INJECTION OF SHEAR ALFVEN WAVES IN THE INNER RADIATION BELT USING ARECIBO

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Ionospheric Interactions Workshop
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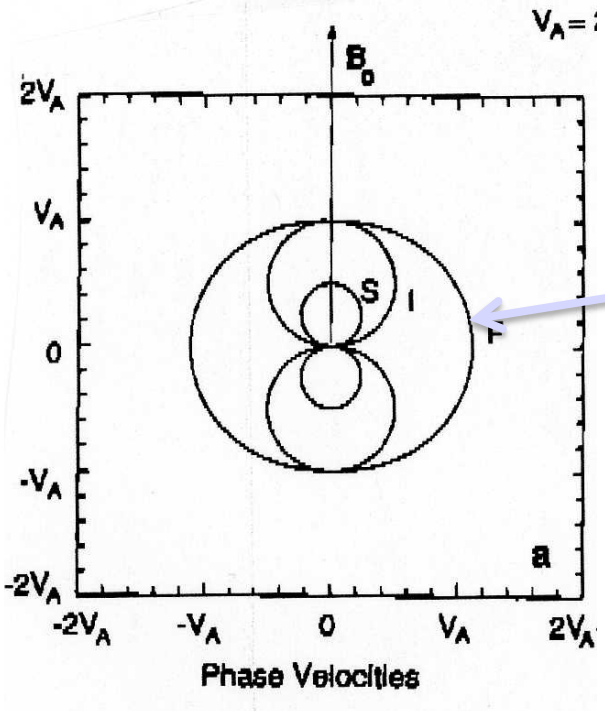
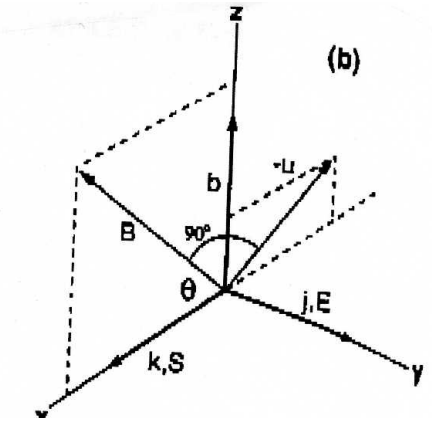
Santa Fe, New Mexico

MHD MODES

MHD WAVES - MS



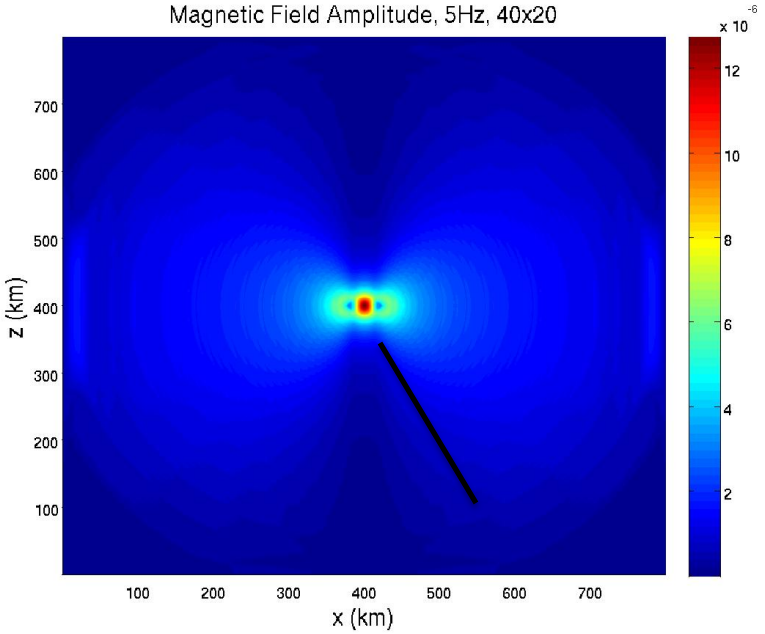
MAGNETO-SONIC MS



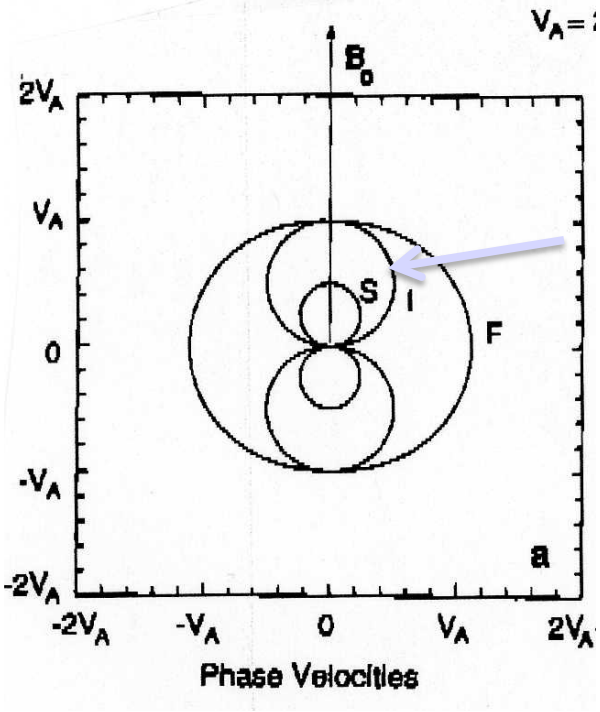
$$\omega / k = V_A \,, \omega / k_z = V_A \cos\theta$$

$$Q \equiv \nabla_\perp \cdot \vec{E}_\perp = 0$$

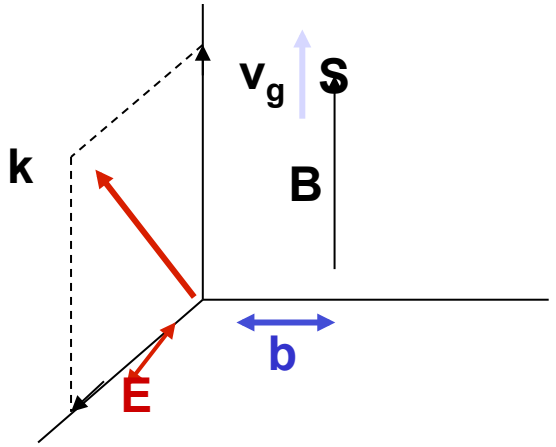
$$M \equiv \nabla_\perp \times \vec{E} \neq 0$$



MHD WAVES - SA



SHEAR
ALFVEN (SA)



FAC

$$\omega / k_z = V_A \,,\; \vec{\mathrm{V}}_{\mathrm{g}} = V_A \hat{b}$$

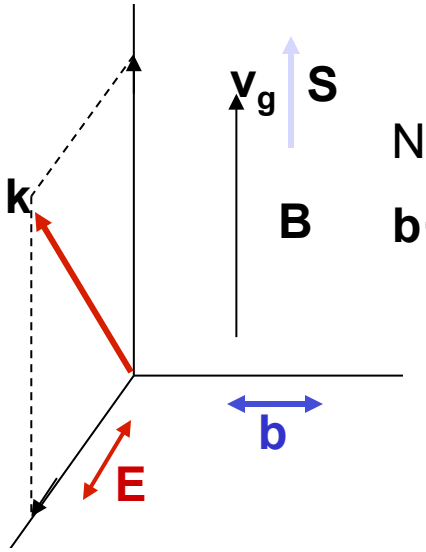
$$M \equiv (\nabla_\perp \times \vec{E}_\perp) \cdot \hat{b} = 0$$

$$Q \equiv \nabla_\perp \cdot \vec{E} \neq 0$$

IONOSPHERIC MHD PROPAGATION

RESONATORS
AND
DUCTS

Propagation SA Waves – Ionospheric Alfven Resonator (IAR)



Notice

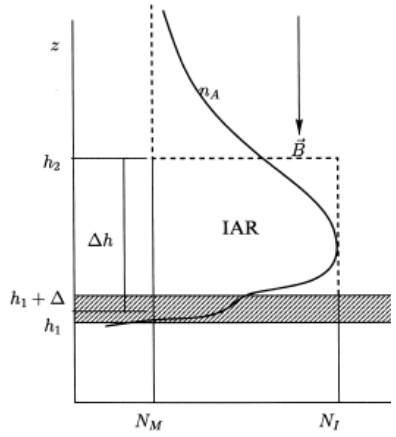
b·B=0

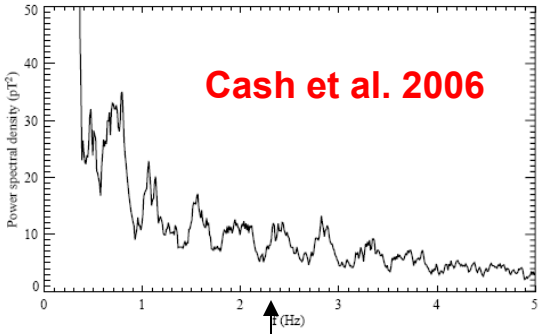
SA wave is guided along the B field

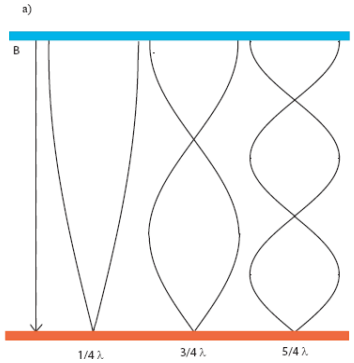
Reflections create standing wave structure

$$\omega_R \approx n \frac{\pi V_A}{(\Delta h)}$$

Reflection due to grad η



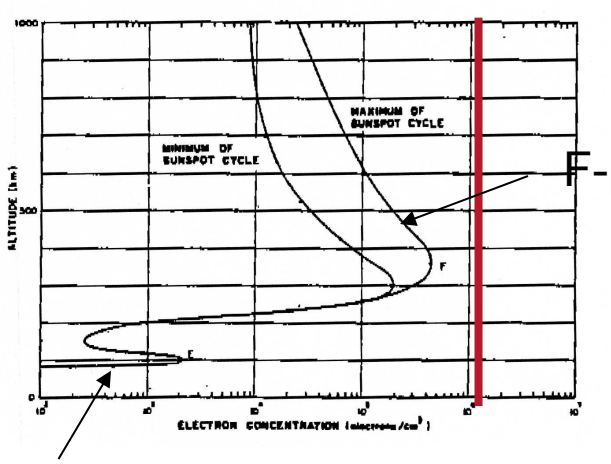




***Fabry-Perot* like Resonator**

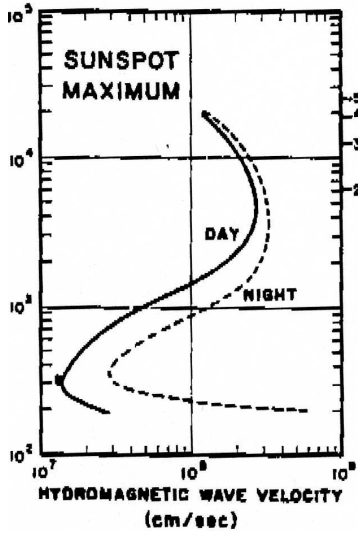
Natural SA waves

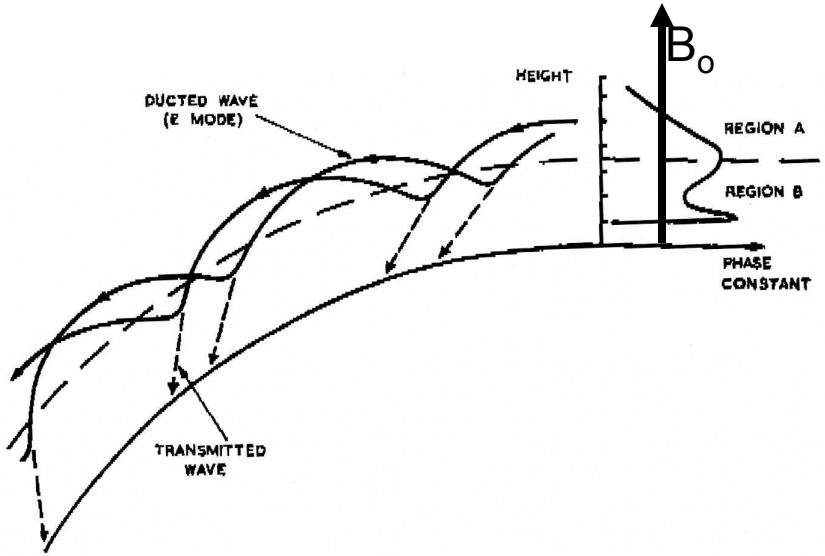
Propagation MS Waves
Alfvenic Duct

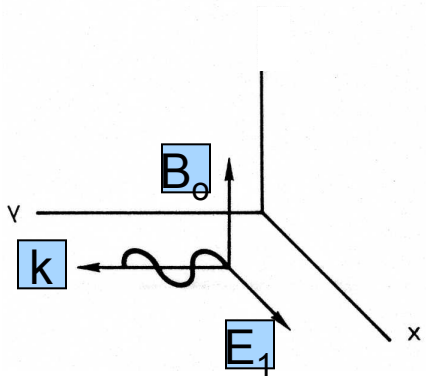


F-peak

D/E Region Ejet







Magnetosonic Alfven Wave (compressional)

SA and MS wave Equations

$$Q = \nabla_\perp \cdot \mathbf{E}_\perp, \quad M = \left(\nabla_\perp \times \mathbf{E}_\perp\right) \cdot \mathbf{i}_z, \mathrm{J_z} = (\nabla_\perp \times \mathbf{B}_\perp) \cdot \mathbf{i}_z$$

$$\left(\varepsilon \frac{\partial}{\partial t} + \sigma_P\right) Q = -\sigma_H M - \frac{\partial J_z}{\partial z}, \quad \left(\varepsilon \frac{\partial}{\partial t} + \sigma_P\right) M = \sigma_H Q - \frac{1}{\mu_0} \nabla^2 B_z + \frac{1}{B_0} \nabla_\perp^2 \delta p_\perp ,$$

$$\frac{\partial B_z}{\partial t} = -M, \quad \mu_0 \frac{\partial J_z}{\partial t} = -\frac{\partial Q}{\partial z} + \nabla_\perp^2 E_z, \quad \left(\varepsilon_0 \frac{\partial}{\partial t} + \sigma_\parallel\right) E_z = J_z, \quad .$$

Lysak 1998

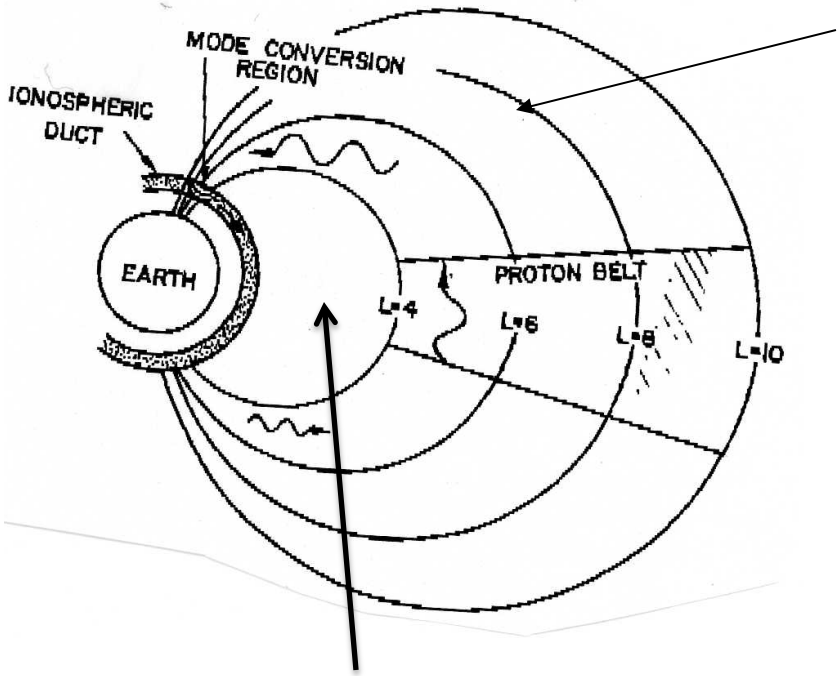
$$\varepsilon(z) = \frac{c^2}{V_A^2(z)[1 + \nu_{in}^2(z)/\Omega_i^2]}$$

