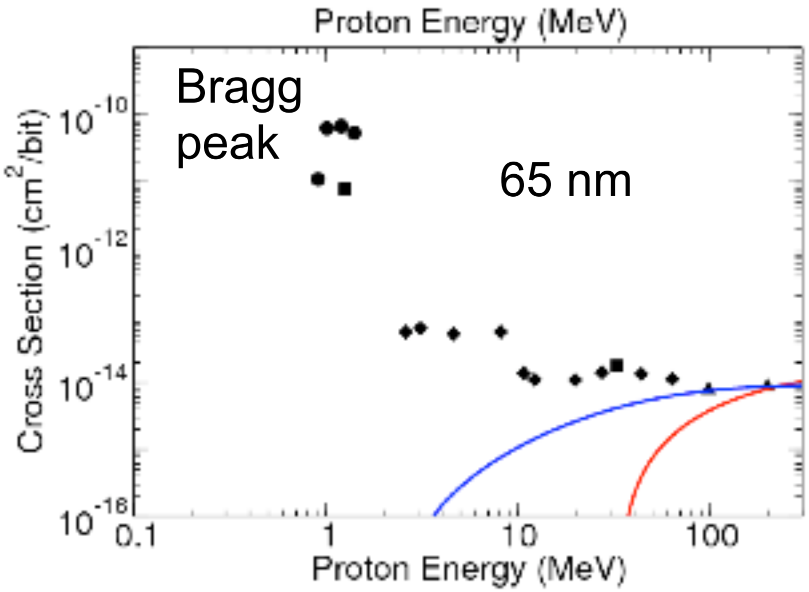
Precipitate Protons
Why –Where - How

•Commercial electronics in Low LEO orbits are affected while traveling through the SAA and during high inclination.

• As COTS sizes shrink, protons become much more of an issue. Historically, proton upset by the creation of secondary particles with higher LET (Linear Energy Transfer). The frequency of such an event is about one in a million

•. As feature size shrinks, parts become so sensitive that they can start upsetting through "direct" ionization by protons. This has been observed in 90nm and 65nm commercial technologies. The upset cross section for low energy protons can increase by several orders of magnitude.

Sierawski et al. 2009



Bendel models provide relationship between kinetic energy and SEU cross section driven by nuclear reactions

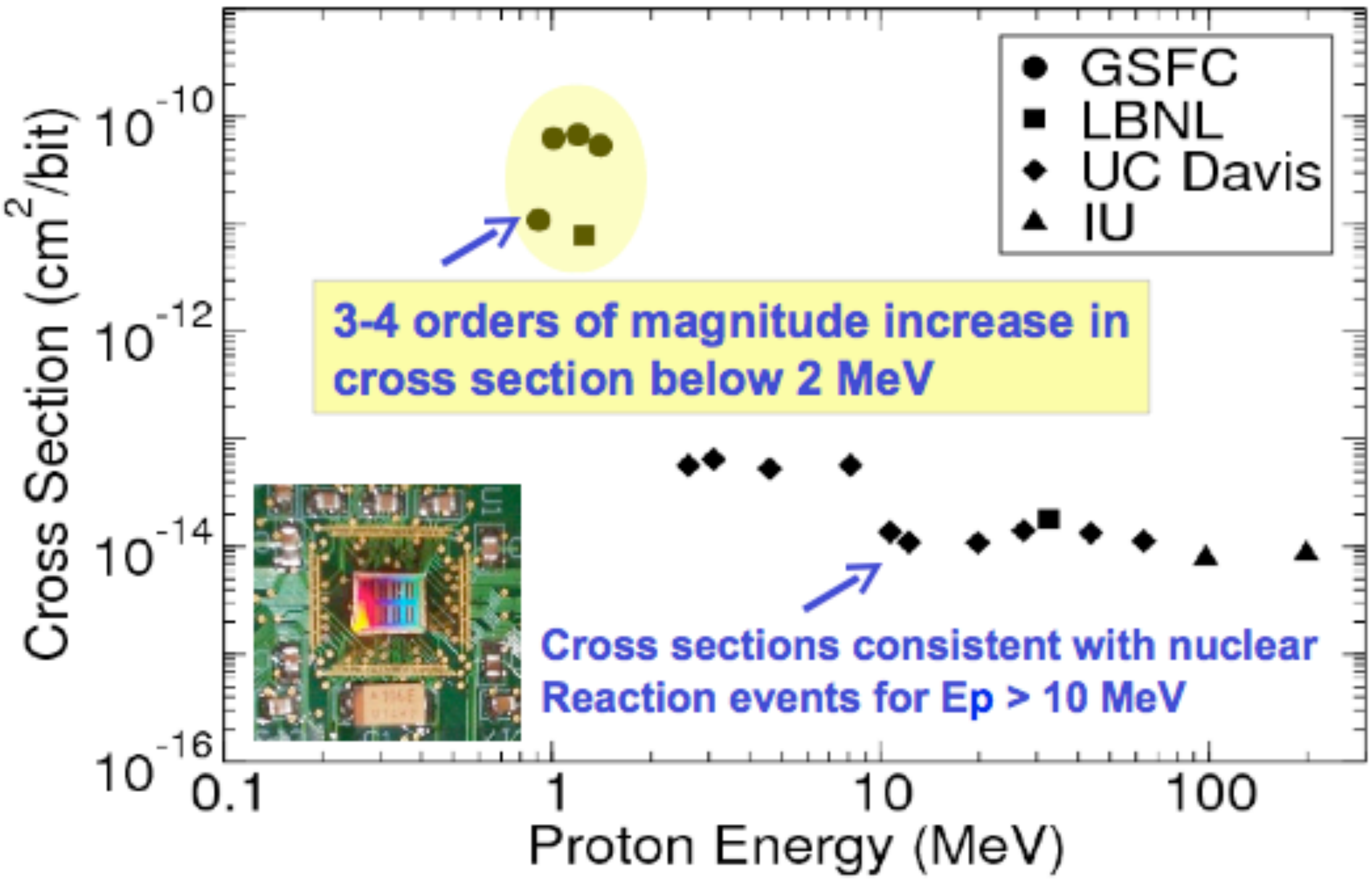
- Neither adequately model the direction ionization mechanism

