# Ionospheric Modifications Using Mobile, High Power HF Transmitters Based on HPM Technology


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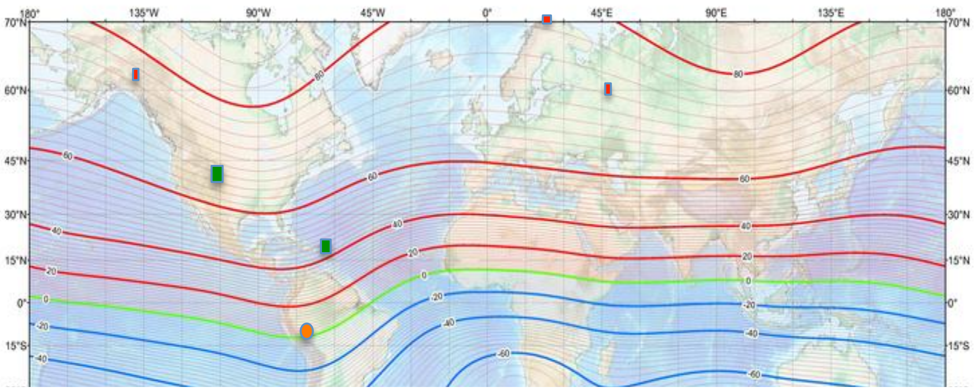
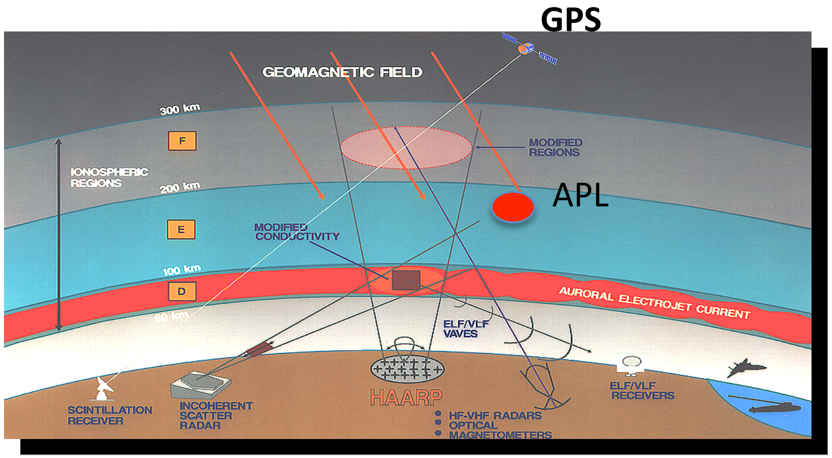
# Ionospheric Modifications Using HF Heaters

## Space as an open plasma laboratory

**Measure in "cause & effect" mode the effects on the ionosphere & magnetosphere plasma due to controlled and targeted HF heating. Triggered response spans from cm to Mm**






| Heater | θ | L | f MHz | $P_R$ MW | Gain dB |
|---|---|---|---|---|---|
| HAARP | 14.5 | 4.9 | 2.7-10. | 3.6 | 30 |
| EISCAT | 12 | 6.1 | 3.9-8.0 | 1.2 | 30 |
| SURA | 19 | 2.6 | 4.5-9.0 | .75 | 26 |
| PLAT | 22 | 2.3 | 2.7-10. | 1.4 | 19 |

**Tests conducted using large, fixed facilities e.g. HAARP (3.6 MW, 95 dBW ERP); physics and apps depend on geomagnetic latitude**

- **Virtual Antennae at ELF/VLF**
- **Artificial Plasma Layers (APL)**
- **Artificial Ionosph. Turbulence (AIT)**
- **Bi-static links at UHF and L-band**
- **Plasma outflows & ducts**

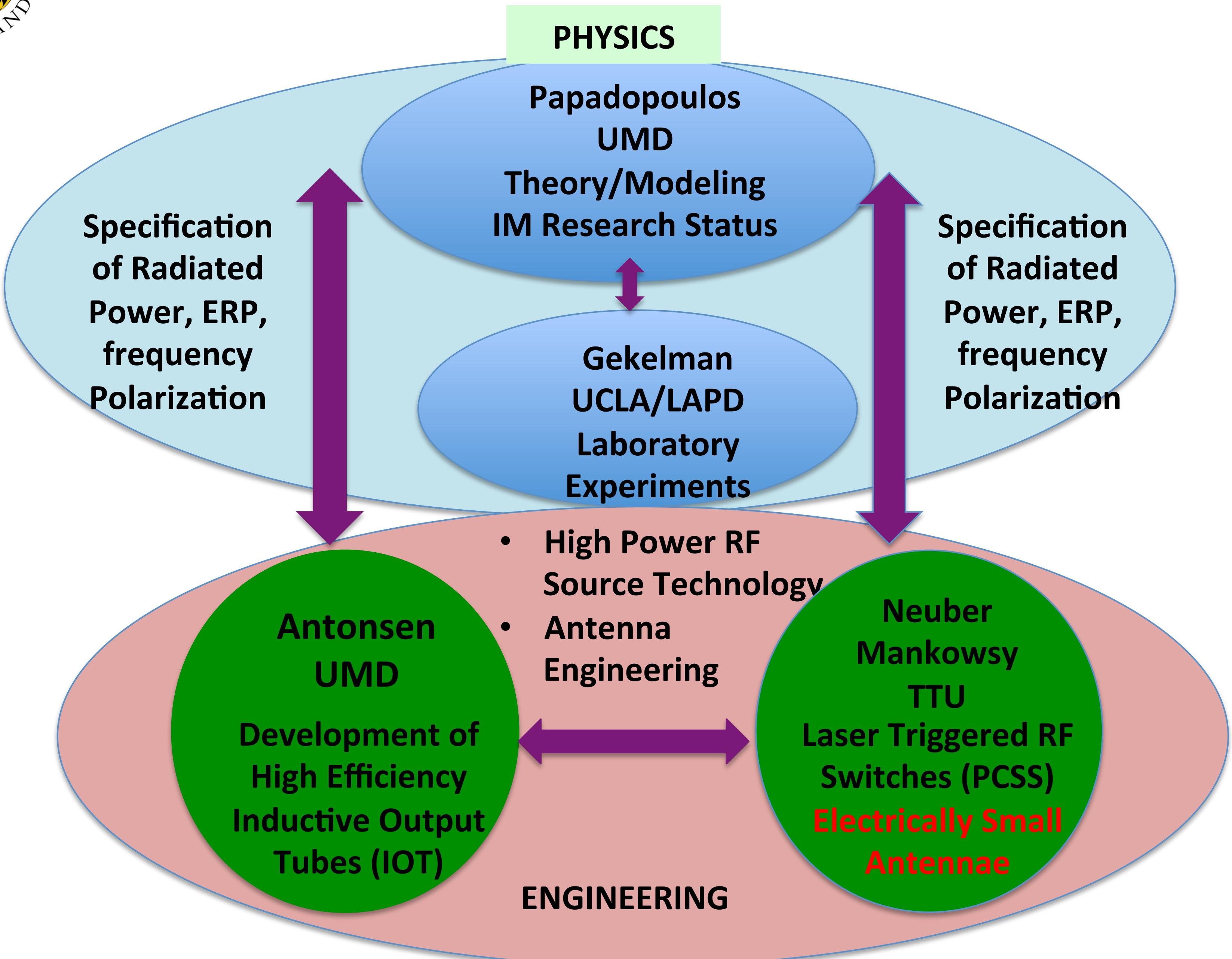
## The AFOSR MURI Challenge

- 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 to design feasibility lab experiments and use to demonstrate and test the results of the IM research.