SAW M=0

MS Q=0

MS-SW Wave Coupling Low Latitude Pc1

.1-5 Hz



1.AIC instability due to proton anisotropy drives SA waves at high L-shells

2. SA partly mode converted by Hall to MS propagate in Alfvenic duct to lower latitude

3. Ground signature due to Hall current driven by the MS interaction with E-region

KEY OBSERVATION: NO SAW OR EMIC WAVES IN INNER RB AND SLOT

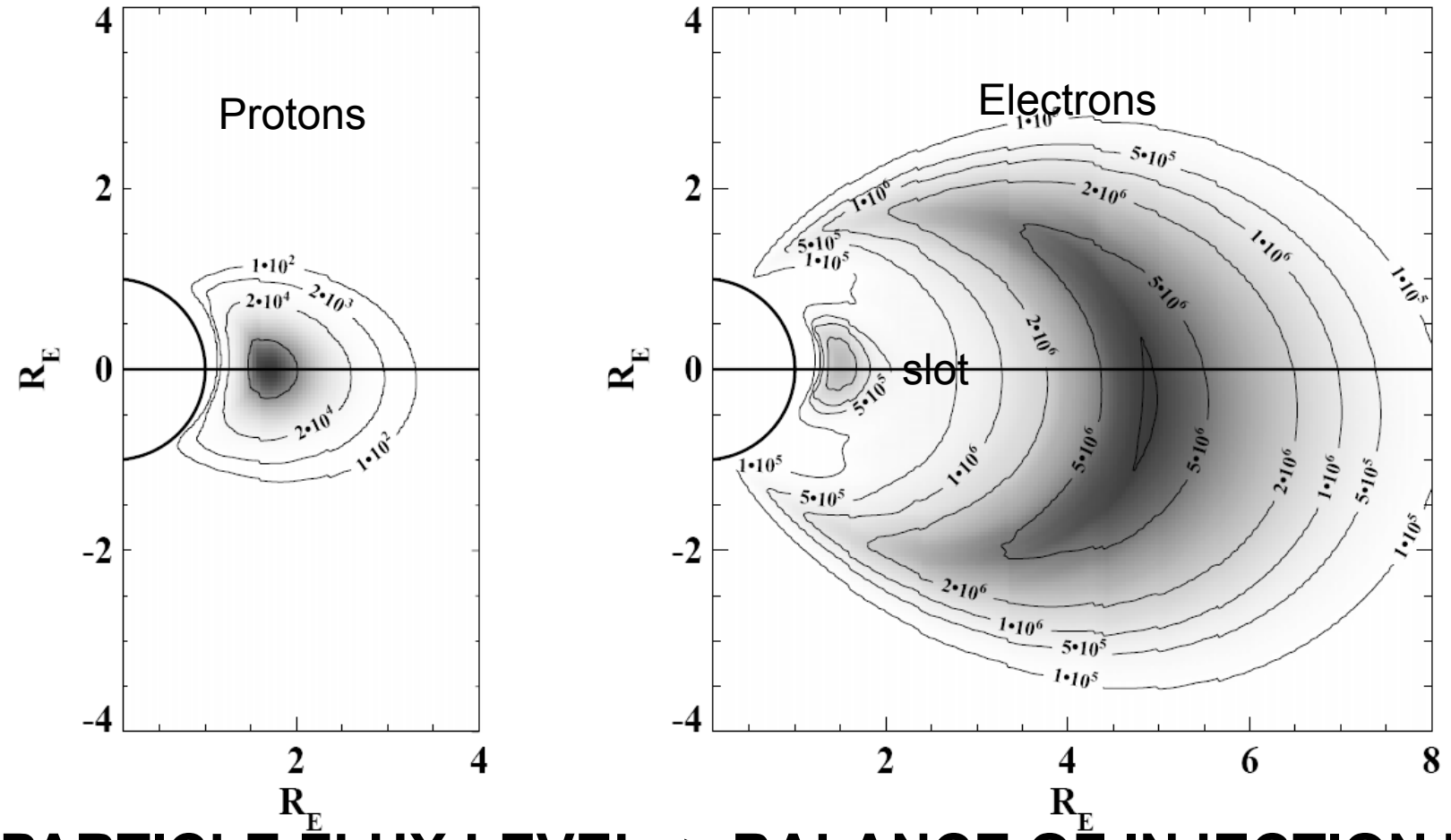
RADIATION BELTS

REGIONS

PARTICLE LIFETIMES

Wave particle Interactions (WPI)
Pitch Angle Diffusion (PAD)

Radiation Belts – Inner - Outer



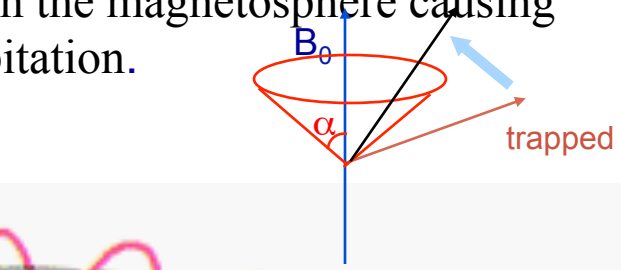
PARTICLE FLUX LEVEL -> BALANCE OF INJECTION TO TRANSPORT AND PRECIPITATION (WPI) RATE Pitch angle diffusion (PAD)

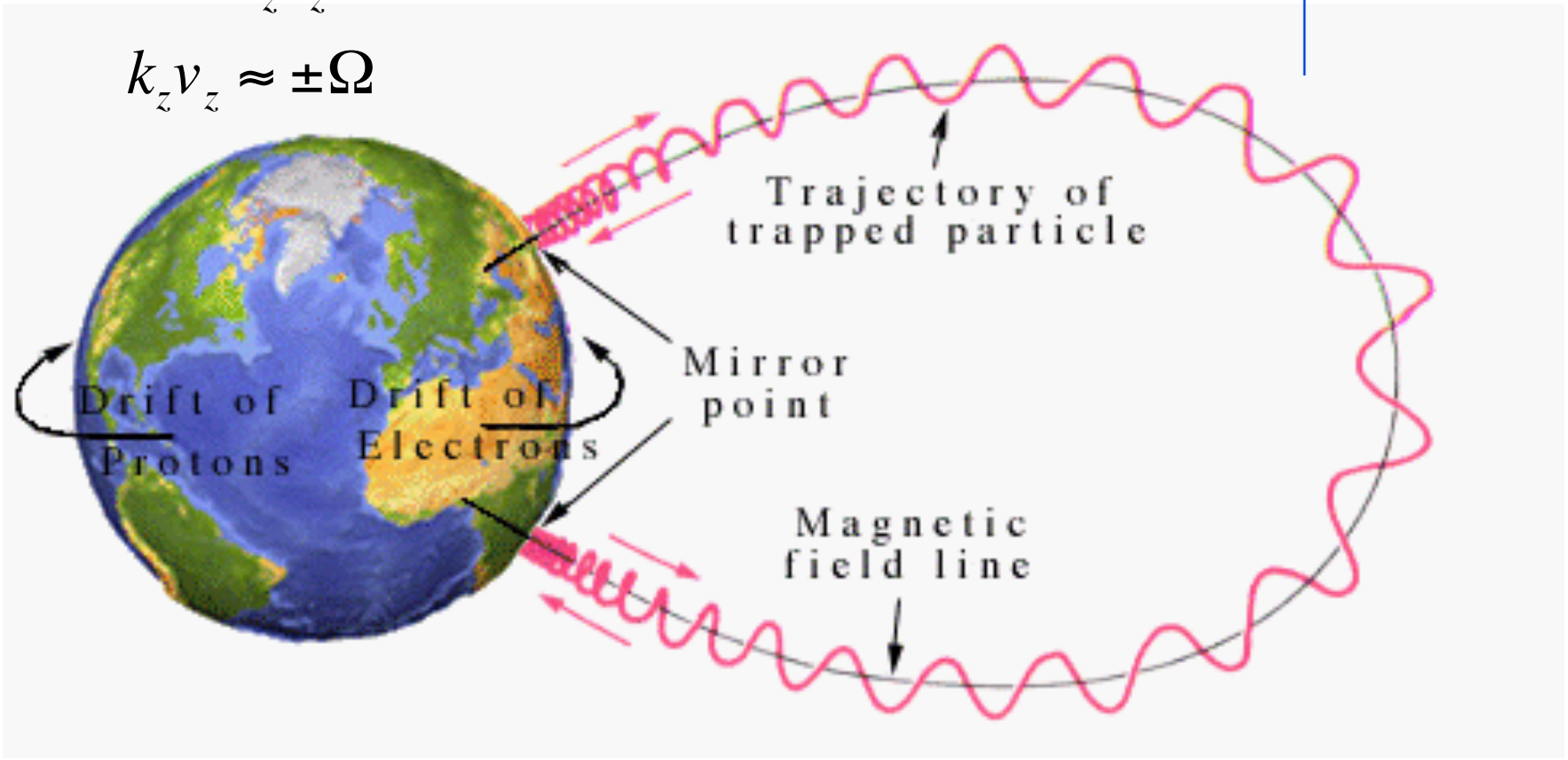
WPI-PAD CONTROL OF LOSS RATE

ULF/ELF/VLF waves resonate with trapped particles in the magnetosphere causing pitch angle scattering and precipitation.

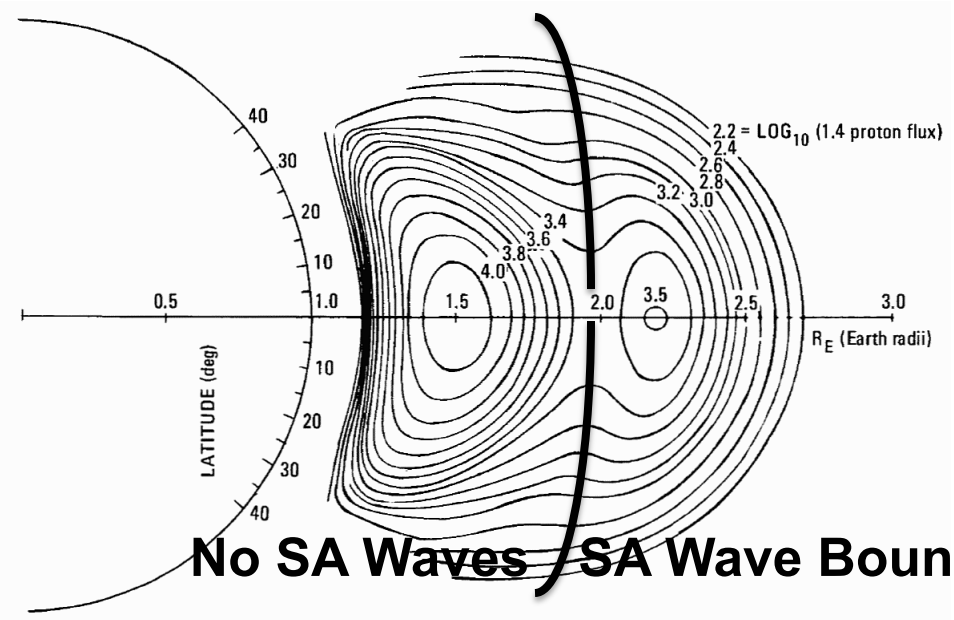
$$\omega - k_z v_z = n\Omega$$

$$k_z v_z \approx \pm\Omega$$





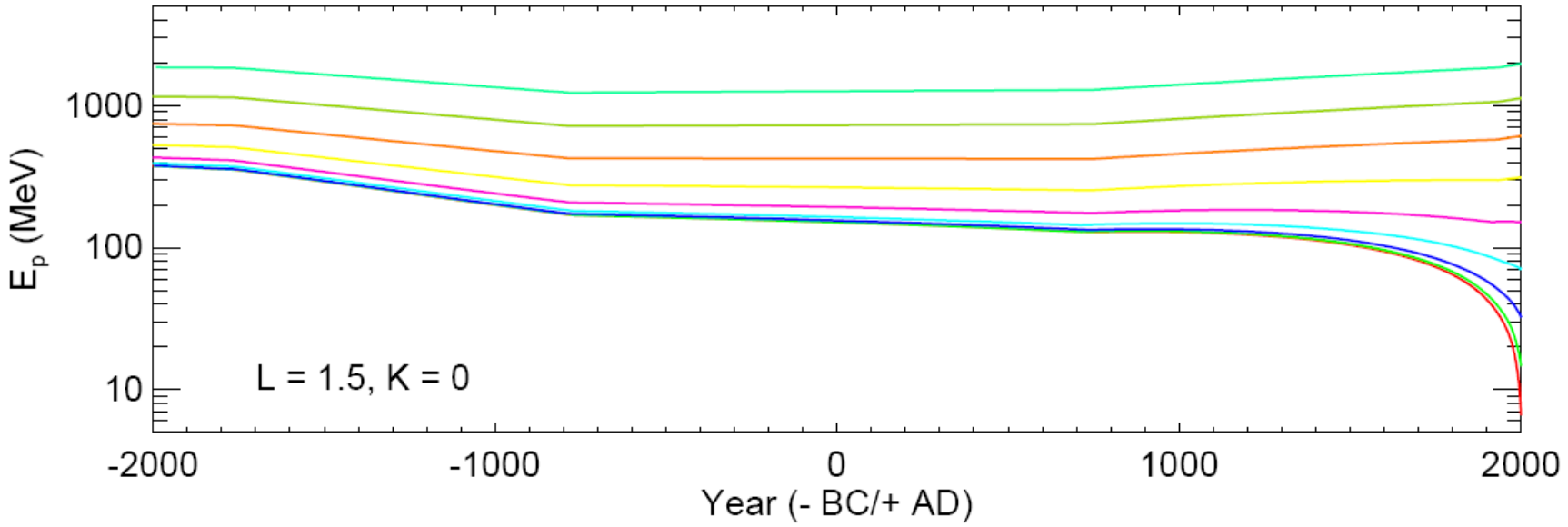
Inner Proton Belt



Typical inner belt proton lifetimes:

- **10 MeV – decades**
- **50 MeV – century**

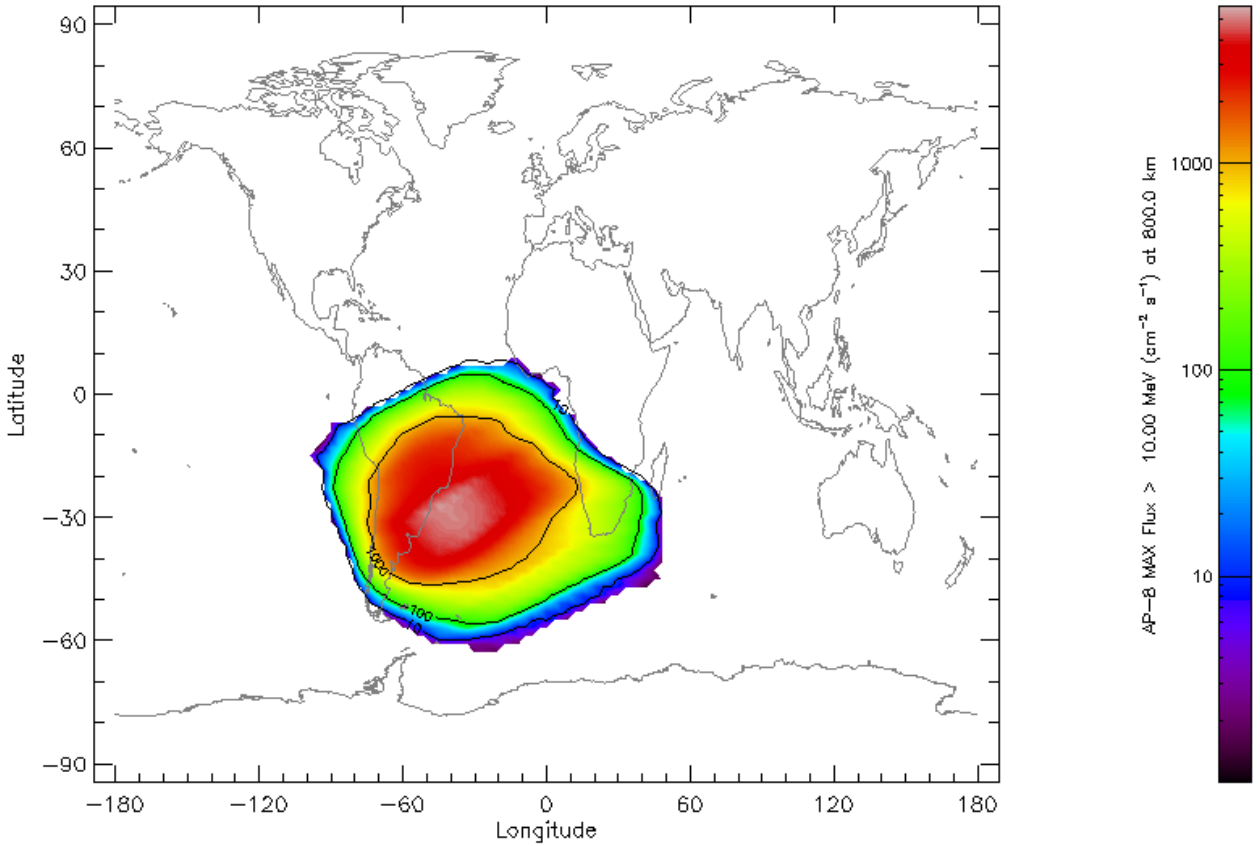
Proton Lifetimes in the Inner Belt are Long