$$\sigma = \left(\frac{B}{A}\right)^{14}\left(1 - e^{(-0.18Y^{\frac{1}{2}})}\right)^{4}$$

$$Y = \left(\frac{18}{A}\right)^{\frac{1}{2}}(E - A)$$

Vanderbilt MURI AFOSR

Data collected by Vanderbilt and NASA Goddard on TI 65 nm bulk CMOS process



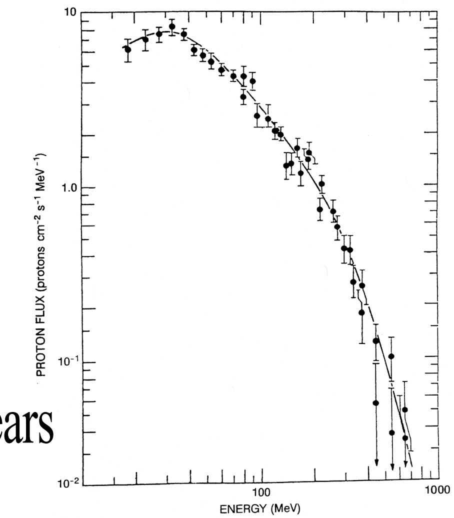
Consistent with evidence of proton direct ionization contributing to single event upsets reported for IBM 65 nm SOI process [Rodbell, TNS 2007][Heidel, TNS 2008]

Precipitate
Inner Belt Protons

Steady State → Source = Loss

Loss → Slowing down by exciting and ionizing electrons in the thermosphere

$$T \approx 2\times10^{4}(E/MeV)^{1.3}(\#cm^{3}/<\rho>)\ \text{years}$$



HANE Protons 55 MeV

How about other energies?