# Consortium Structure

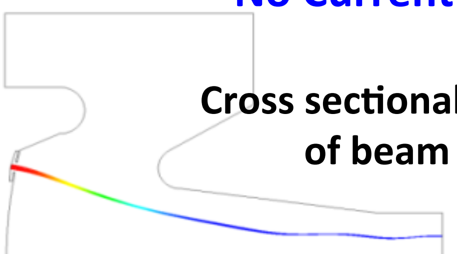


# Technology Drivers - IOT

- Small footprint places premium on power, thereby to high efficiency
  - Operate IOT in class D with modulated e-beam on at full current for ¼ of cycle
    - Develop pulse modulator with short rise time
    - e-gun modulation by varying potential on control anode not intercepting beam current to avoid heating load –Tests with gridded Gun
  - Low loss tunable resonant cavity providing constant impedance over frequency

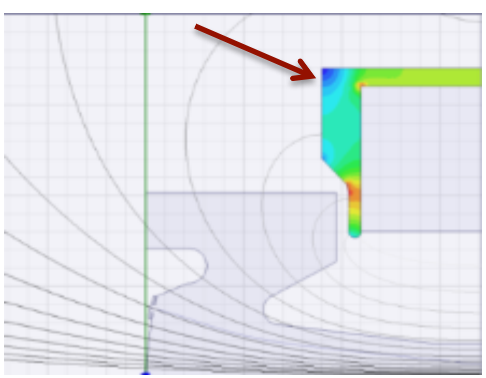
**MICHELLE Code Simulations**

**Annular Beam Cathode – Non-gridded Gun**
**No Current Intercept**

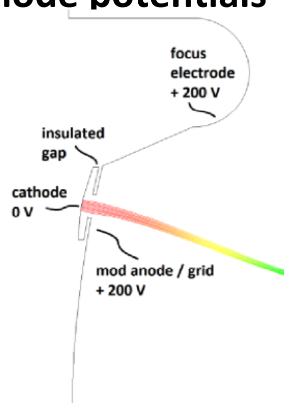


Cross sectional view of beam

Solenoid Field

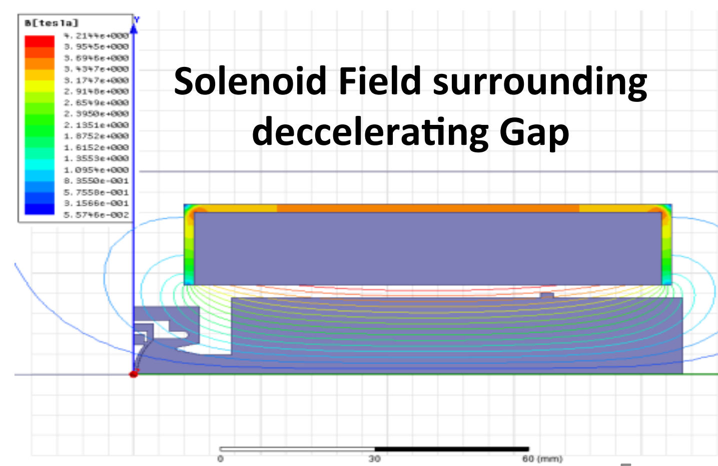


Cathode and mod-anode potentials




**Gridded Gun - Current Intercept**

Decelerating Gap

Solenoid Field surrounding decclerating Gap

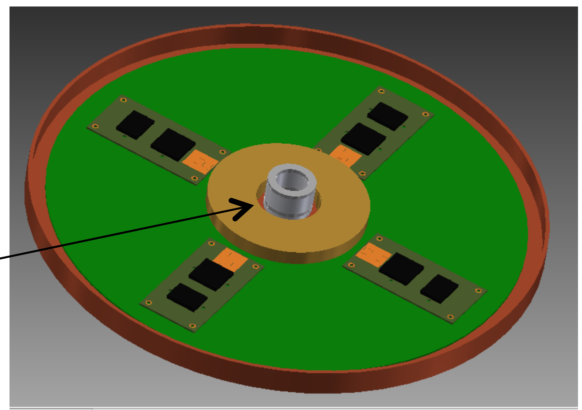
Beaudoin et al. ,Proc. IPAC 2015

# Technology Drivers

## Experimental Test Stand

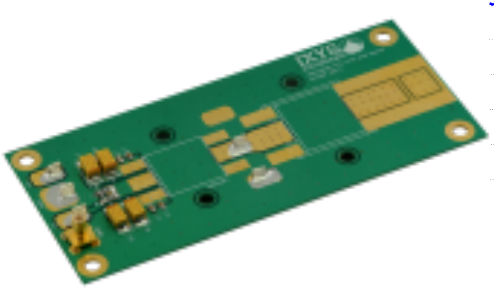
### Prototyping Gridded Gun & Modulator

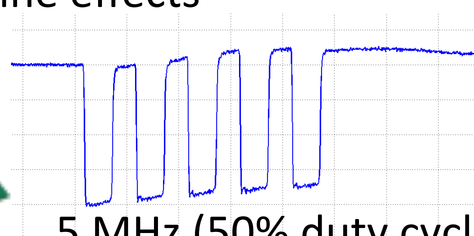
HWEG-128



Beam Parameters
20kV 5.7A

Grid modulator coaxially mounted around gun to eliminate transmission line effects



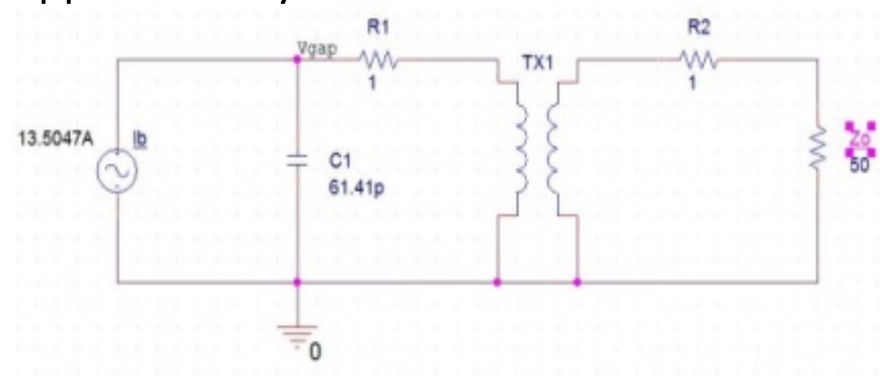


5 MHz (50% duty cycle) output into 50Ω

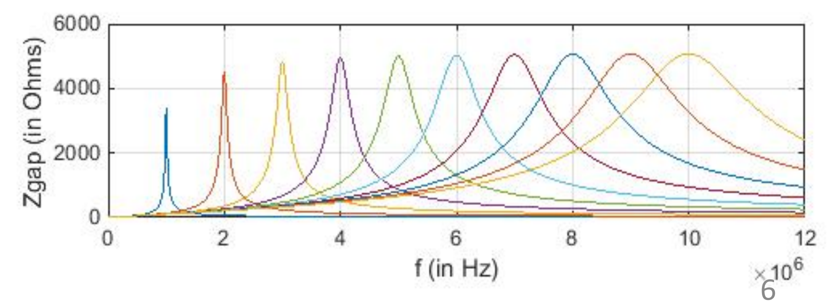
IXYS Boards with FETs capable of 1 kV at 20 A within 5 ns.

### Constant Impedance Cavity

Lumped Parallel LC Circuit operating at approximately 1-2 MW at 1-10MHz.

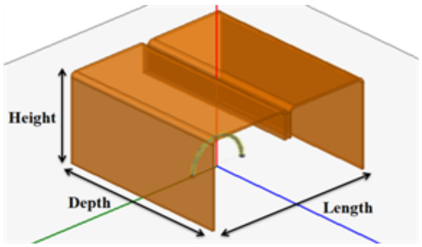



Maintaining a constant gap impedance across the frequency range of interest with a fixed turns ratio, will require that the quality factor vary over that range.




- B.L. Beaudoin, T. M. Antonsen Jr., G. Nusinovich, *et. Al.*, Proceedings of IPAC2015.

# Source and Antenna Development




*4 to 10 MHz antenna*

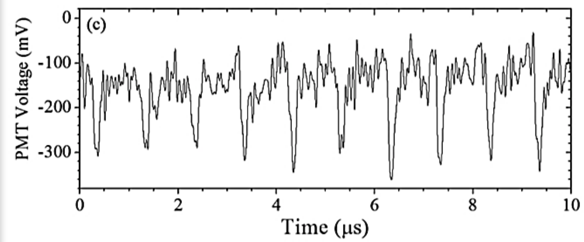
**ESA** – Electrically Small Antenna to interface with UMD 50 Ohm impedance rf source.