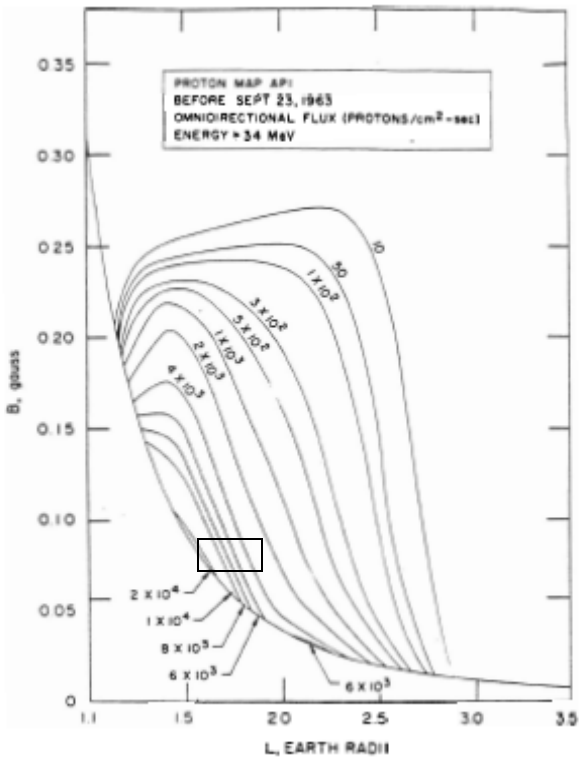
Typical inner belt proton lifetimes:

- 10 MeV – decades
- 100 MeV – centuries
- 1000 MeV – millennia

South Atlantic Anomaly



Over the south Atlantic, the inner proton belt is closest to the surface
Protons in this region are the largest radiation source for LEO satellites



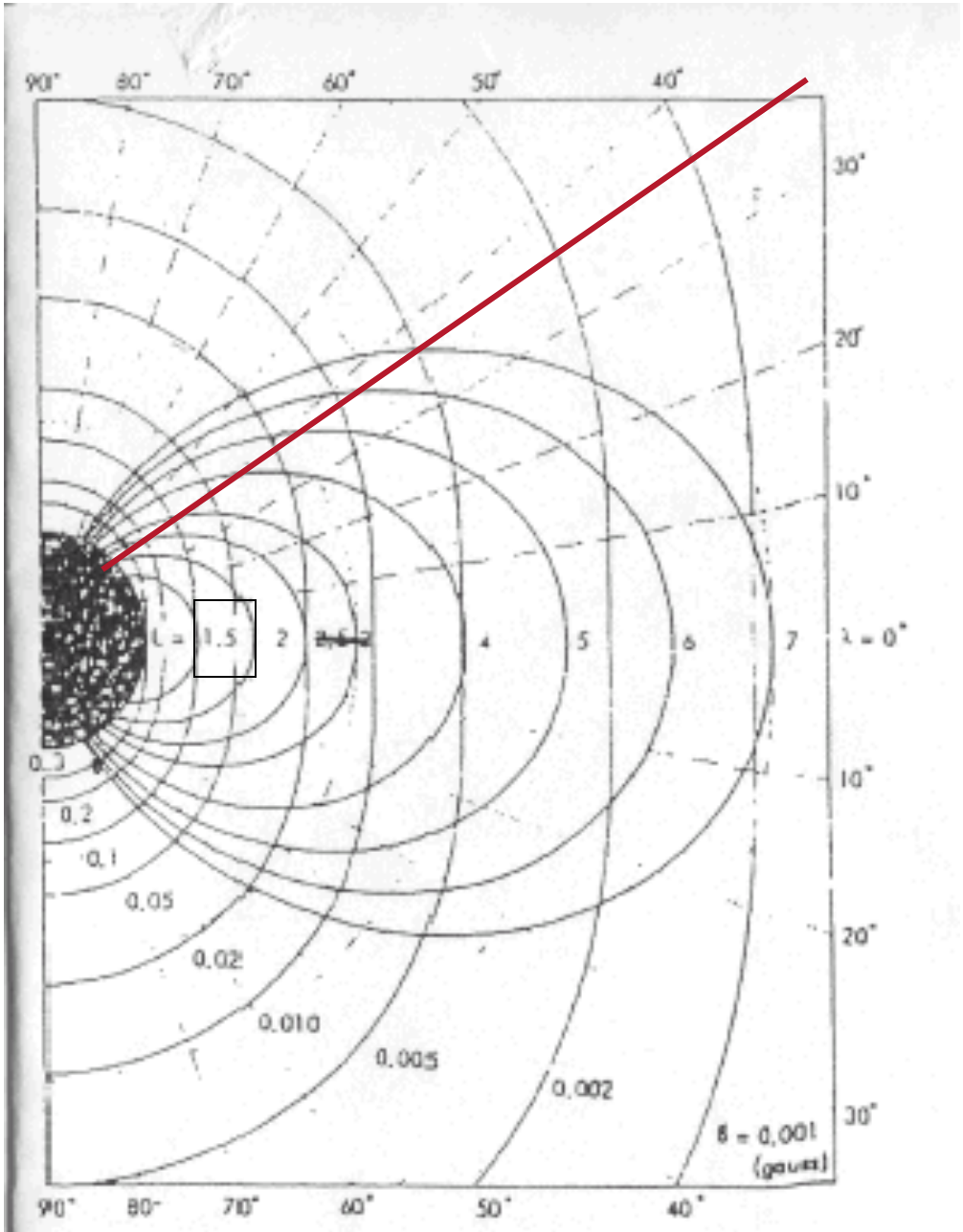
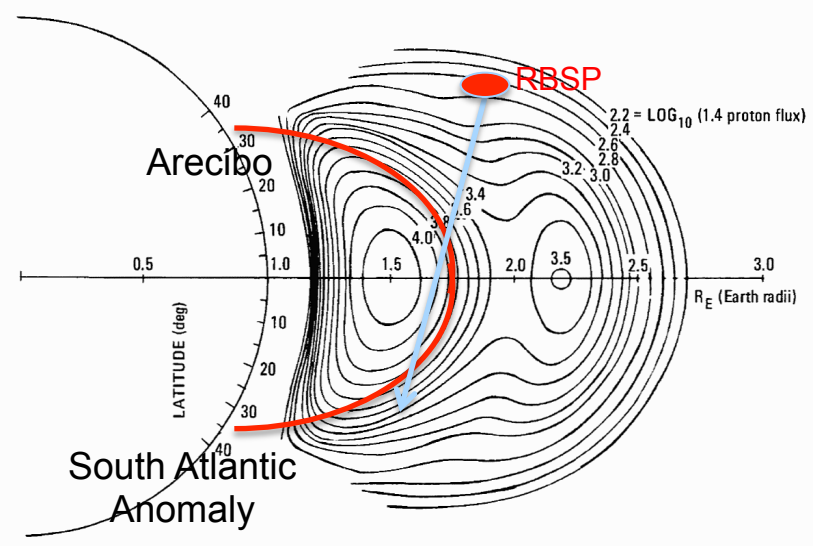


Figure 2-8. Constant-B surfaces in a dipole field.

MAJOR RESEARCH OPPORTUNITY

ACTIVE CAUSE AND EFFECT PROBING OF THE INNER BELT

Active Probing of Inner RB Using the Arecibo Heater

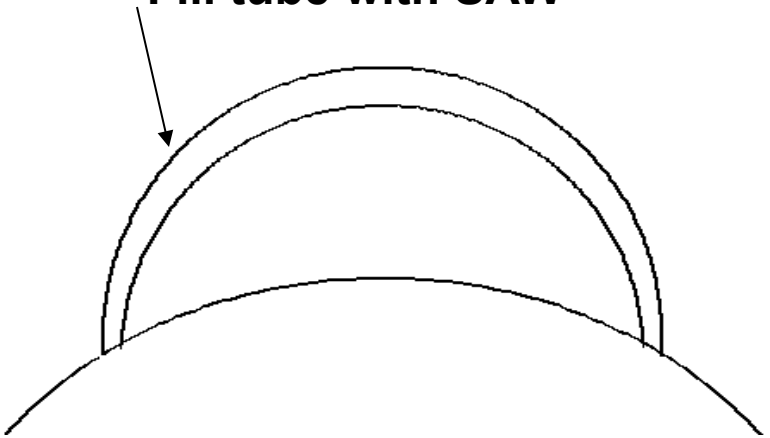


Focus on SAW for protons and EMIC for electrons

WPI critical aspect of RB physics. RBSP will study interactions in the natural environment, A wave injection facility at Arecibo at frequencies that resonate with energetic protons and electrons offer cause and effect understanding of the induced transport processes with RBSP

Frequency Selection for Protons

Example for L=1.5
Fill tube with SAW

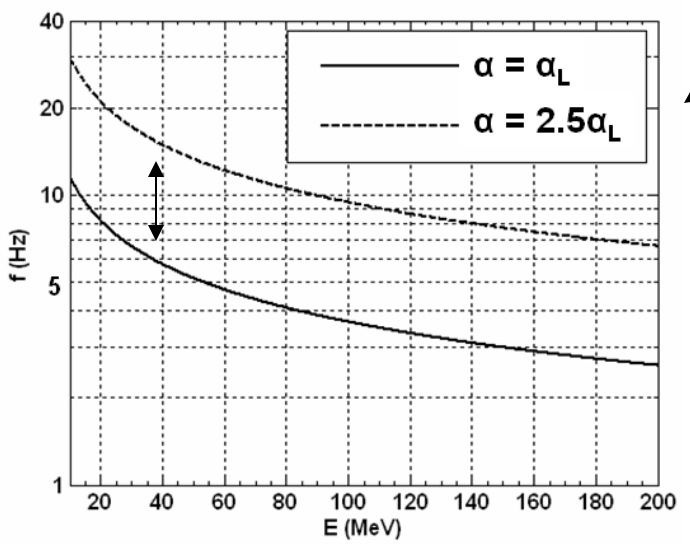


Frequency Selection for Resonance of Protons with SAW

$$\omega \approx k_z V_p$$

$$\omega = k_z V_A$$

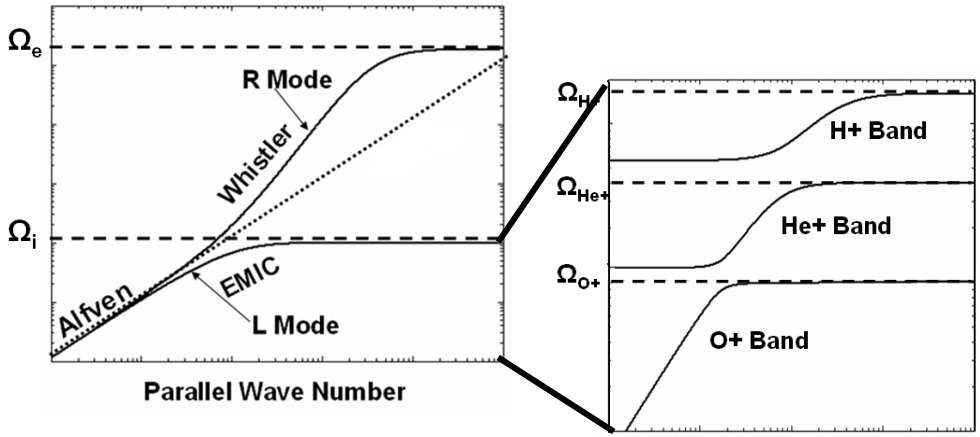
$$\omega(E,\alpha) \approx \frac{\Omega}{\cos\alpha}\sqrt{\frac{MV_A^2}{2E}}$$



Frequency requirement for equatorial resonance with SAW at L=1.5

Frequency range 5-30 Hz

ENERGETIC ELECTRON WP INTERACTIONS DUE TO EMIC WAVES



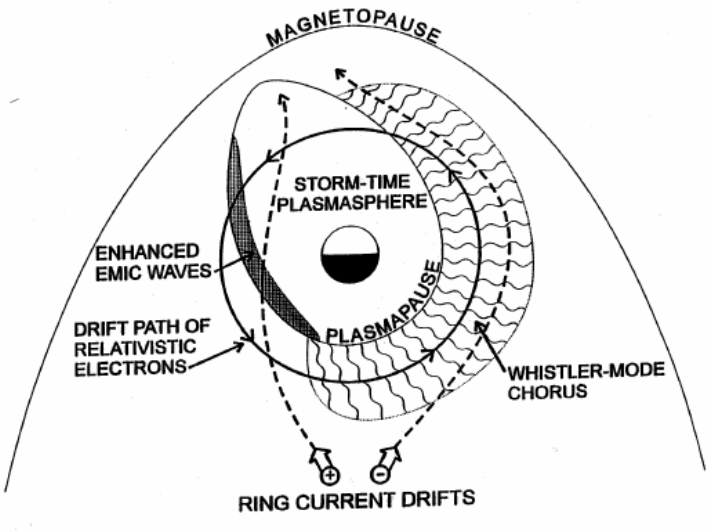
$$-k_z v_z = |\Omega_e| / \gamma$$

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

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

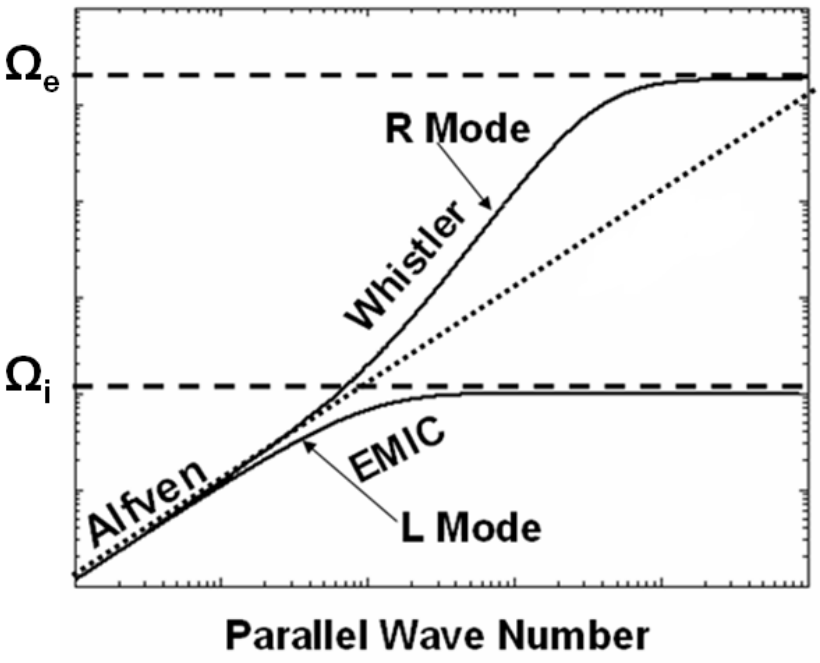
As a result $1/k_z \to |\Omega_e| / \gamma v_z$ before reaching resonance $(1/k_z \to 0)$