MURI study

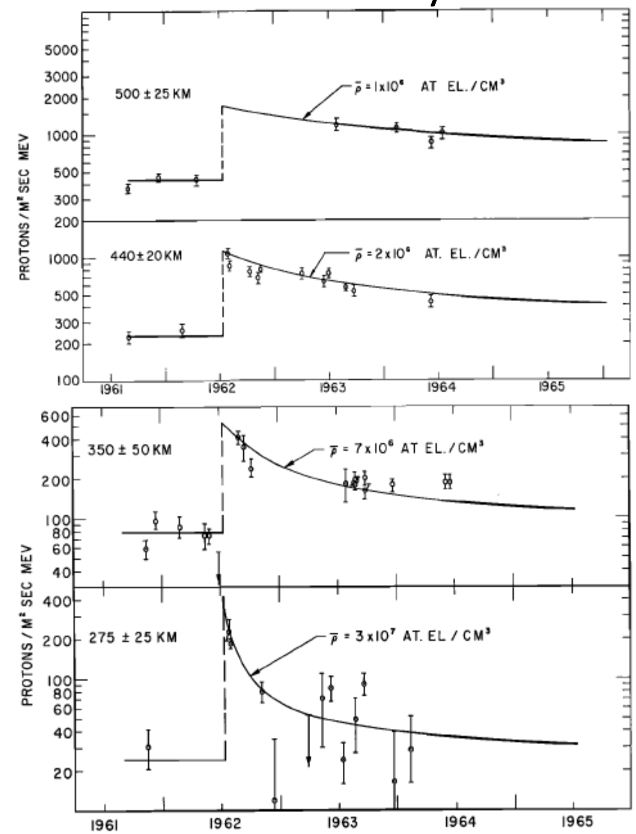
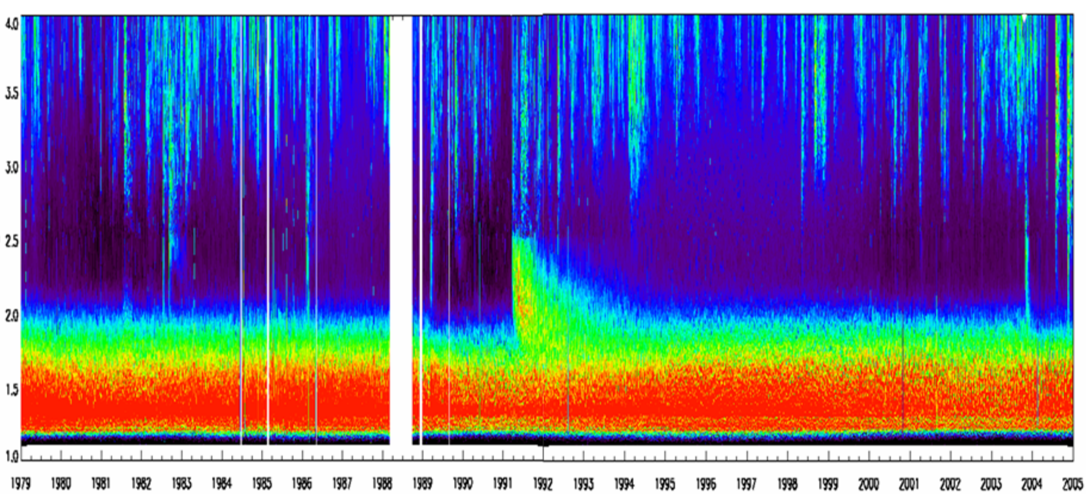


Fig. 10. Time variation of the 55-Mev proton flux for altitudes of H_e = 275, 350, 440, and 500 km from August 1961 to July 1964. The solid curves drawn for the period after July 1962 are the theoretical decay curves based on the first data point following July 1962.



26 years

PRBR by Injection of Shear Alfven Waves (SAW) from Ground Transmitters

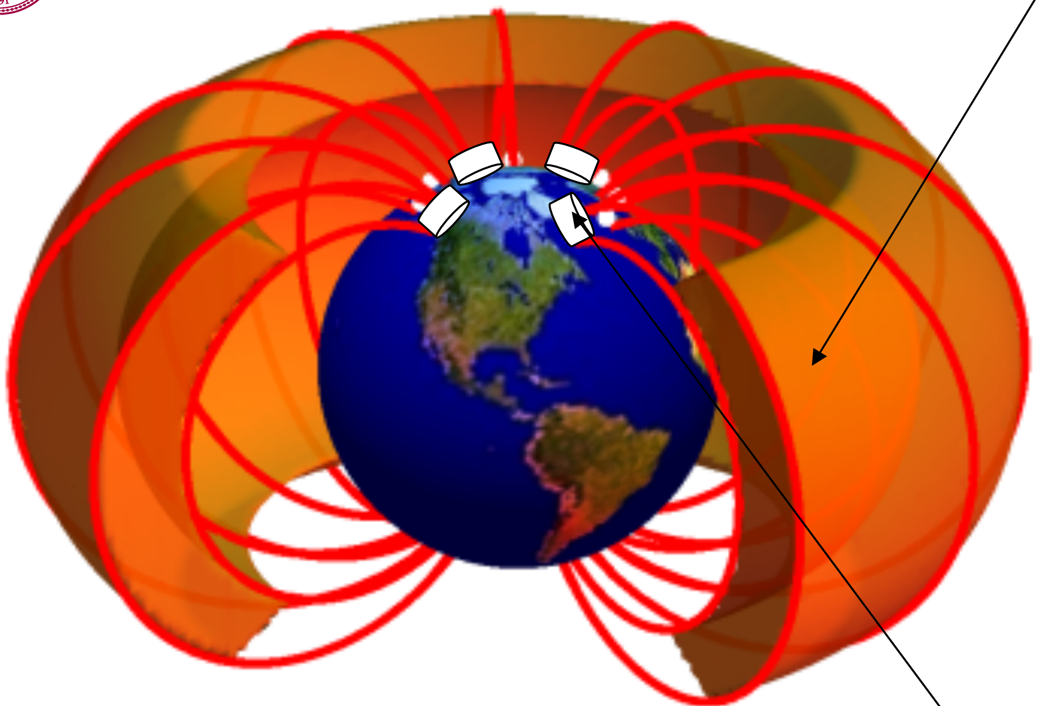
- Removal is accomplished in the same way as HANE electron remediation: increase the pitch angle diffusion rate so that protons precipitate into the atmosphere