- Factor of several smaller than dipole
- Frequency tunability demonstrated

**Highly repetitive light sources**

• Driver for PCSS

• Modulated UV narrowband light source with high power (~ 100 W) at rf frequencies



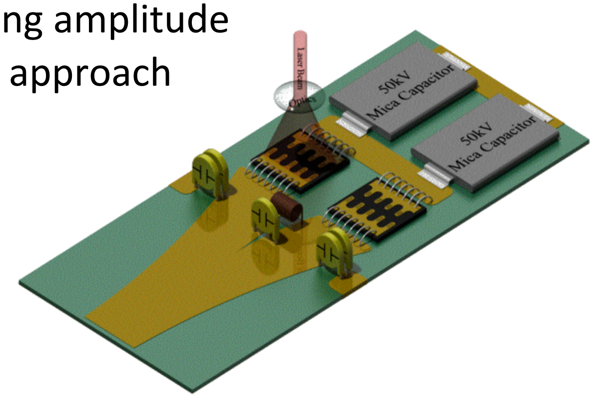

*1 MHz light pulse train*

**PCSS –** Photoconductive Semiconductor Switching

• Achieved 700 kV/cm switching field

• Demonstrated repetition rates of up to 65 MHz at 20 kV switching amplitude

• Direct rf drive approach




*Direct Drive Concept*

**Challenges**

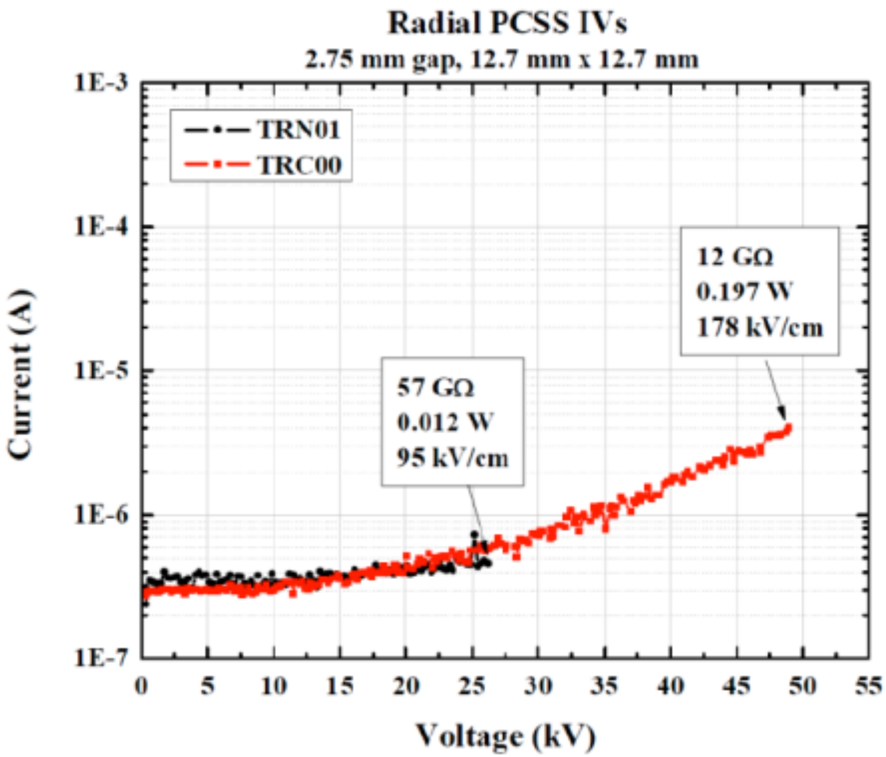
• Optimize tradeoff between antenna efficiency/size/tunablity

• Improve PCSS photonic efficiency

• Increase output power of light source

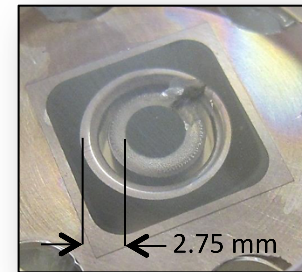

*PCSS die for size comparison*

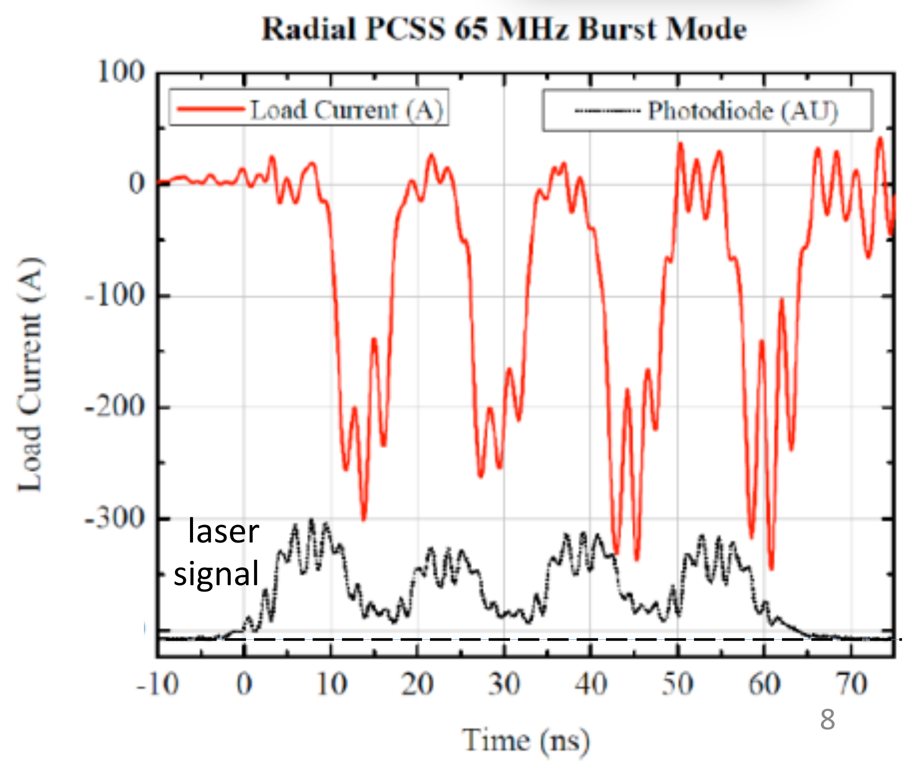
# Photoconductive Solid State Switches




***Radial PCSS***

***Photoconductive Solid State Switch***




20 kV 65 MHz burst mode switching into a 52 Ω load (6 MW peak electrical power)