Outer Belts

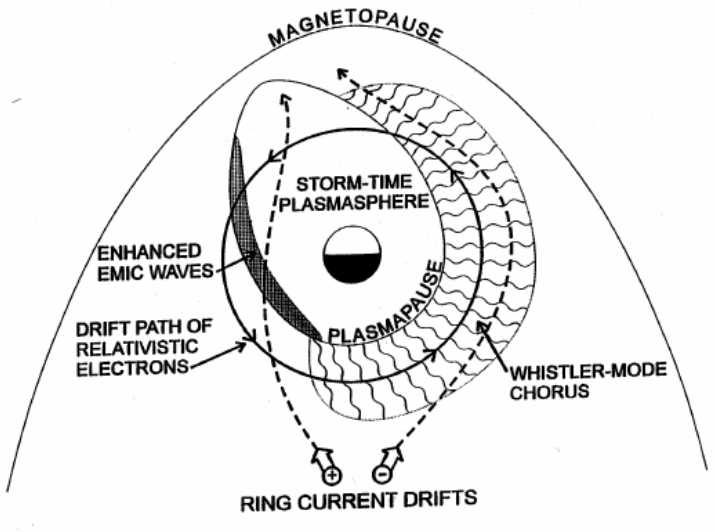


Summers et al., 1998, 2000, 2003

Frequency Selection for Electrons EMIC

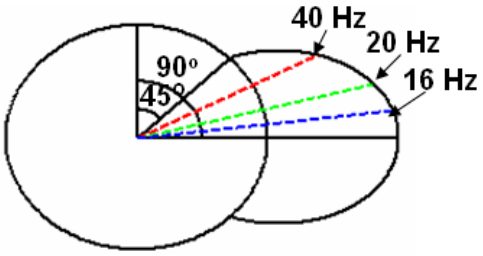


Outer Belts



Summers et al., 1998, 2000, 2003

Helium branch

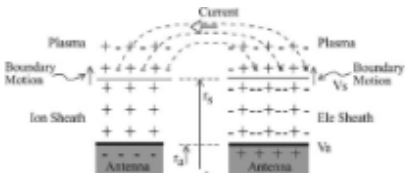


For midlatitude MeV electrons

HOW TO INJECT SA AND EMIC WAVES FROM ARECIBO

HAARP PEJ VS. ICD

SA Wave Generation During Electrojet
PEJ Anenna



Injects whistlers and SAW

FAC

E_o

E

J

Hall

$J_P / J_H = \nu_{en} / \Omega_e$

$\nu_{en} : T_e^{\alpha}$

$\varepsilon\omega = \sigma$

$E = E_o$ 0<t<T

$E = 0$ T<t<2T

$\nu << \Omega_e$

$\nu = \Omega_e$

$\nu >> \Omega_e$

J

Pedersen

Bottom of the ionosphere

$\varepsilon\omega = \sigma$

Near field

Far field

Bo

E

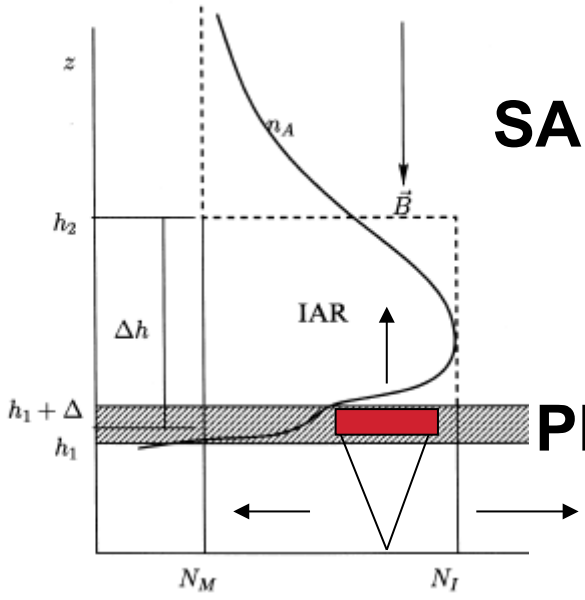
TEM mode

H

heater

T

MHD Wave Generation by the PEJ



SA will be guided by the magnetic field to the conjugates – No lateral propagation through the plasma

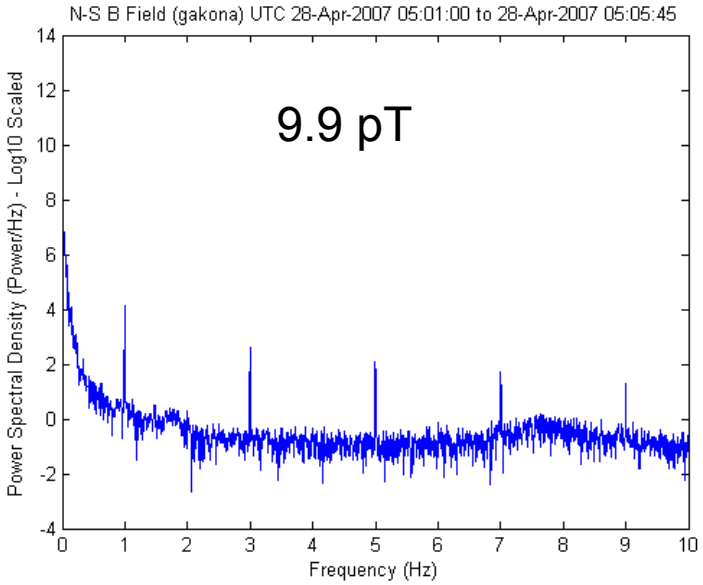
$$f \approx c / 2\pi R_E \approx 8Hz$$ **Schumann**

Evanescent in EI Waveguide if f<8Hz

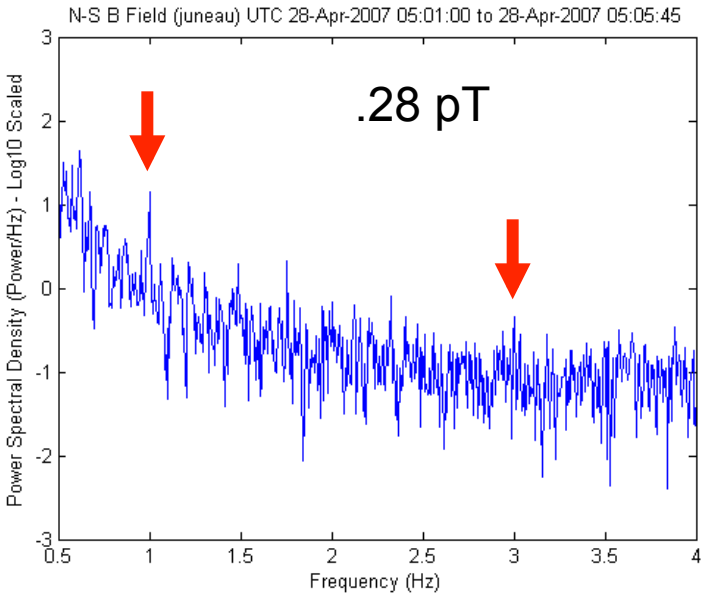
- **SA waves can be detected: (a) In the near zone below the heated spot and (b) By satellites over-flying the heated spot but confined to the magnetic flux tube that spans the heated spot (c) Through the EI waveguide for f>8 Hz (Schumann Resonance)**

ULF Signal Propagation Evanescent Mode (1 Hz)

Gakona

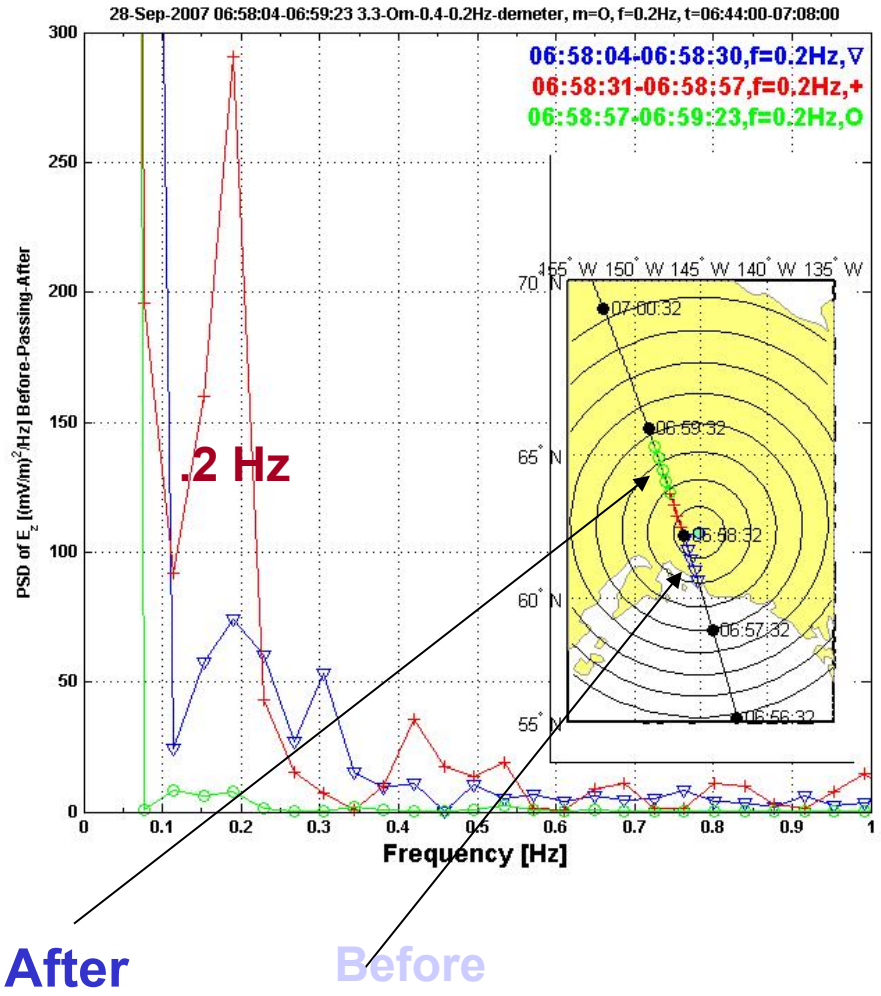


Juneau – 800 km



- 28 April, 2007 UTC 05:01:00 – 05:05:45
- HAARP at 2.88 MW and 3.3 MHz
- Detected 1 Hz & 3 Hz peaks
- B~1/R^2 wave evanescent (Frequencies below Schumann Resonance)

SAW DEMETER Detection



Frequency .2 Hz

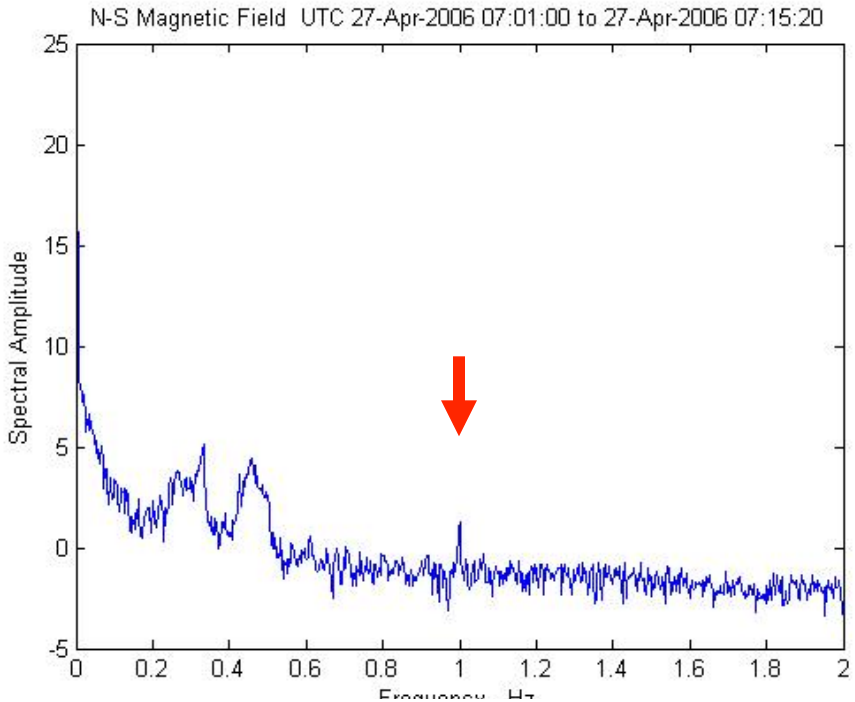
Closest distance 80 km

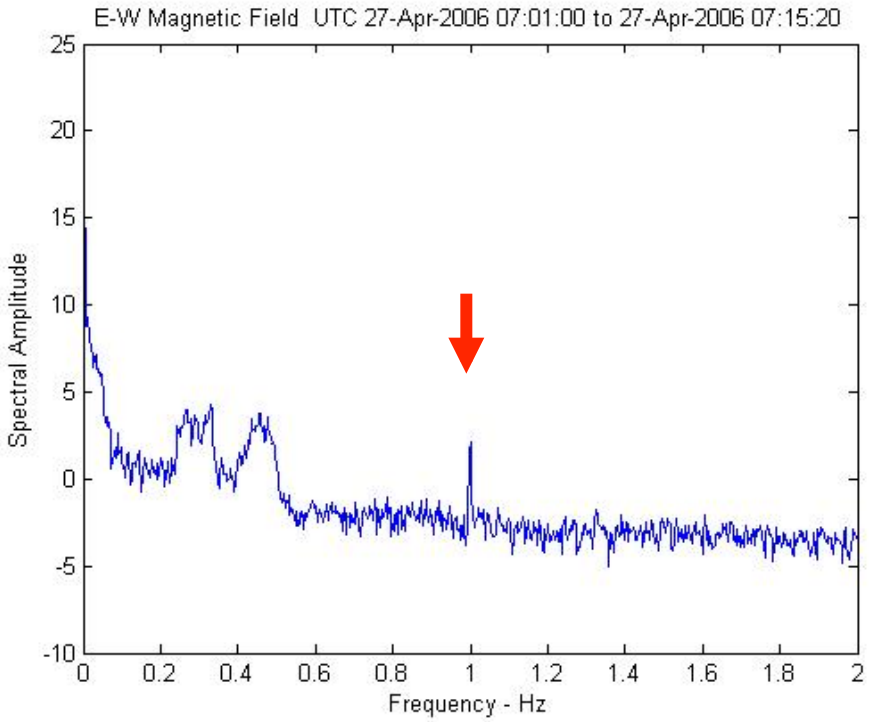
Detection time 25 sec

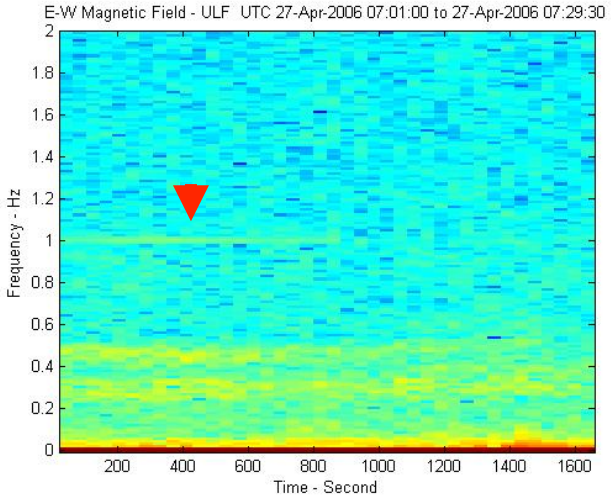
Detection distance 150 km

1.5 pT on the ground

IAR Excitation by the PEJ





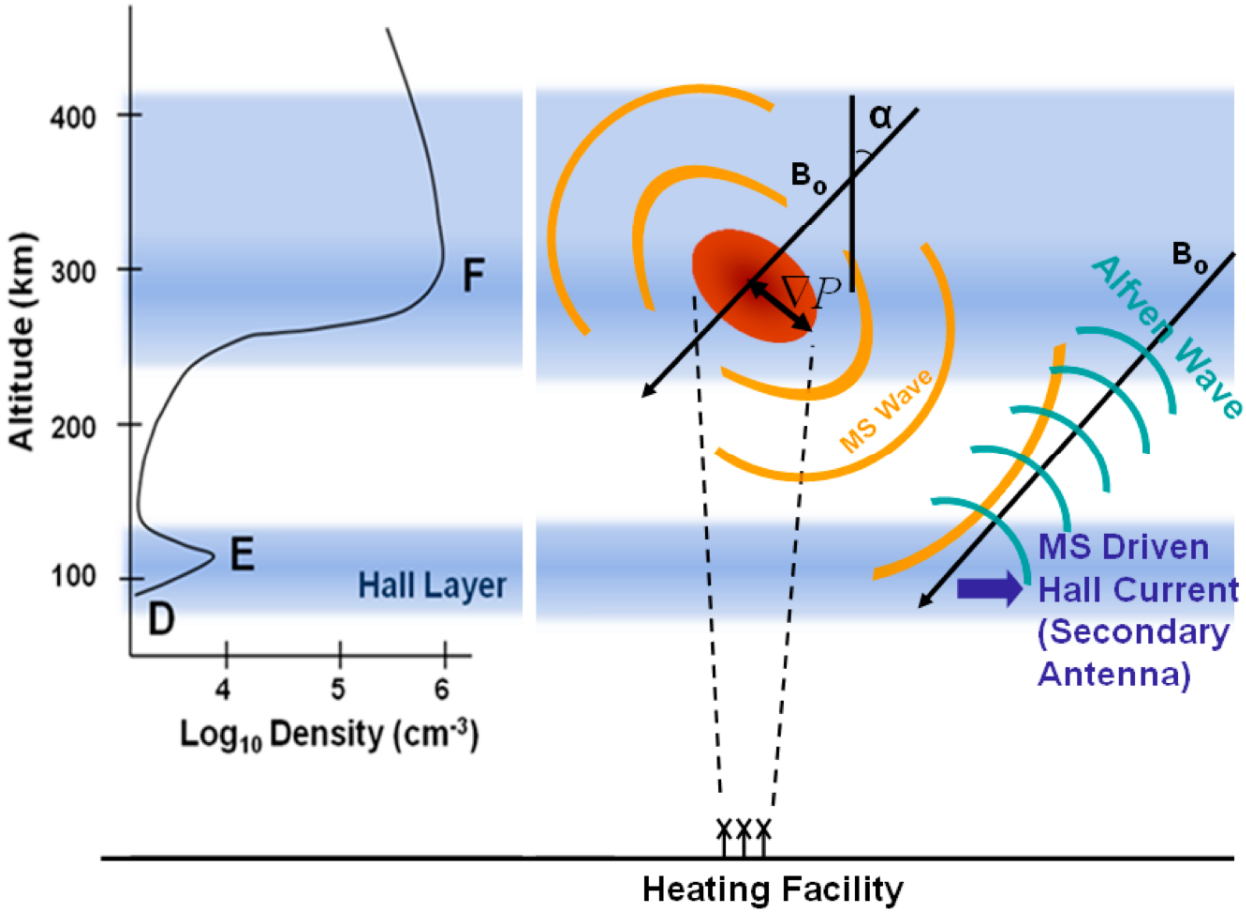


Excitation of the IAR due naturally excited waves at .25 Hz and .5 Hz and by HAARP generated SA at 1.0 Hz.