- Pitch angle diffusion rate is increased by producing waves with the proper wavelength to resonate with energetic protons
  - ULF waves in the 1 – 30 Hz band

- Unlike HANE electrons, inner belt protons are produced by very slow processes so remediation can be done periodically (e.g. for 1-2 years every 10 years) as well as monitored

- Remediation of natural inner belt protons would have an immediate operational impact, as well as alleviate current problems

Schematic of PRBR Concept



Maintain an average amplitude of approximately 25 pT of Shear Alfven Waves (SAW) with 5-30 Hz frequency in the L=1.5-1.8 shells of the inner belt. These waves induce Pitch Angle Diffusion (PAD) on 1-100 MeV protons, by satisfying the resonance condition

$$\omega - k_z v_z = \pm\Omega$$

$$k_z v_z \approx \Omega$$

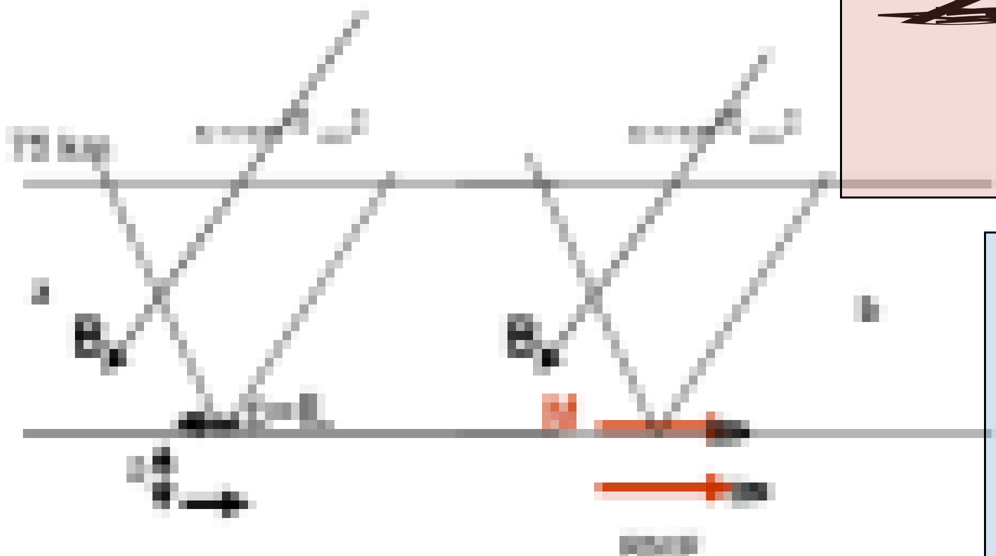
SAW injected using ground based transmitters

- Energy stored in volume for ΔL=.1 is 75 kJ
- Loss time for 1-100 MeV protons < 3 years
- Injection power required to maintain it depends on SAW confinement time ~ 10-15 kW

For physics details Papadopoulos and Shao (2009) and Shao et al.(2009)

How to Inject kW Level SAW Power Ground-based Transmitter Options

- **Conventional ULF/ELF transmitters HED (grounded dipoles)**
- **Rotating electromagnets (conventional and low and high temperature superconducting)**



HED

Need $M \sim IL^2 \sim 2x10^2$ A-m^2 $2x10^{10}$ A-m^2

RMF

Need RMF with M [illegible] $5x10^9$ A-m^2