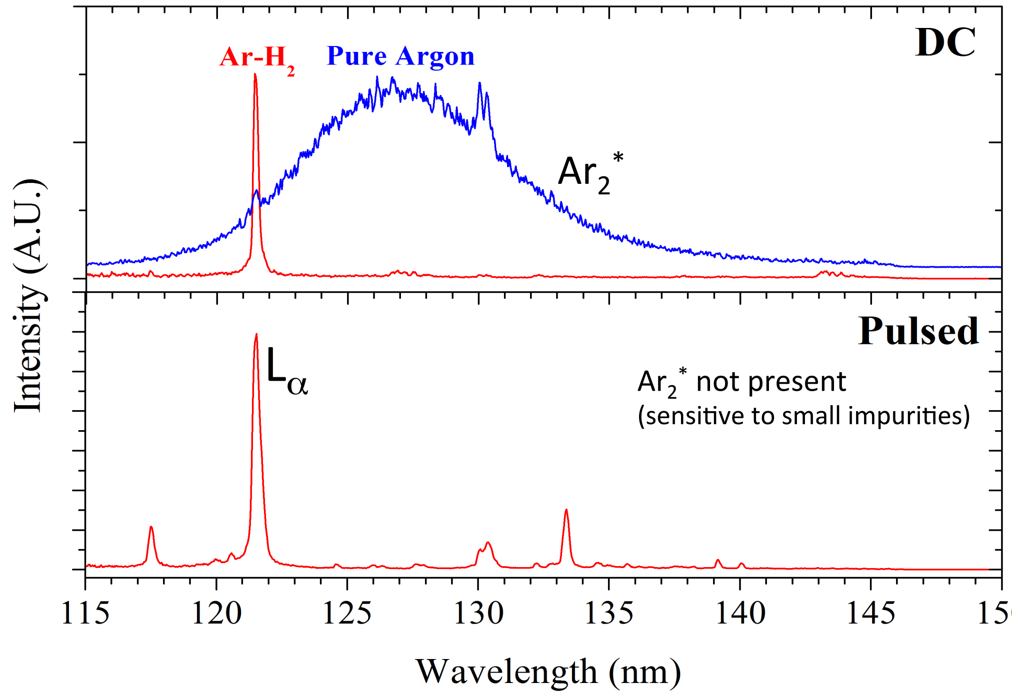
# MHz Repetitive UV/VUV Light Source

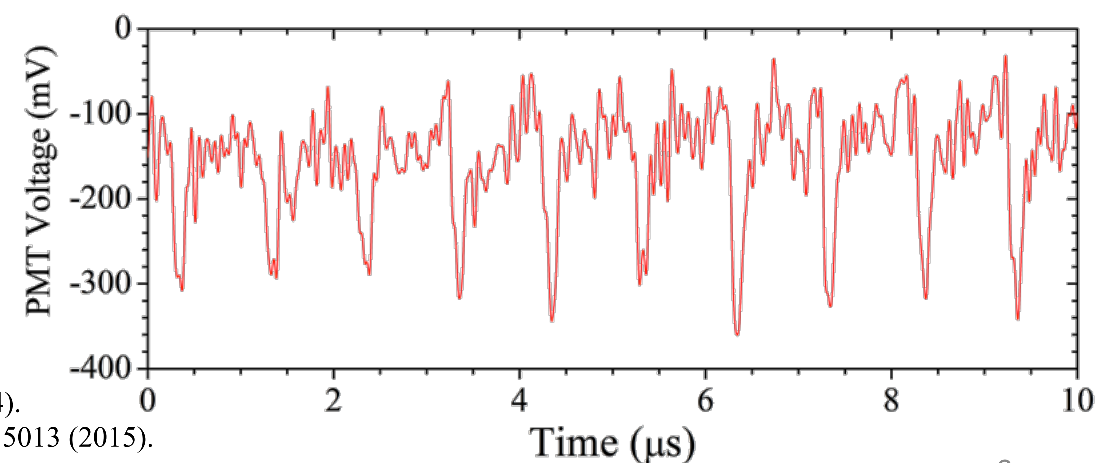
## Experimental Conditions

- $Ar:H_2$ (99.7:0.3%), 50 Torr
- Microhollow cathode discharge (MHCD)

## Results

- $Ar:H_2$ Lyman-α can be achieved under very high input power
- High VUV power and efficiency
  - For 80 ns, pulses at 1 MHz
    - 3.4 W/42.8 W (avg/peak) VUV power
    - 0.63 % efficiency
  - For 50 ns pulses at 100 kHz
    - 310 mW/62 W (avg/peak) VUV power
    - 1.1% efficiency
- Overall 2 to 3 orders of magnitude higher instantaneous power over DC case.
- About 30 x increased efficiency

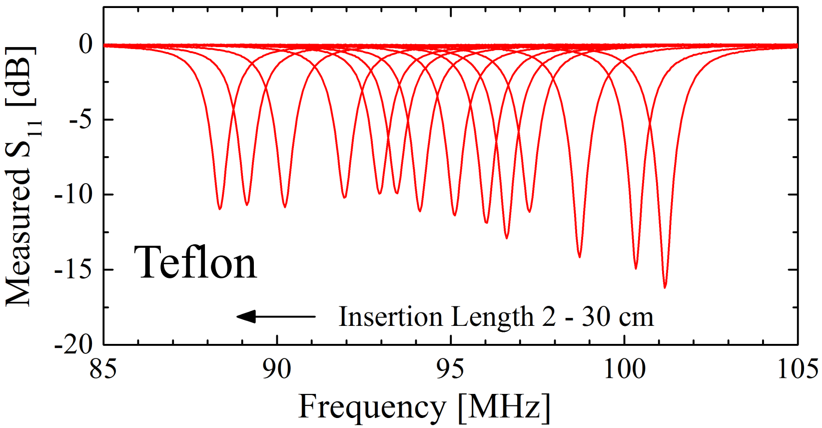


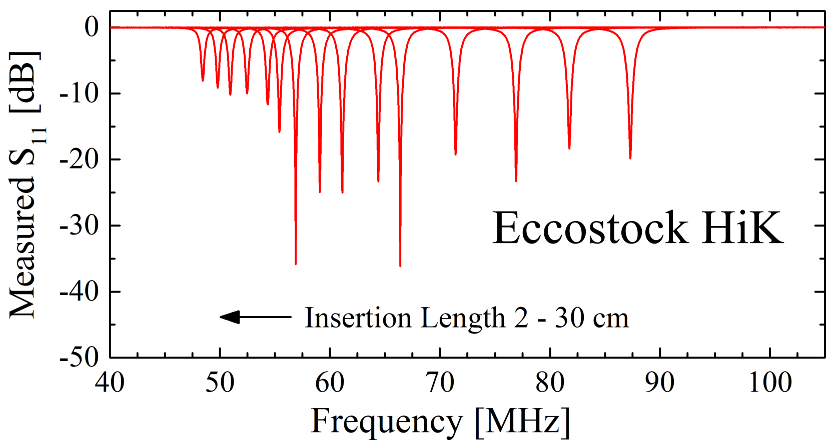





J. Stephens, A. Neuber, *et al*. Appl. Phys. Lett. **104**, 074105 (2014).
J. Stephens, A. Neuber, *et al*. Plasma Sources Sci. Technol. **24**, 015013 (2015).

# Tunable Electrically Small Antenna



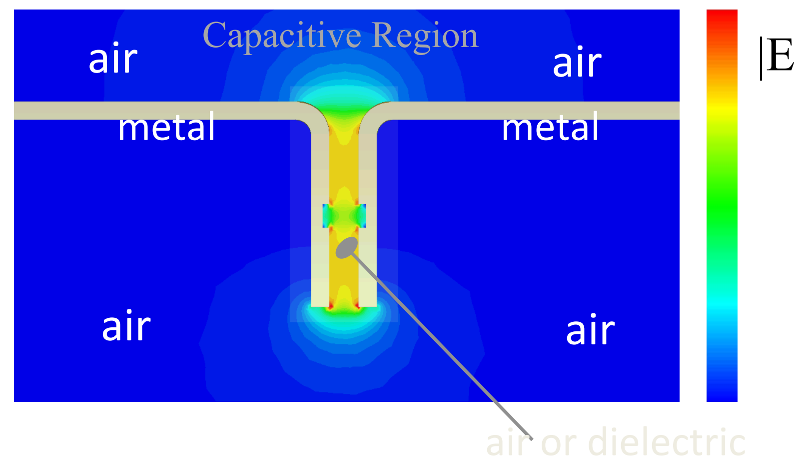

Experimentally demonstrated tunability via progressive insertion of dielectric slab.

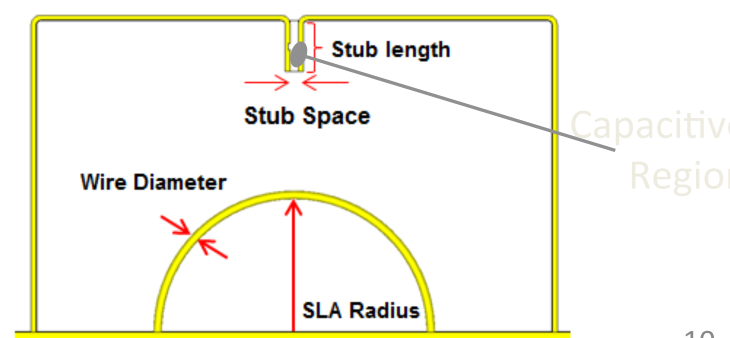
(ESA antenna size: ~ 1/5th in size compared to dipole)

**Scaled to 10 MHz:**

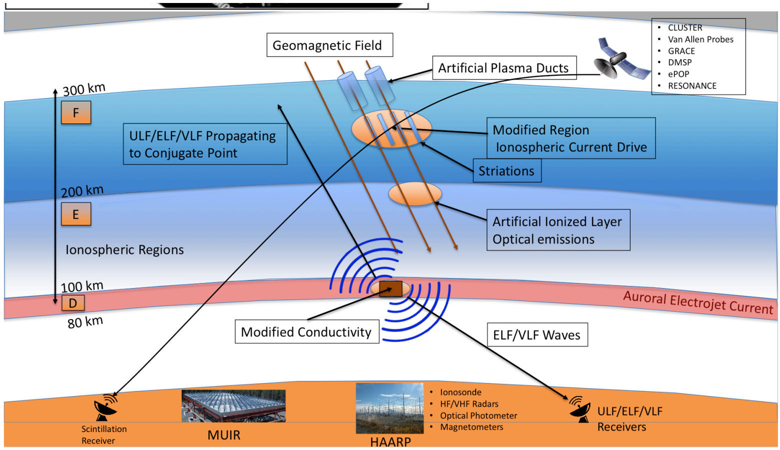
CST simulated peak power capabilities:

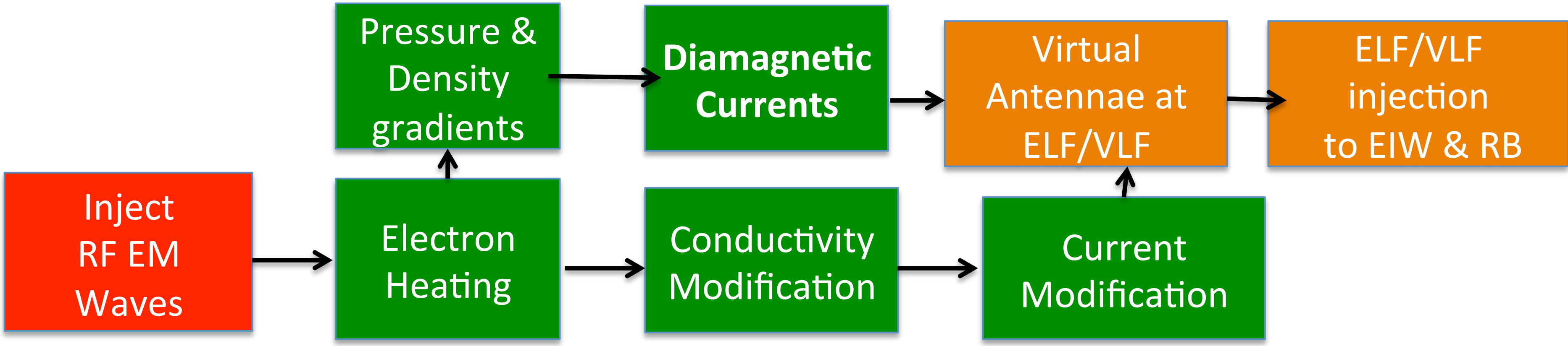
- 20 to 30 kV/cm limit
  (assumed dielectric strength of air)
  - ~ 2.5 MW max power limited by field in capacitive region
  - Power limit extends with use of dielectric



# Ionospheric Modifications
# Virtual Antennae



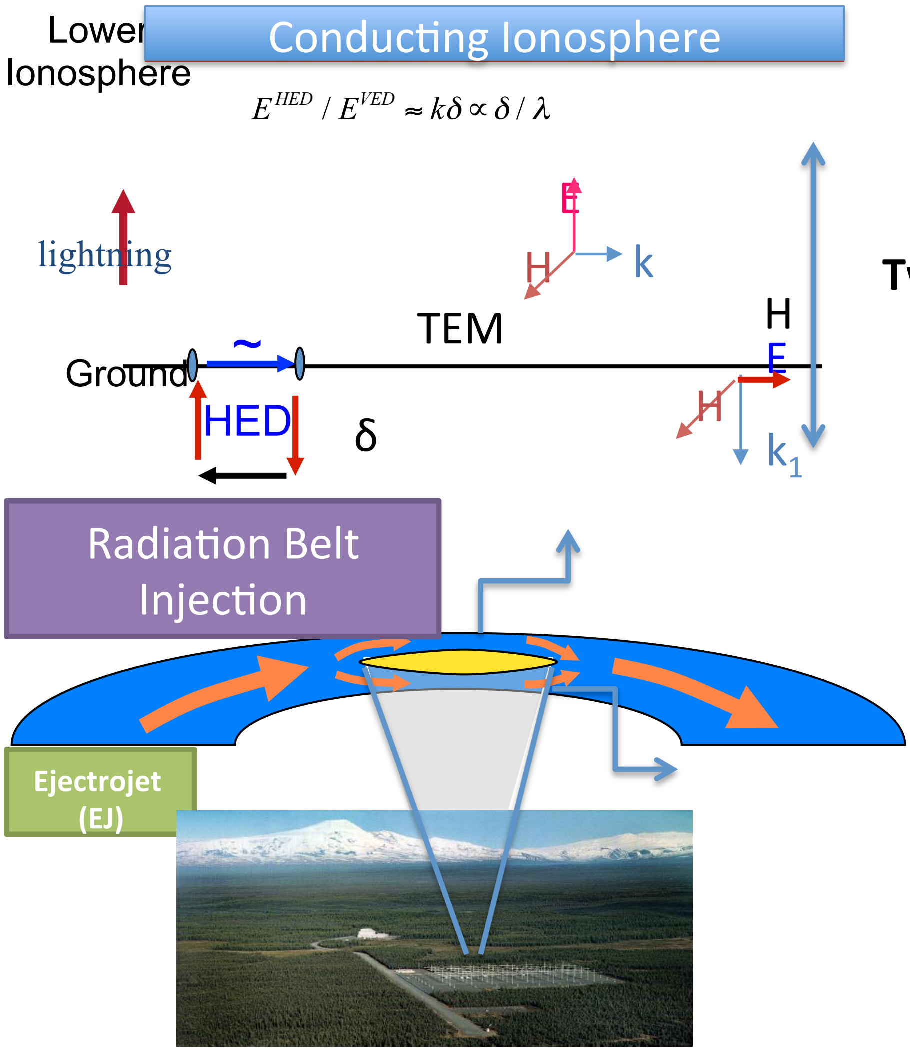



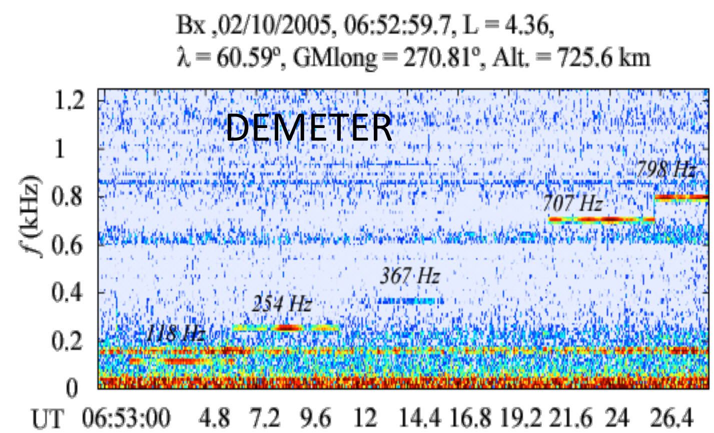
# Virtual Antenna @ ELF/VLF

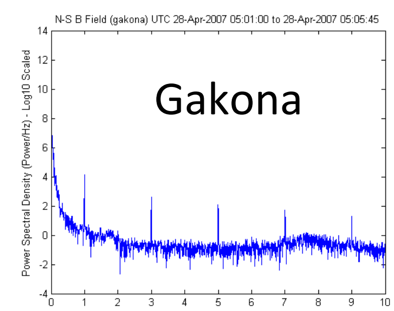
**ELF/VLF applications: Underwater Comm, Underground Imaging, Radiation Belts (w-p interactions, Remediation, Alfven Maser, Micropulsations, hiss, EMIC & chorus emissions,..)**

**Low efficiency of HED due to return current M=ILδ. Lifting antenna to height h reduces cancellation resulting in M=ILh (h>>δ). If we drive an ac current in the ionosphere M=ILH**

**Two concepts: 1. Electrojet current modulation**



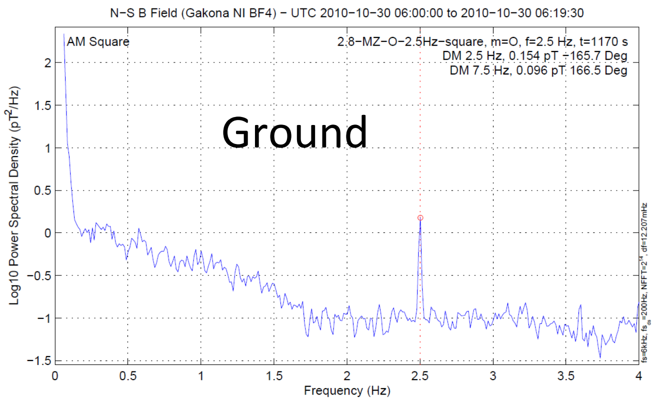



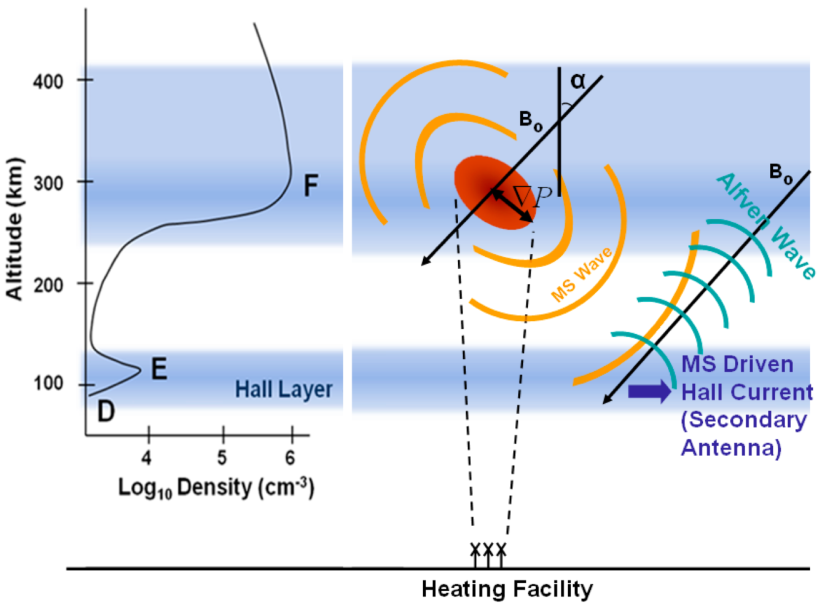
# Virtual Antenna @ ELF/VLF (cont.)