Ionospheric Current Drive (ICD) Concept

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

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



Injects SAW upwards and ELF in the Earth-Ionosphere Waveguide

Model of CID for Vertical B

$$Q = \nabla_\perp \cdot \mathbf{E}_\perp, \quad M = \left(\nabla_\perp \times \mathbf{E}_\perp\right) \cdot \mathbf{i}_z, \mathrm{J_z} = (\nabla_\perp \times \mathbf{B}_\perp) \cdot \mathbf{i}_z$$

$$\left(\varepsilon \frac{\partial}{\partial t} + \sigma_P\right) Q = -\sigma_H M - \frac{\partial J_z}{\partial z}, \quad \left(\varepsilon \frac{\partial}{\partial t} + \sigma_P\right) M = \sigma_H Q - \frac{1}{\mu_0} \nabla^2 B_z + \frac{1}{B_0} \nabla_\perp^2 \delta p_\perp ,$$

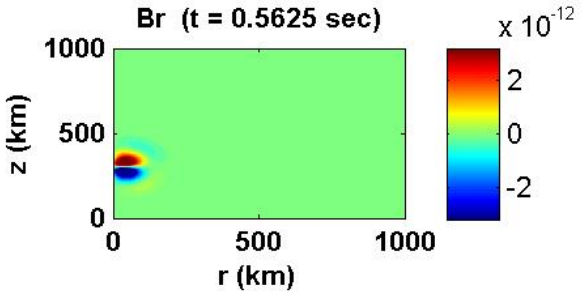
$$\frac{\partial B_z}{\partial t} = -M, \quad \mu_0 \frac{\partial J_z}{\partial t} = -\frac{\partial Q}{\partial z} + \nabla_\perp^2 E_z, \quad \left(\varepsilon_0 \frac{\partial}{\partial t} + \sigma_\parallel\right) E_z = J_z, \quad .$$

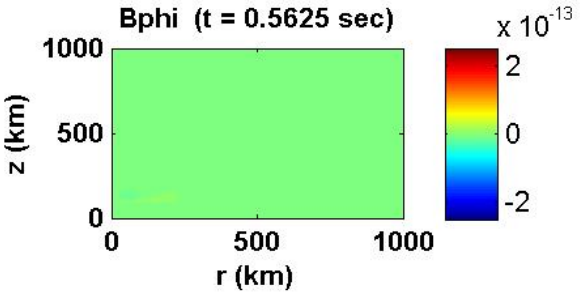
$$\varepsilon(z) = \frac{c^2}{V_A^2(z)[1 + \nu_{in}^2(z)/\Omega_i^2]}$$

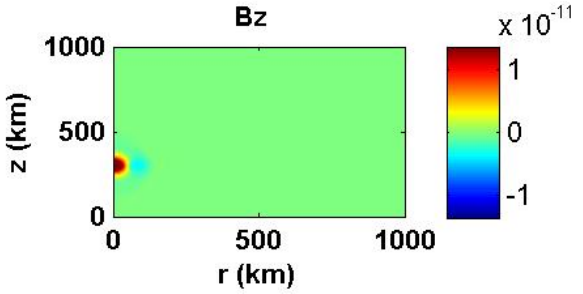
Lysak 1998

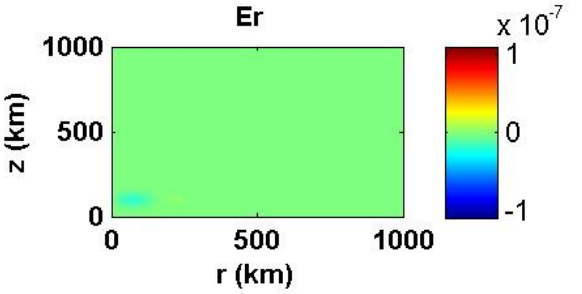
Cylindrical Coordinates

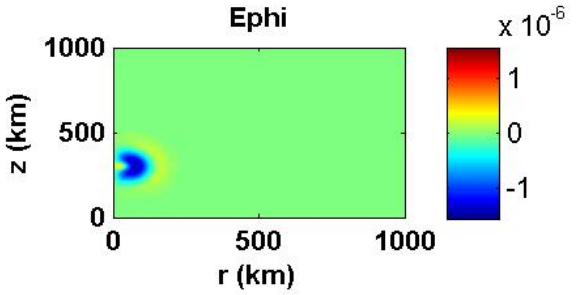
Papadopoulos et al. GRL 2011

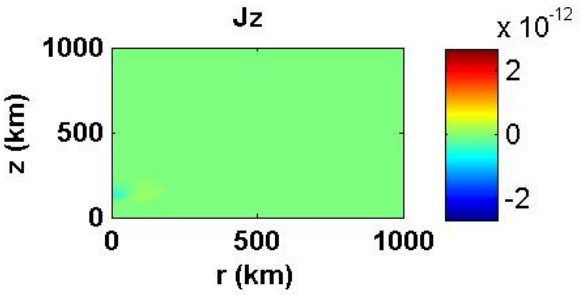






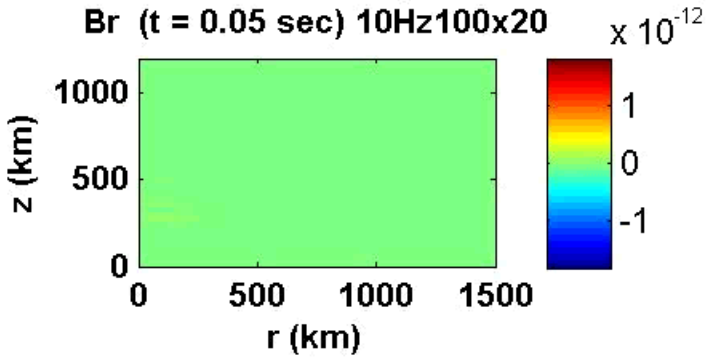


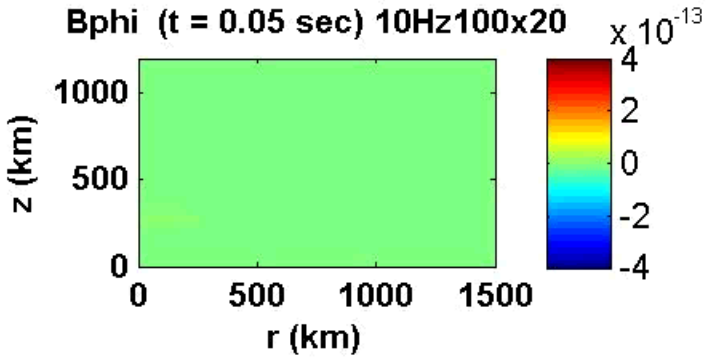


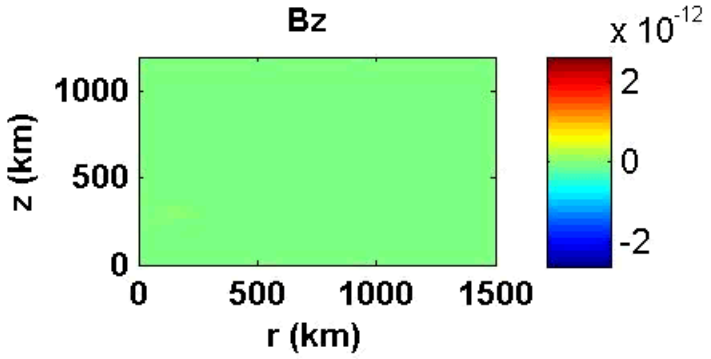


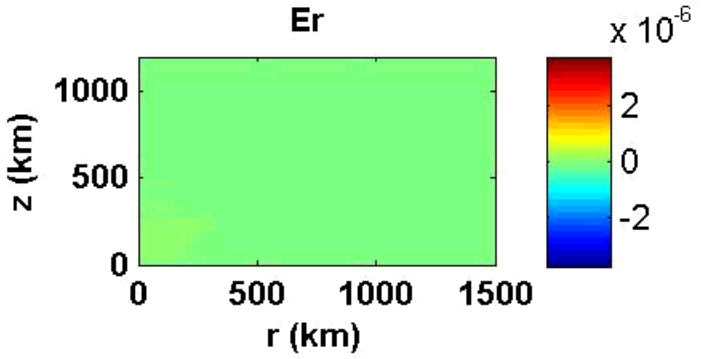
MS

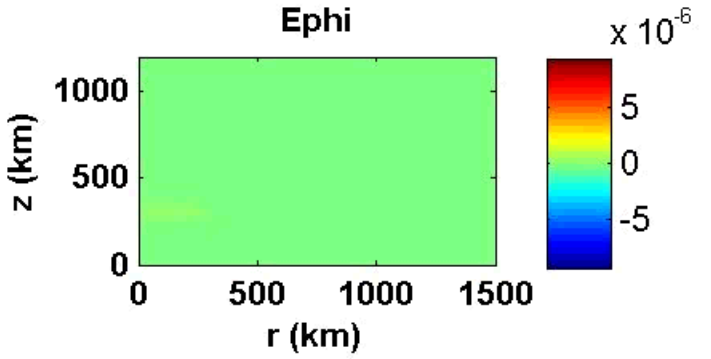
SAW

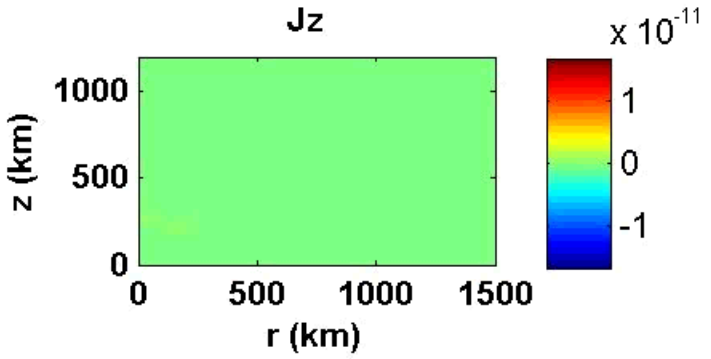

Br (t = 0.05 sec) 10Hz100x20
x 10^-12
1
0
-1
1000
500
0
z (km)
0
500
1000
1500
r (km)


Bphi (t = 0.05 sec) 10Hz100x20
x 10^-13
4
2
0
-2
-4
1000
500
0
z (km)
0
500
1000
1500
r (km)


Bz
x 10^-12
2
0
-2
1000
500
0
z (km)
0
500
1000
1500
r (km)

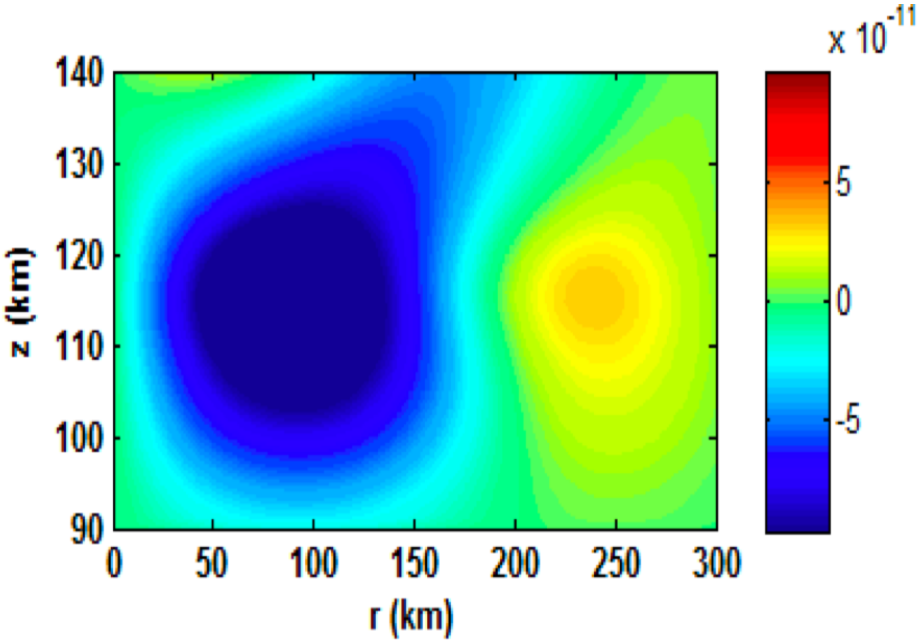

Er
x 10^-6
2
0
-2
1000
500
0
z (km)
0
500
1000
1500
r (km)


Ephi
x 10^-6
5
0
-5
1000
500
0
z (km)
0
500
1000
1500
r (km)

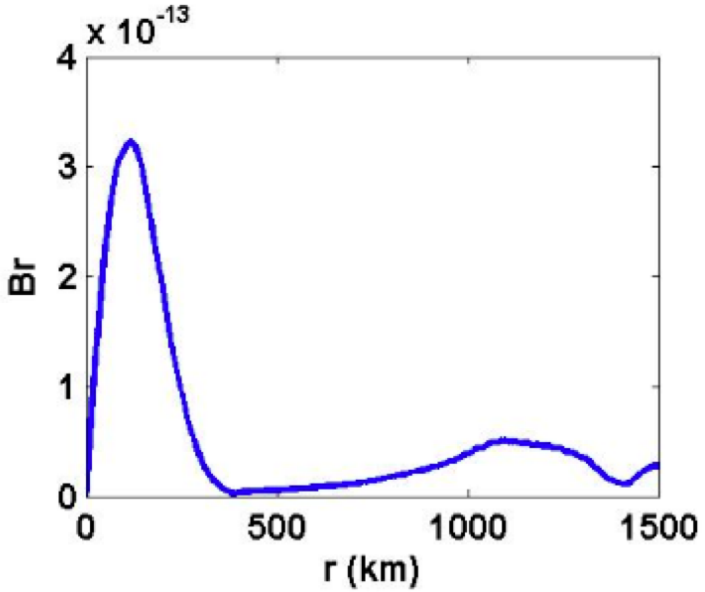

Jz
x 10^-11
1
0
-1
1000
500
0
z (km)
0
500
1000
1500
r (km)

10 Hz

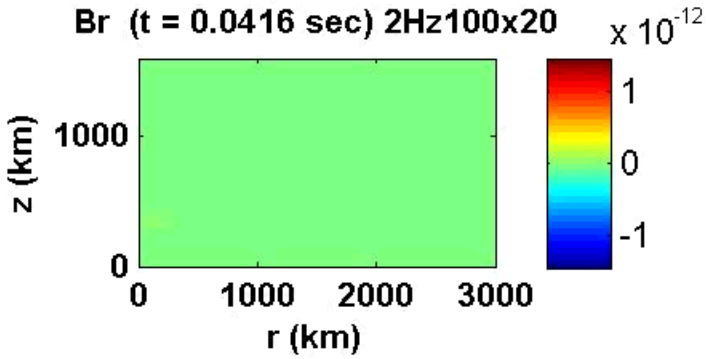
Secondary Antenna Current and Ground Field