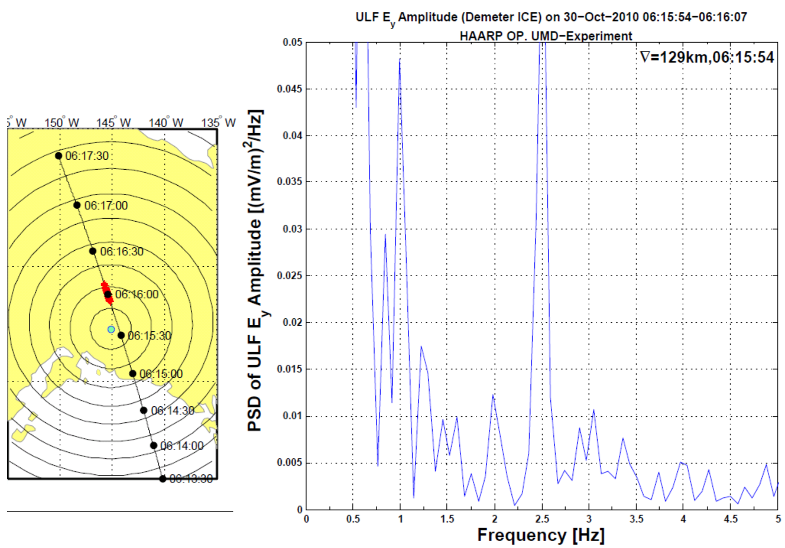
## 2. Ionospheric Current Drive (ICD) Concept

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

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

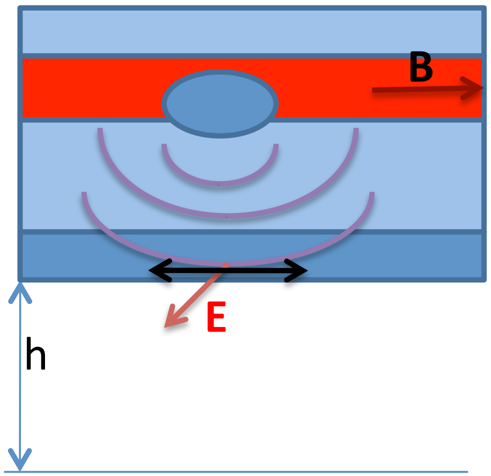


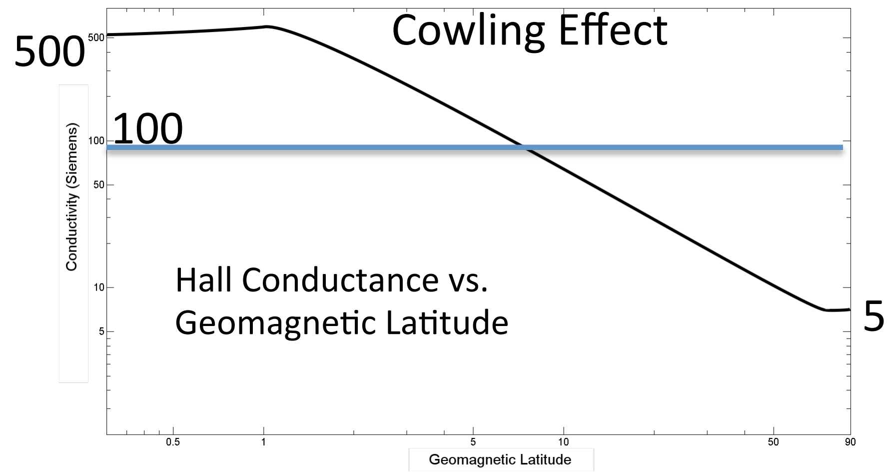



# Mobile Heater Requirements for Virtual Antenna

**Whether ICD or Electrojet the moment of the virtual antenna scales linearly with the conductance Σ of the D/E region, i.e.** $M_{eff} \approx ILh,\ \ I \approx \Sigma EL,\ M_{eff} \propto \Sigma$

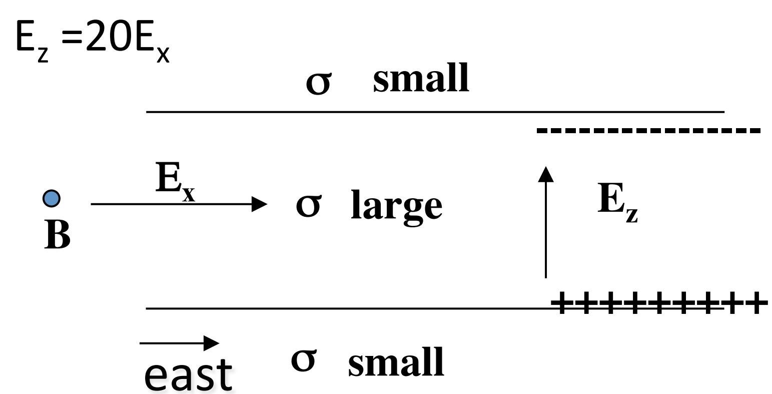



$$M_{eff} \approx ILh \approx (\Sigma EL)Lh$$

$$M_{eff}(\lambda) \approx (5\times 10^9)[\frac{\Sigma(\lambda)}{5S}](\frac{P_{HF}}{3.6MW})A-m^2 \approx$$

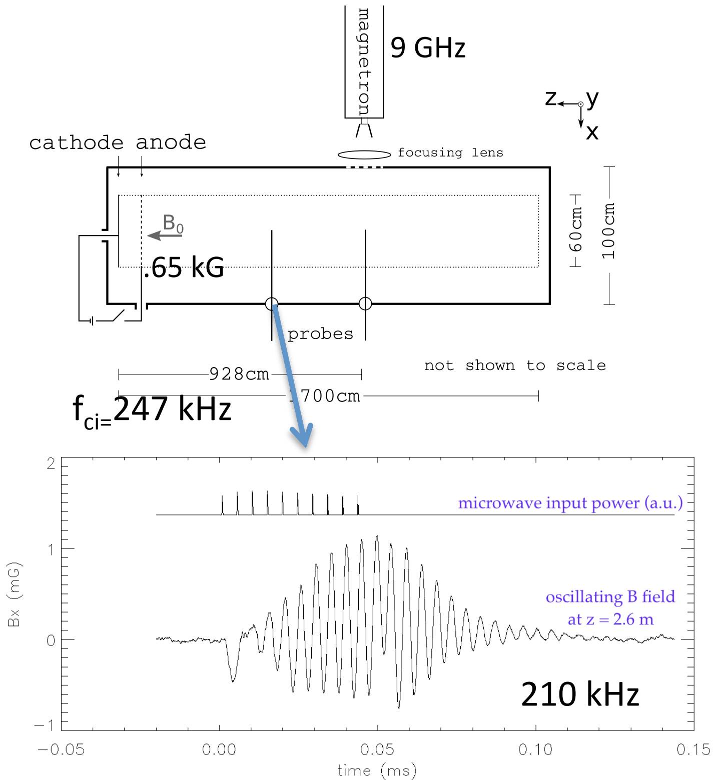
$$\approx (2.7\times 10^8)\Sigma(\lambda)(P_{HF}/MW)A-m^2$$

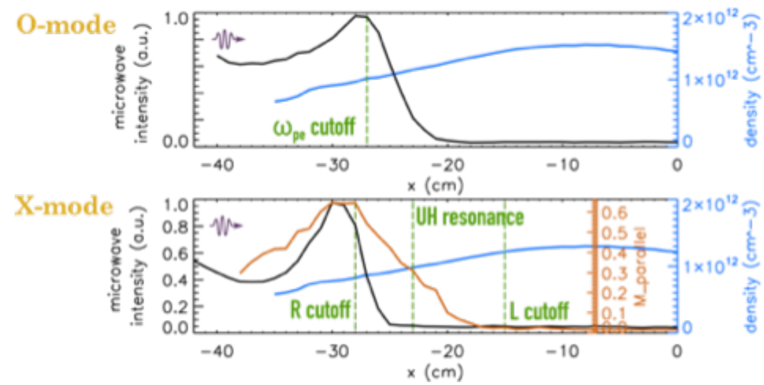


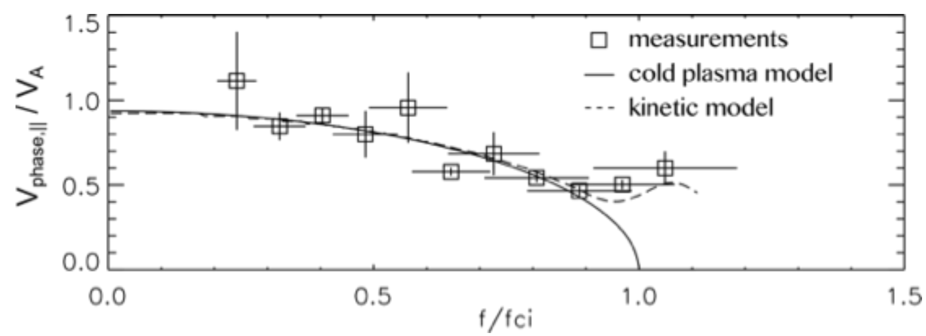

**Mobile heater:**

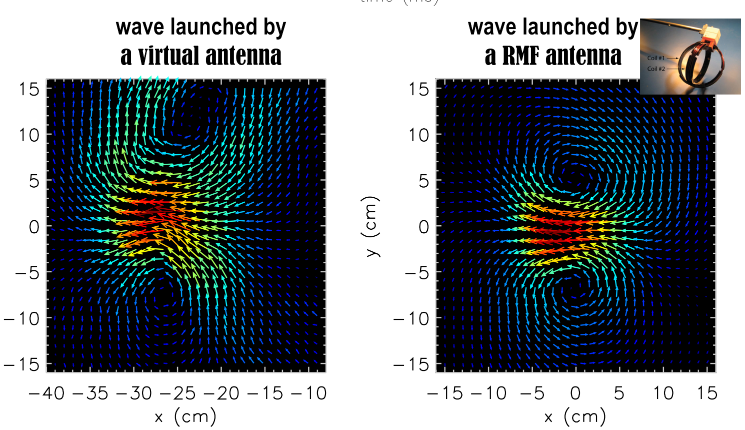
- **Half dipole with reflector (5dBi)**
- **P=1 MW; Total 65 dB**
- **$M_{eff}$ ≈$10^{11}$A-m$^2$ (λ=0), 2x$10^{10}$A-m$^2$(λ=6°)**

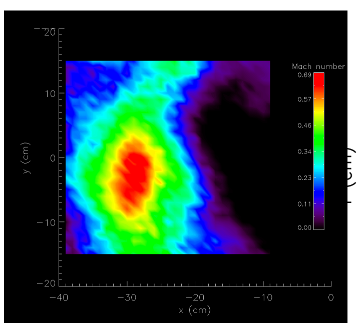
# Need for Lab Exps
# An Unexpected Virtual Antenna

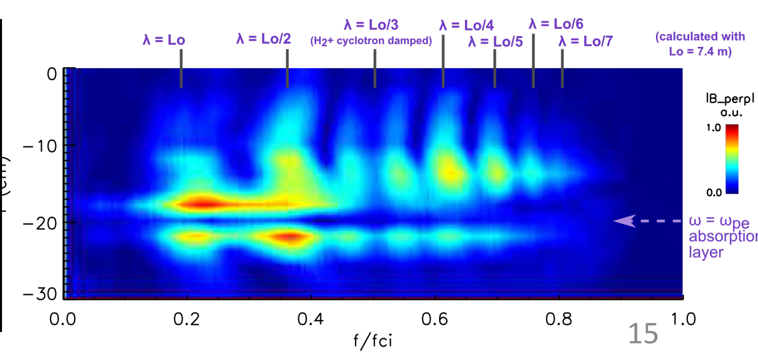


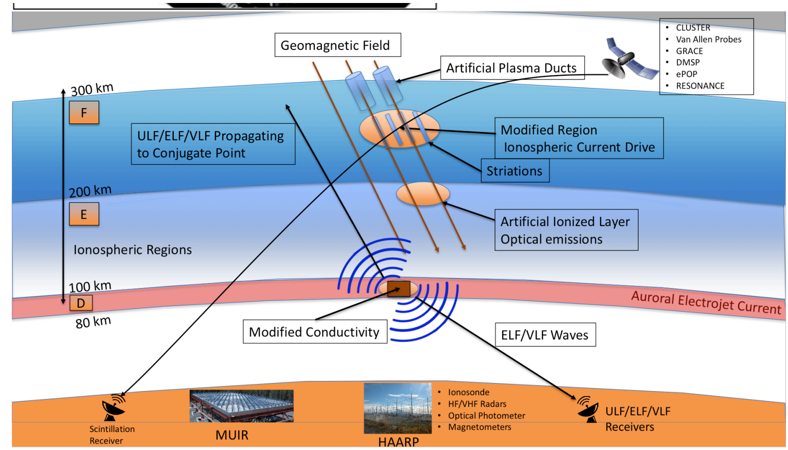



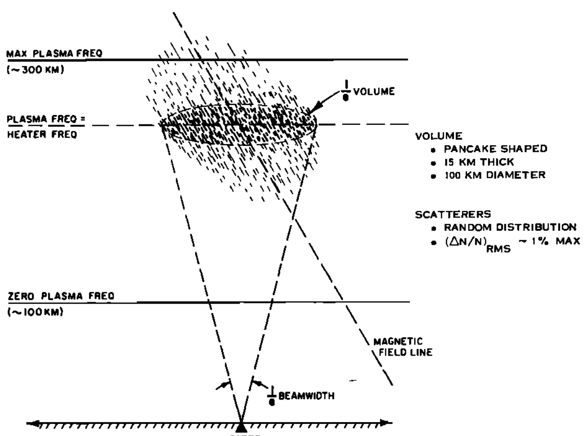
# Ionospheric Modifications - AIT




Bragg Reflectors ← Density Irregularities AIT → HF/UHF/L-band scintillations

Pressure & Density gradients → **Diamagnetic Currents** → Virtual Antennae at ELF/VLF → ELF/VLF injection to EIW & RB

Inject RF EM Waves → Electron Heating → Conductivity Modification → Current Modification



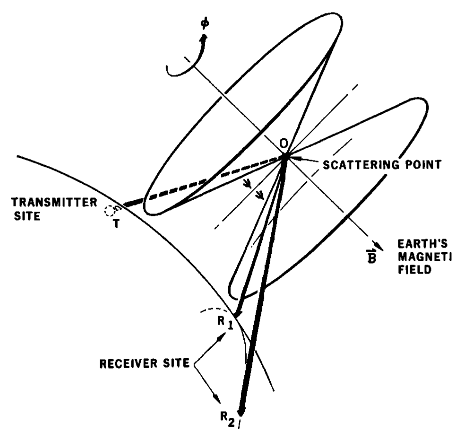



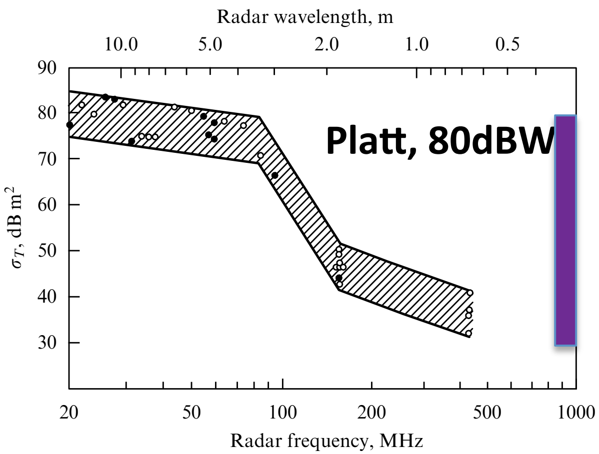

Fig. 1. Mirror scattering geometry.