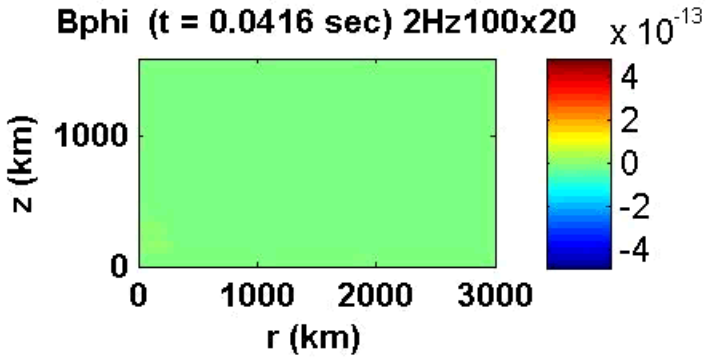


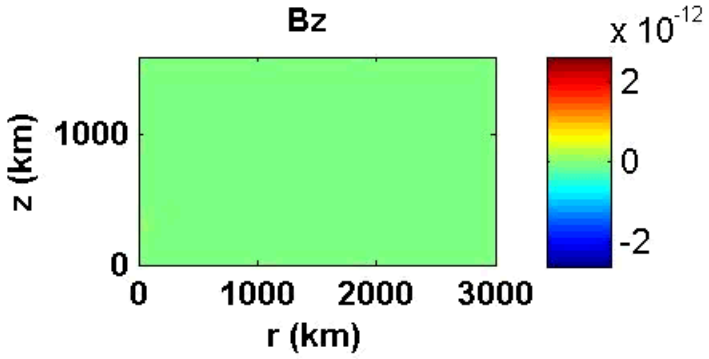
J_θ

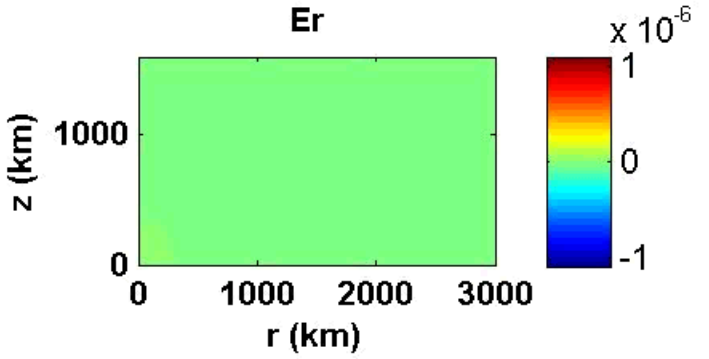


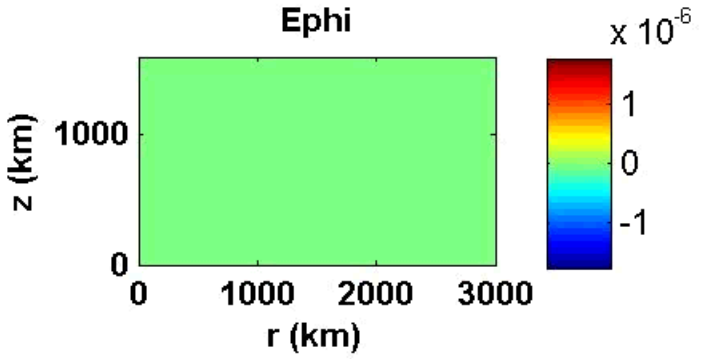
B_r

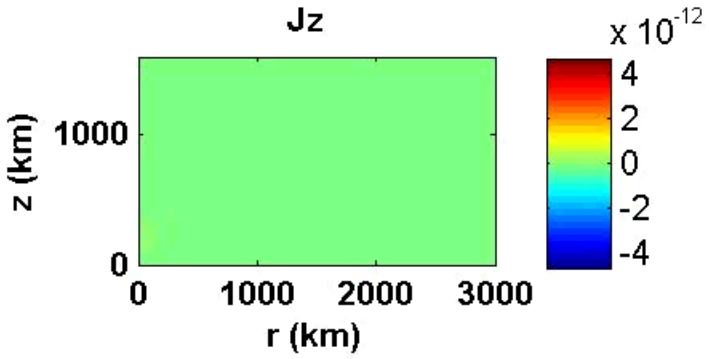

Br (t = 0.0416 sec) 2Hz100x20
x 10^-12
1
0
-1
z (km)
1000
0
0
1000
2000
3000
r (km)


Bphi (t = 0.0416 sec) 2Hz100x20
x 10^-13
4
2
0
-2
-4
z (km)
1000
0
0
1000
2000
3000
r (km)


Bz
x 10^-12
2
0
-2
z (km)
1000
0
0
1000
2000
3000
r (km)

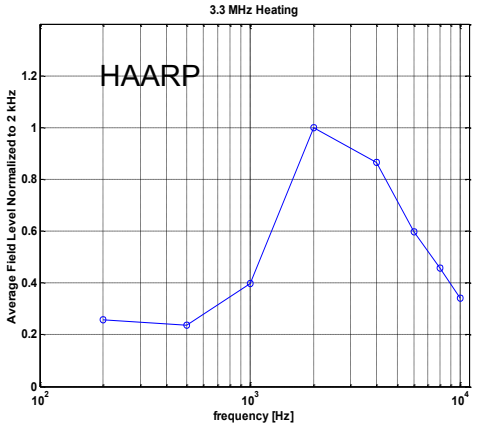

Er
x 10^-6
1
0
-1
z (km)
1000
0
0
1000
2000
3000
r (km)

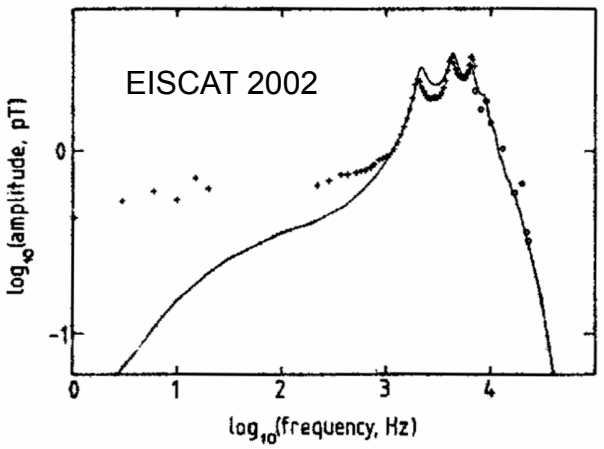

Ephi
x 10^-6
1
0
-1
z (km)
1000
0
0
1000
2000
3000
r (km)

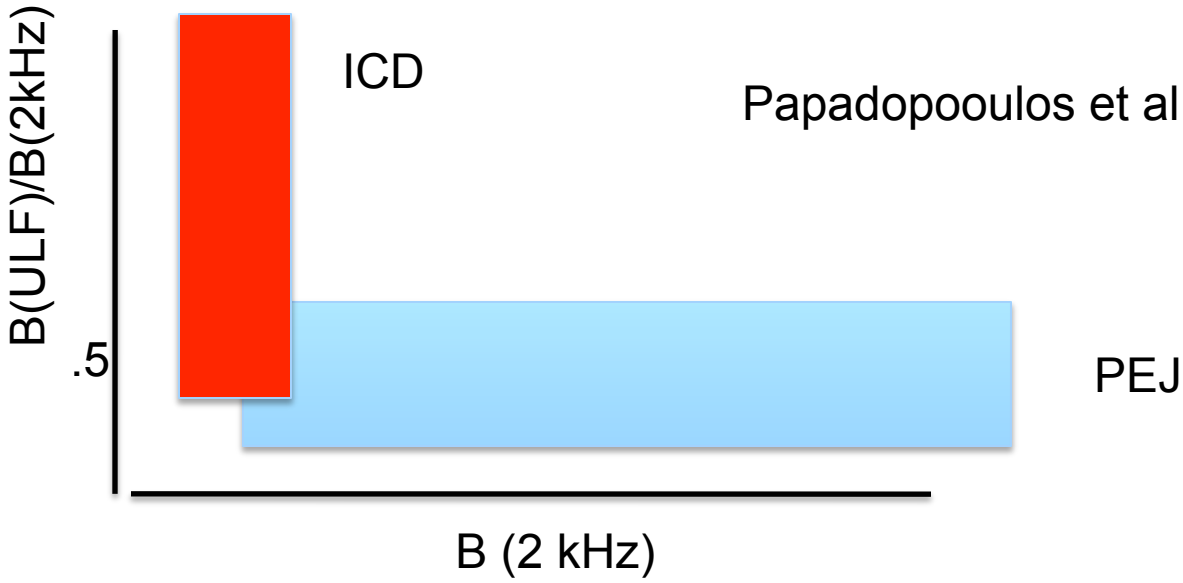

Jz
x 10^-12
4
2
0
-2
-4
z (km)
1000
0
0
1000
2000
3000
r (km)

2 Hz

ICD vs. PEJ How to Distinguish 2 kHz as ejet proxy

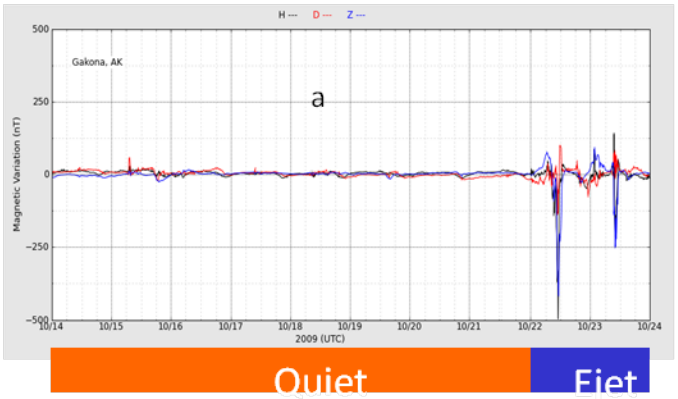


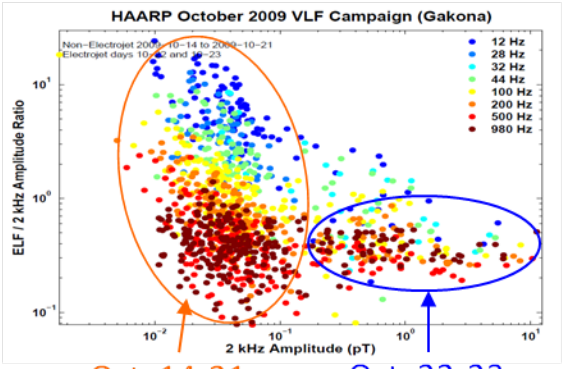




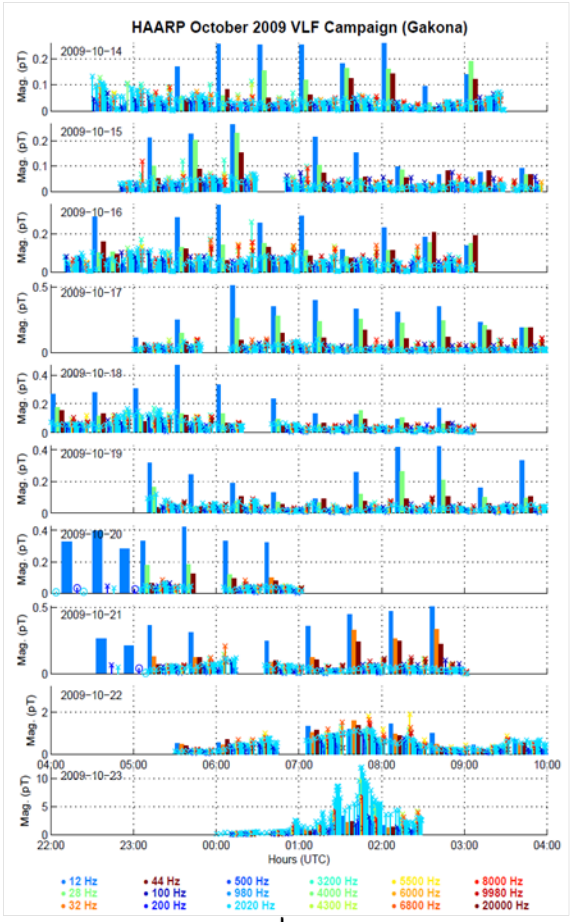
Papadopooulos et al. GRL 2005

ICD PoP





c

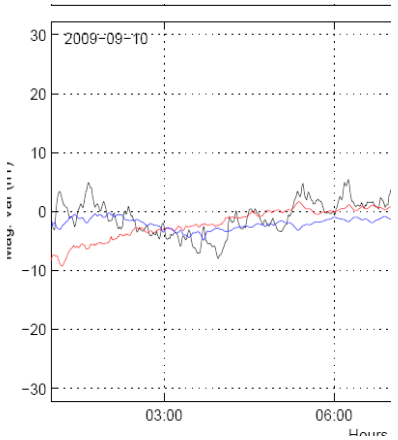


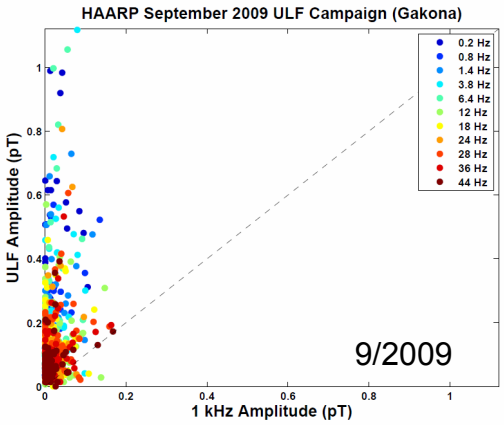
b

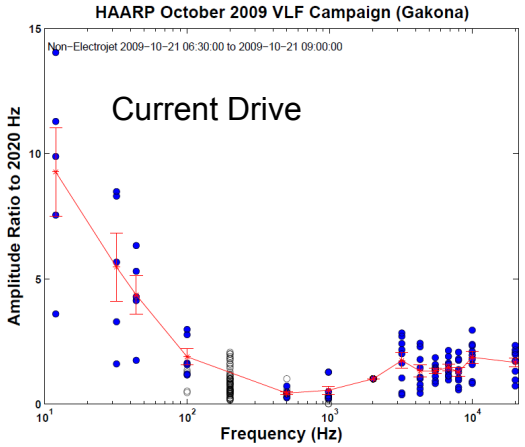
Chang et al GRL submitted

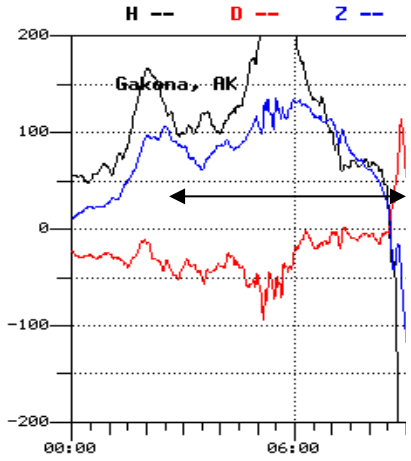
ICD Further PoP Tests

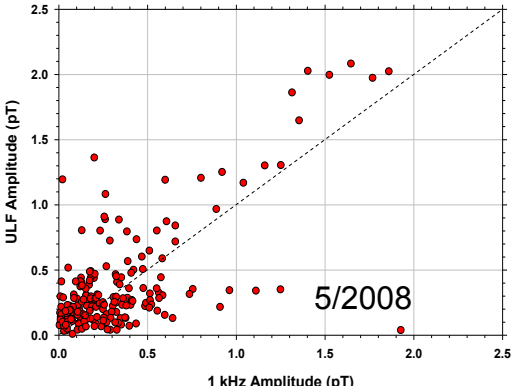
Ejet Current Strength

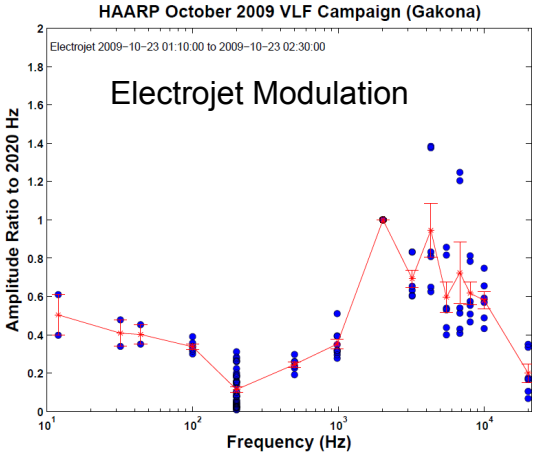








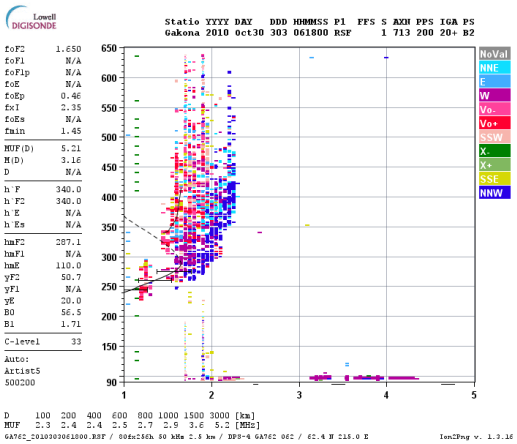


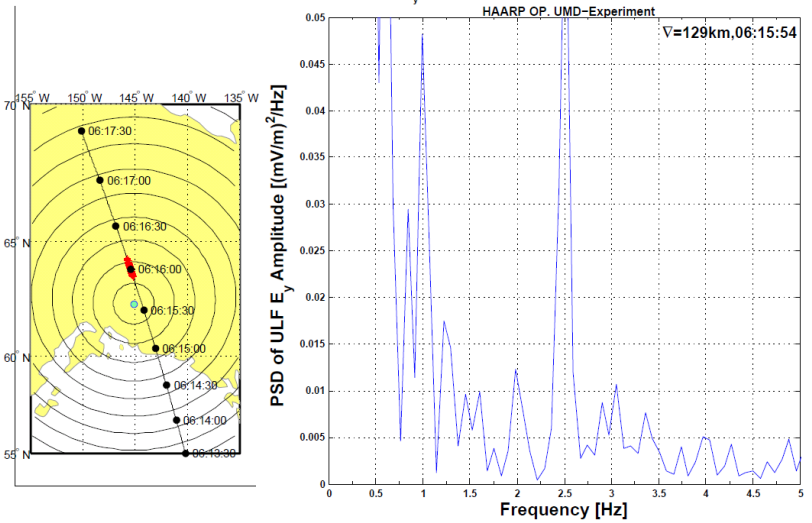


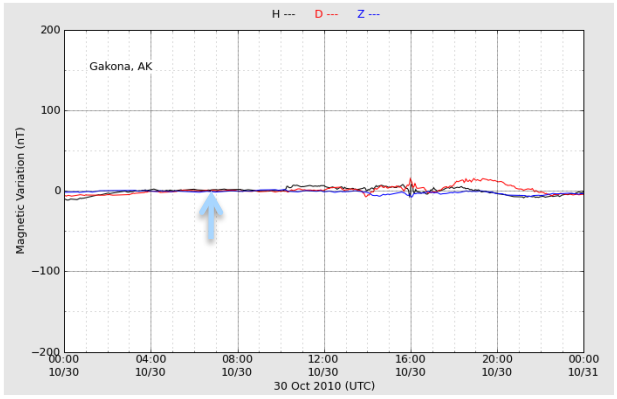
Proof of Concept ICD Experiment – Conducted under DARPA/BRIOCHE

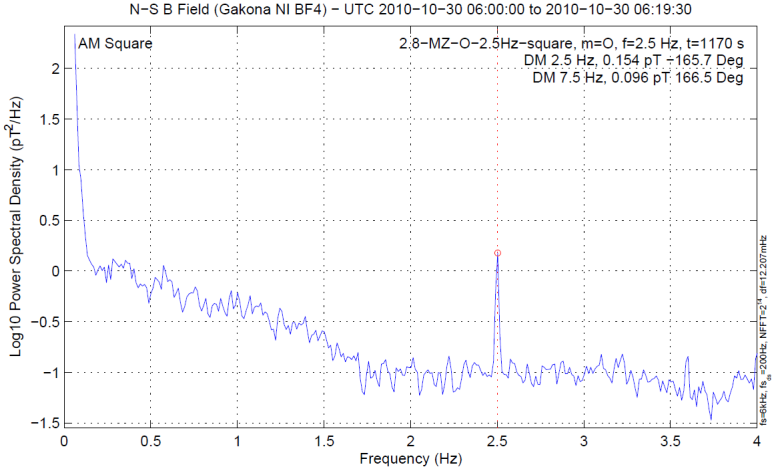
Chang-Lebinsky-Milikh-Papadopoulos

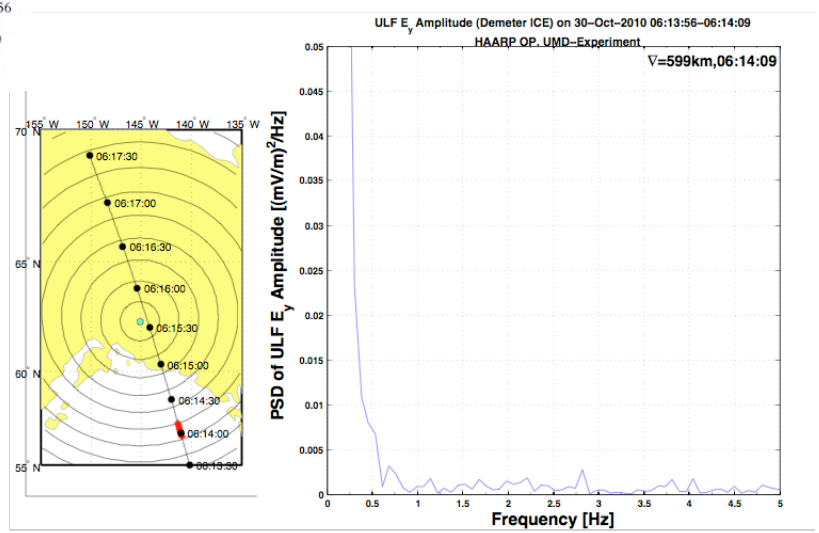
2.8 MHz, O-mode

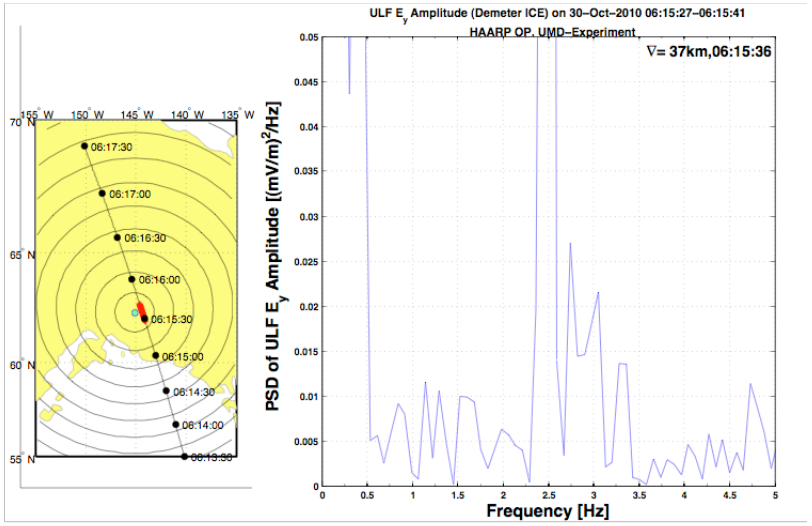


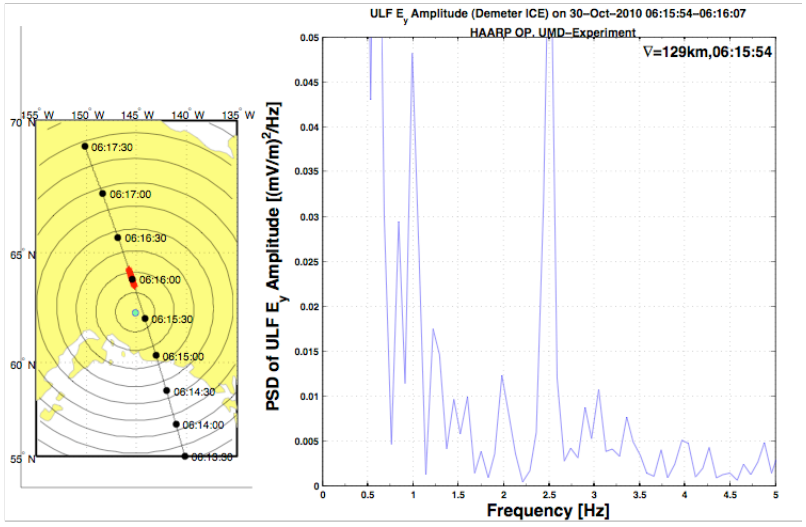


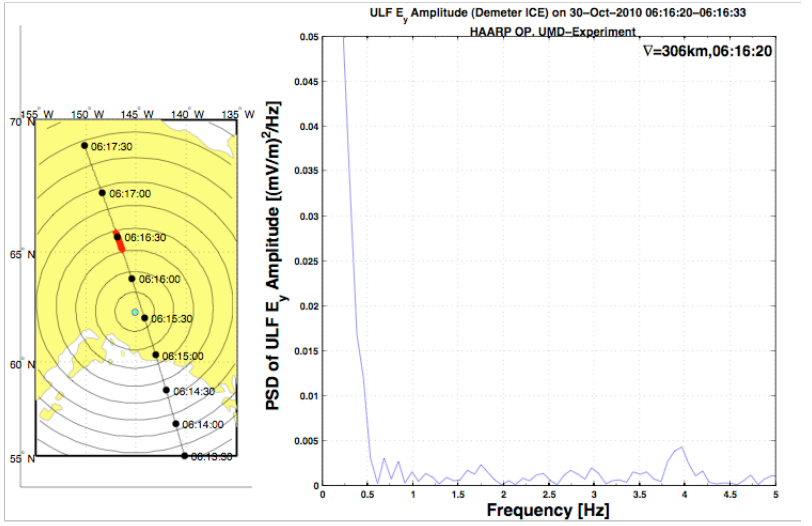





ULF E$_y$ Amplitude (Demeter ICE) on 30–Oct–2010 06:13:56–06:14:09
HAARP OP. UMD–Experiment
∇=599km,06:14:09
PSD of ULF E$_y$ Amplitude [(mV/m)^2/Hz]
Frequency [Hz]

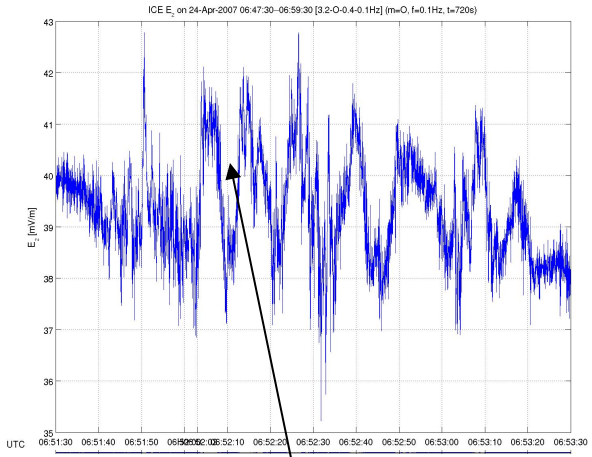

ULF E$_y$ Amplitude (Demeter ICE) on 30–Oct–2010 06:15:27–06:15:41
HAARP OP. UMD–Experiment
∇= 37km,06:15:36
PSD of ULF E$_y$ Amplitude [(mV/m)^2/Hz]
Frequency [Hz]


ULF E$_y$ Amplitude (Demeter ICE) on 30–Oct–2010 06:15:54–06:16:07
HAARP OP. UMD–Experiment
∇=129km,06:15:54
PSD of ULF E$_y$ Amplitude [(mV/m)^2/Hz]
Frequency [Hz]

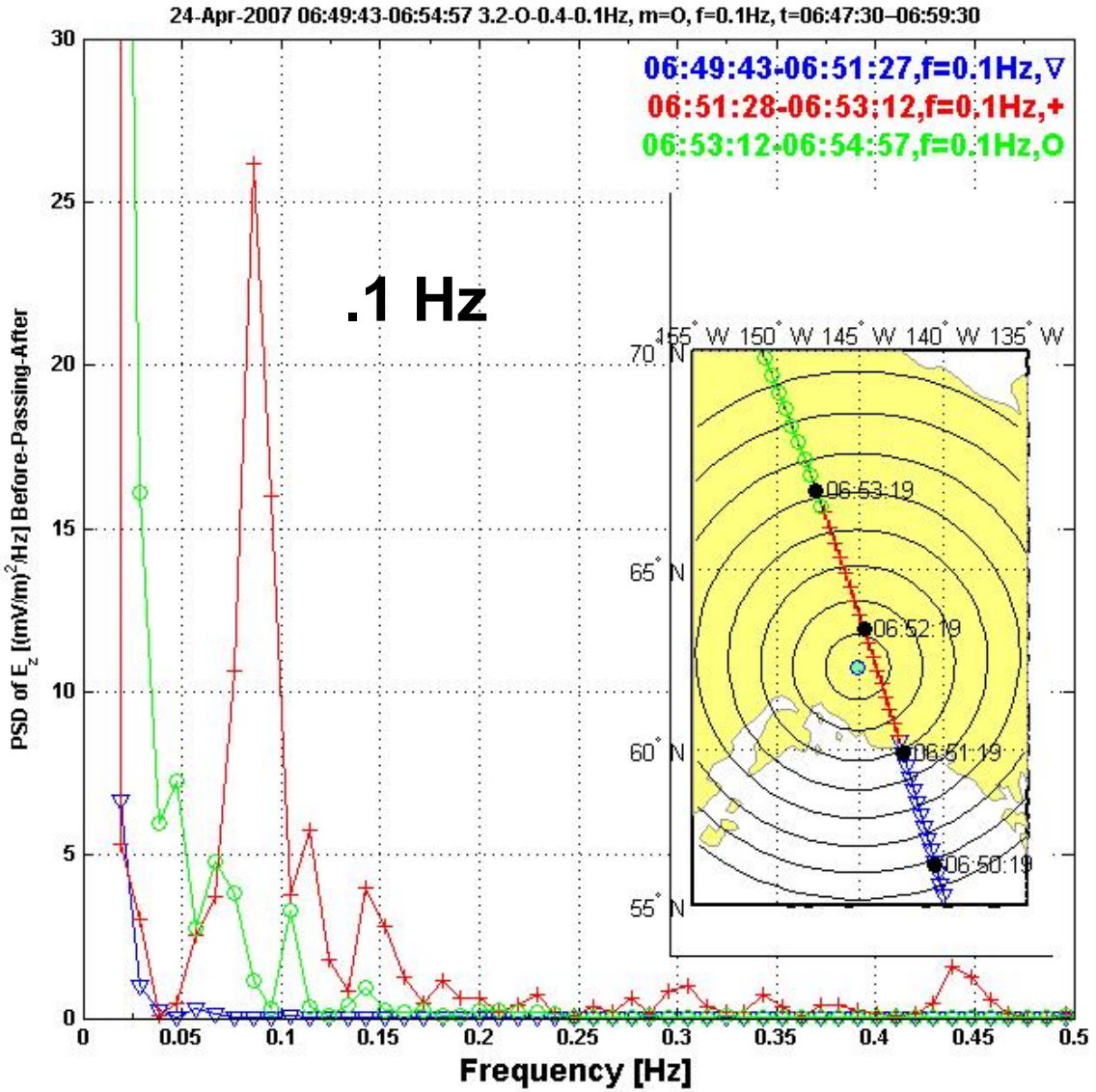

ULF E$_y$ Amplitude (Demeter ICE) on 30–Oct–2010 06:16:20–06:16:33
HAARP OP. UMD–Experiment
∇=306km,06:16:20
PSD of ULF E$_y$ Amplitude [(mV/m)^2/Hz]
Frequency [Hz]

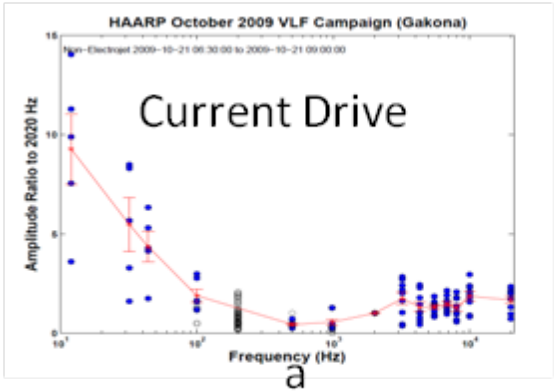
Msonic Wave Injection

DEMETER

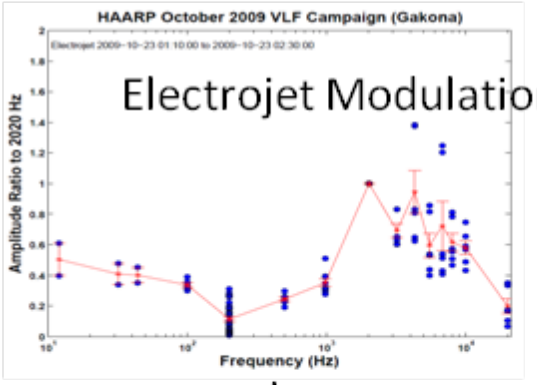


10 sec oscillations

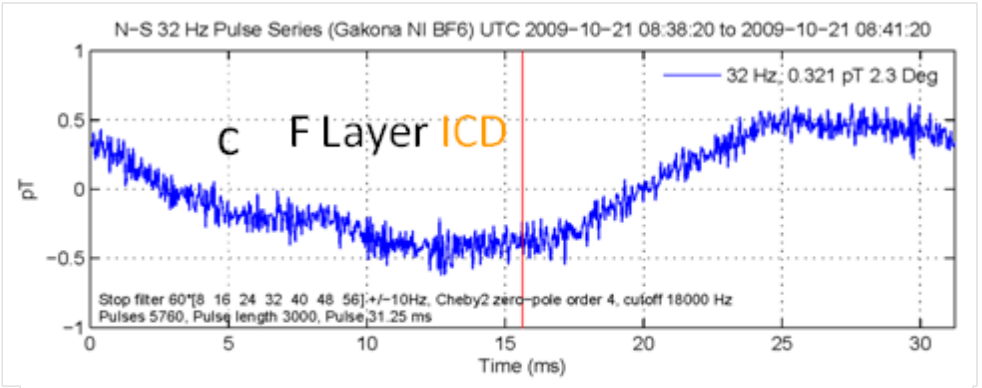




a



b



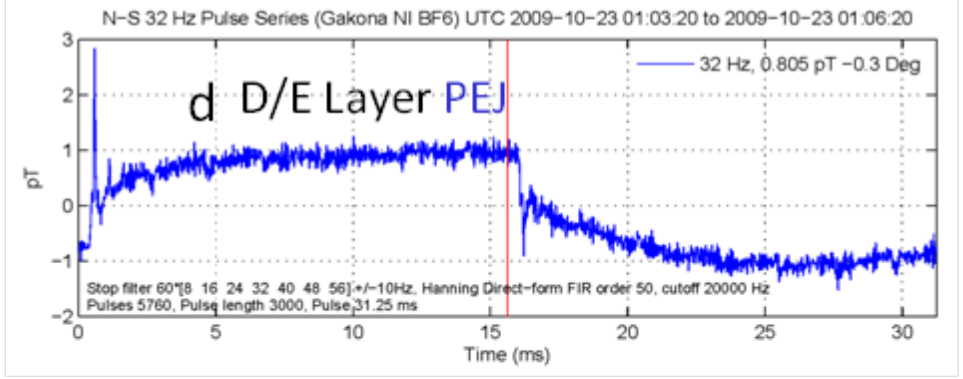
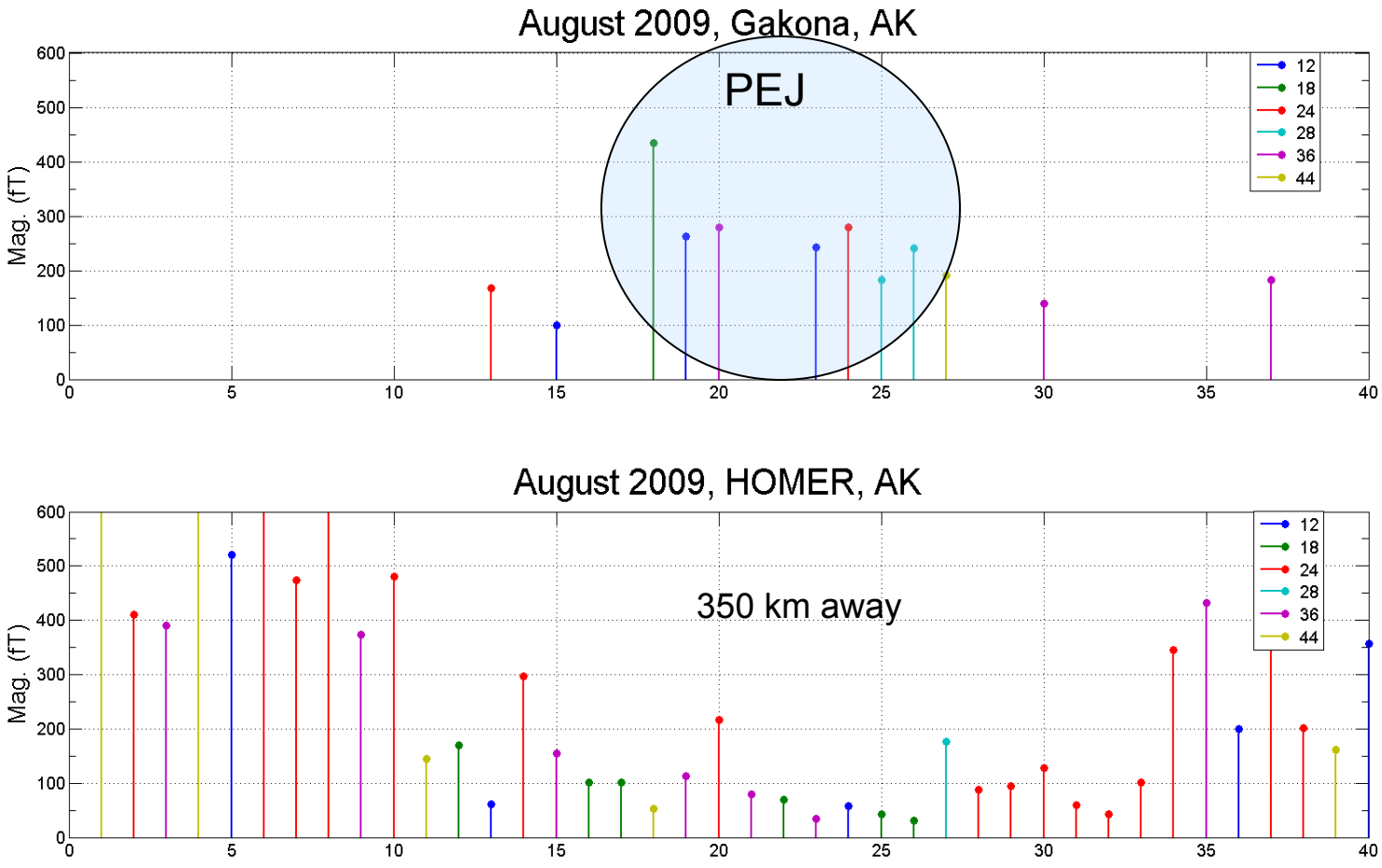


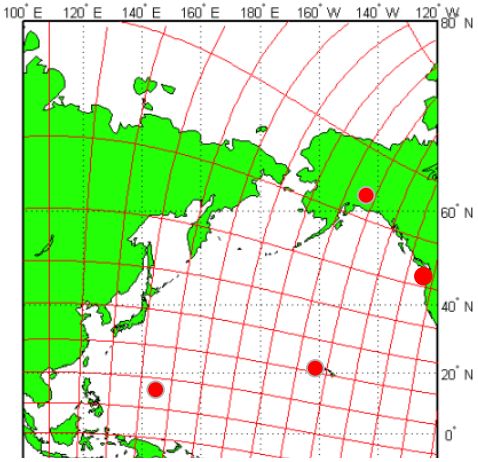
Figure 4: Key differences between ICD and PEJ driven waves. Amplitude-Frequency scaling for (a) ICD, (b) PEJ. Waveform at 30 Hz for (c) ICD, (d) PEJ

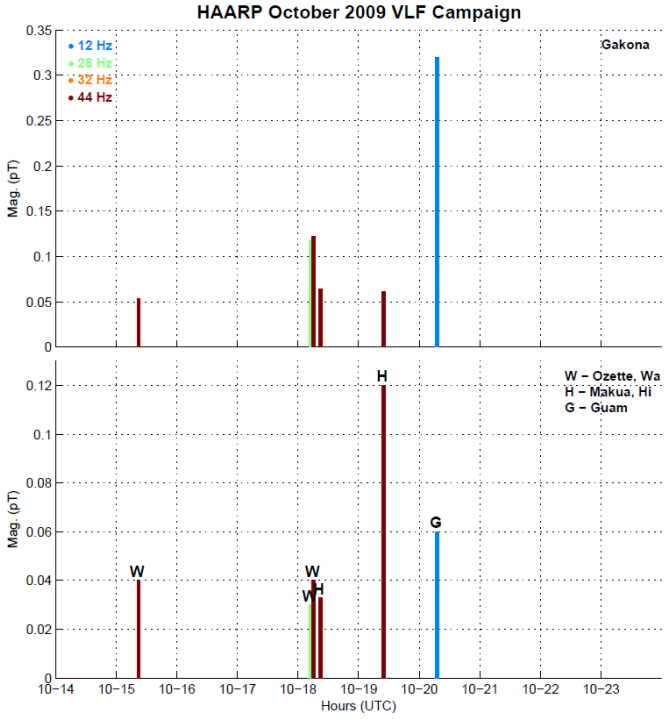
Two site measurements - ICD vs. PEJ



ELF detection at Distant Sites

- Distance to 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



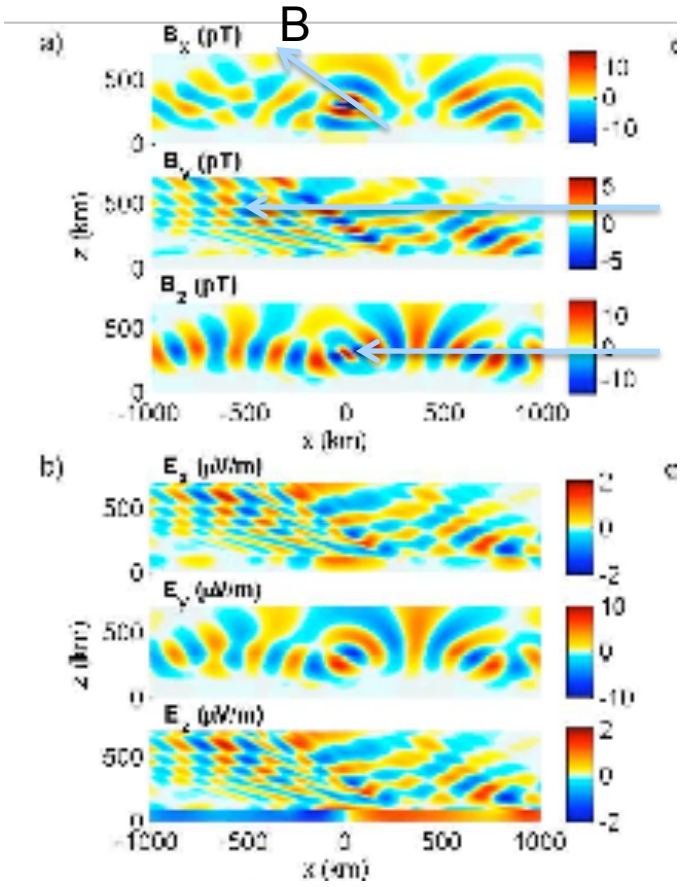


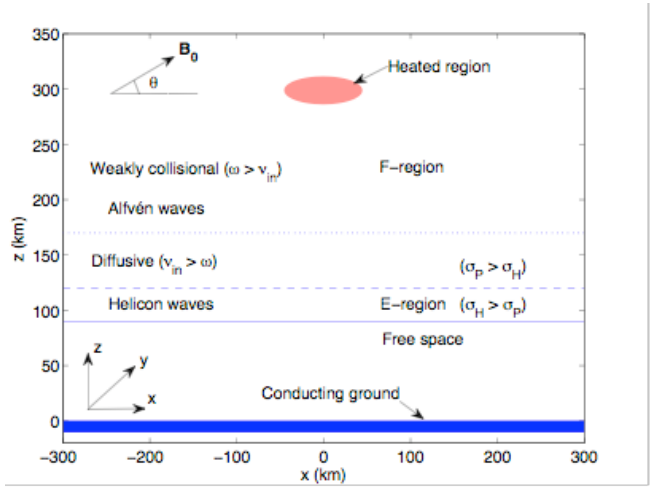
Implications of ICD to RB and RBR – Potential Arecibo Tests

Eliasson-Papadopoulos: Oblique model includes spontaneous B field generation

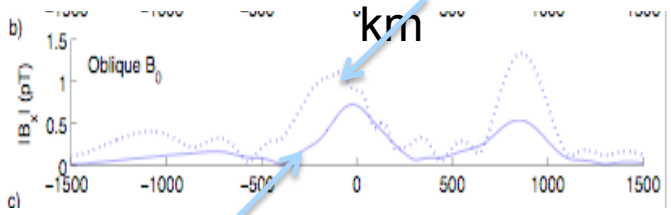
$$\partial B / \partial t = (c/ne)\nabla n \times \nabla T$$

Papadopoulos and Chang GRL, 1985





B field at 90 km



Ground B field

ICD provides explanation for puzzling Arecibo experiment

Ganguly-Gordon-Papadopoulos PRL 1985

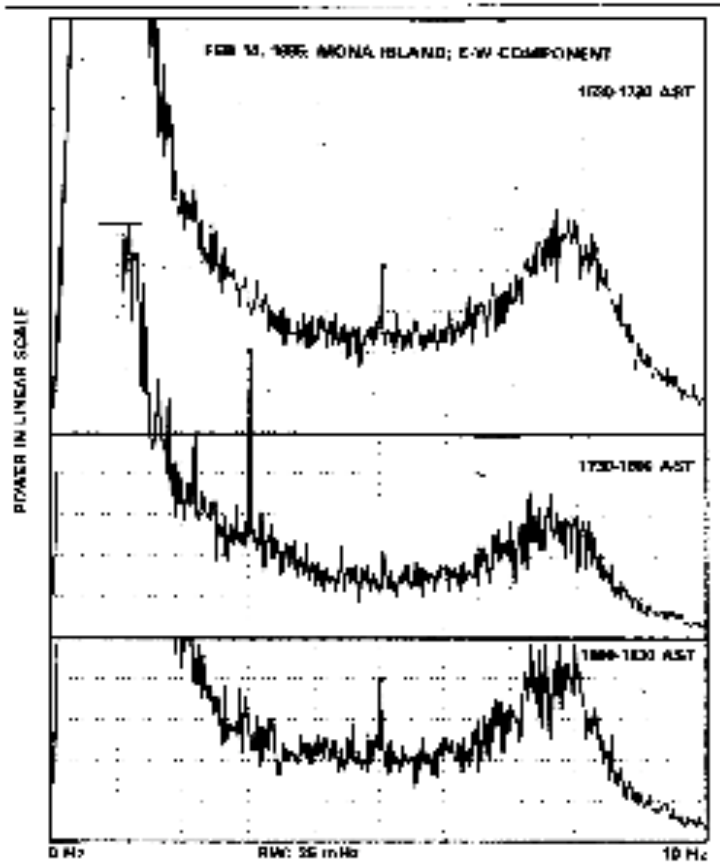


FIG. 1. Spectra of the received signal in the 0–10-Hz band (14 February 1985). Receiver was located at Monn Island. Data cover the period 16:30–18:30 AST. The HF transmitters were operated at 5.1 MHz and with a difference frequency Δf of 5 Hz during 16:30–17:30 AST, which was changed to 3 Hz during 17:30–18:00 AST and changed back to 5.0 Hz during 18:00–18:30 AST. The magnitude of the 5.0-Hz signal is about 160 $\mu\gamma$ Hz$^{-1/2}$ and that of the 3.0-Hz signal is about 340 $\mu\gamma$ Hz$^{-1/2}$.

Summary

- **HAARP experiments have helped transition of of cartoon HF low frequency current drive in the ionospheric plasma to reality.**

- **The physics understanding of ICD provided by HAARP allows for active probing of the physics controlling the inner radiation belt and could lead to techniques that can actively reduce the flux of trapped proton and electrons.**