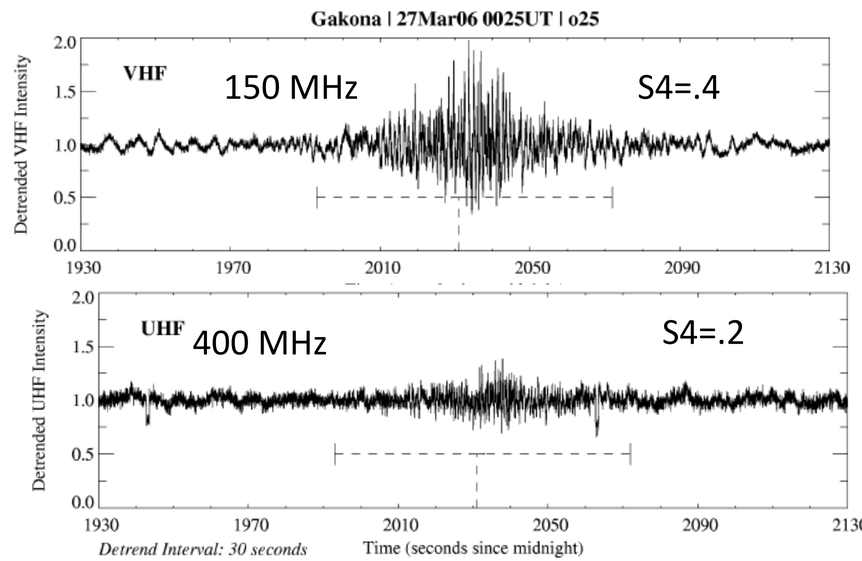
**Bragg Aspect Sensitive Scattering or Field Aligned Scattering (FAS)**

# Artificial Ionospheric Turbulence AIT

## Inspiration & Challenge

**HAARP @ .96 MW**




**MUF at GHz**

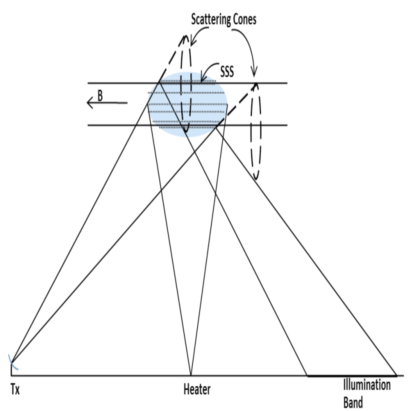
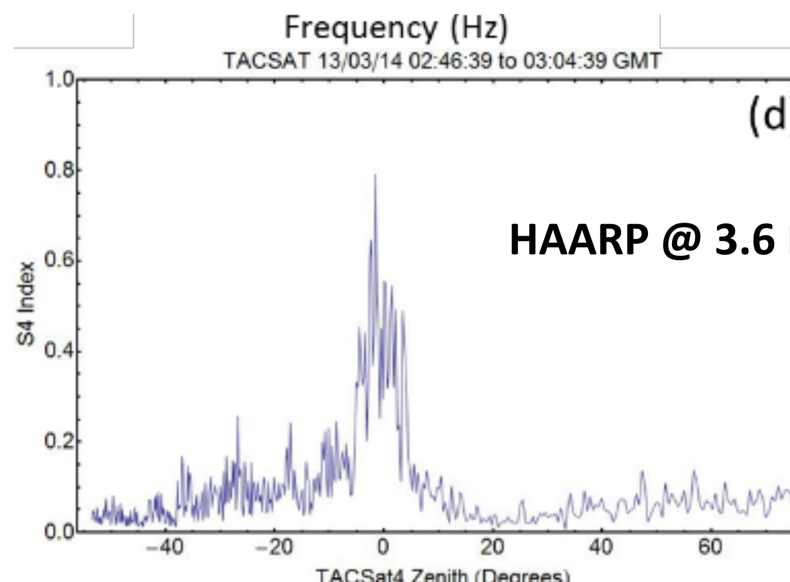
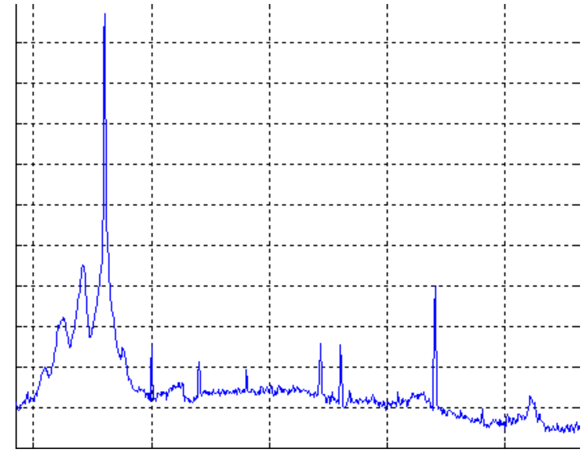


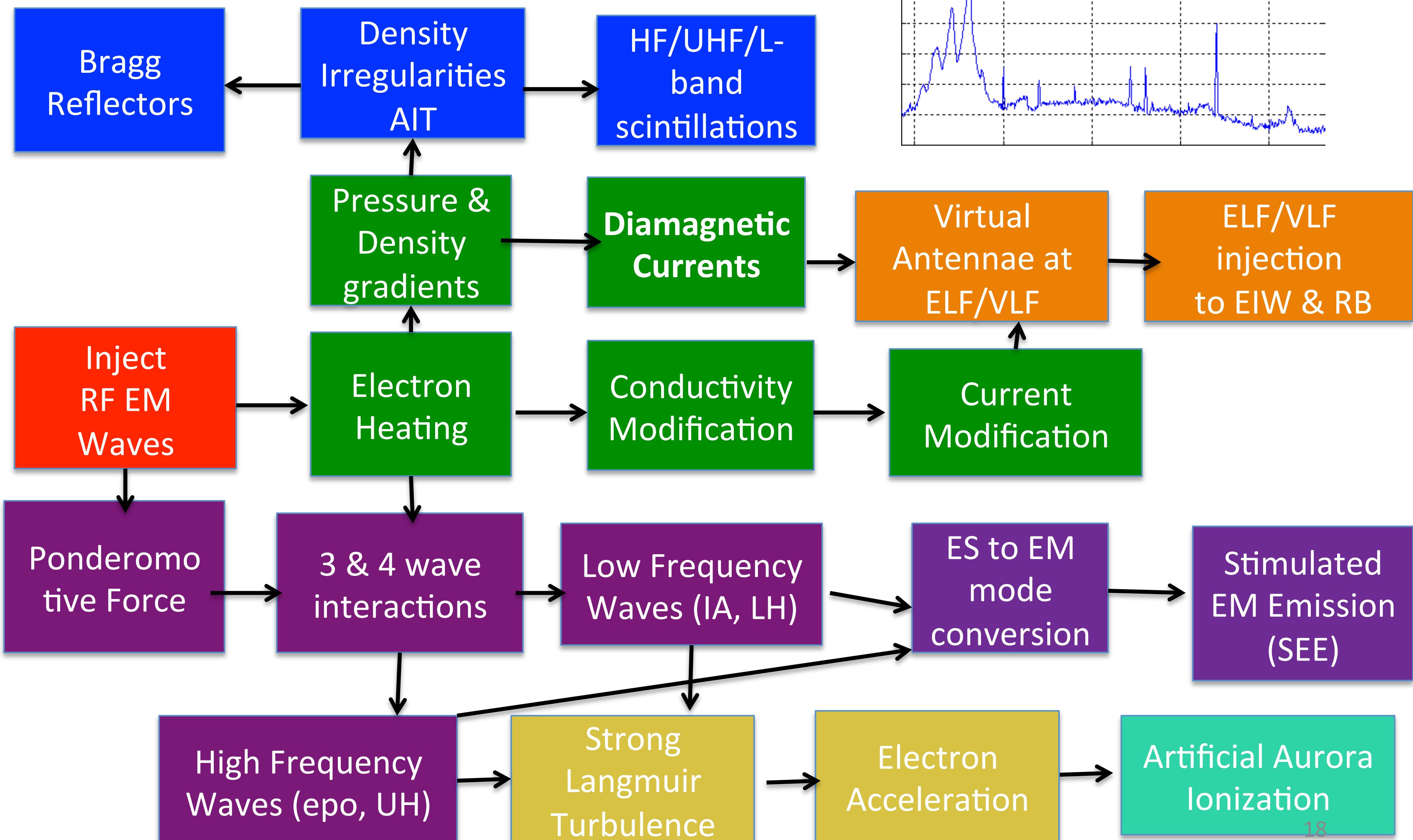

Fig. 1: Schematic of SSS FAS system at GHz.



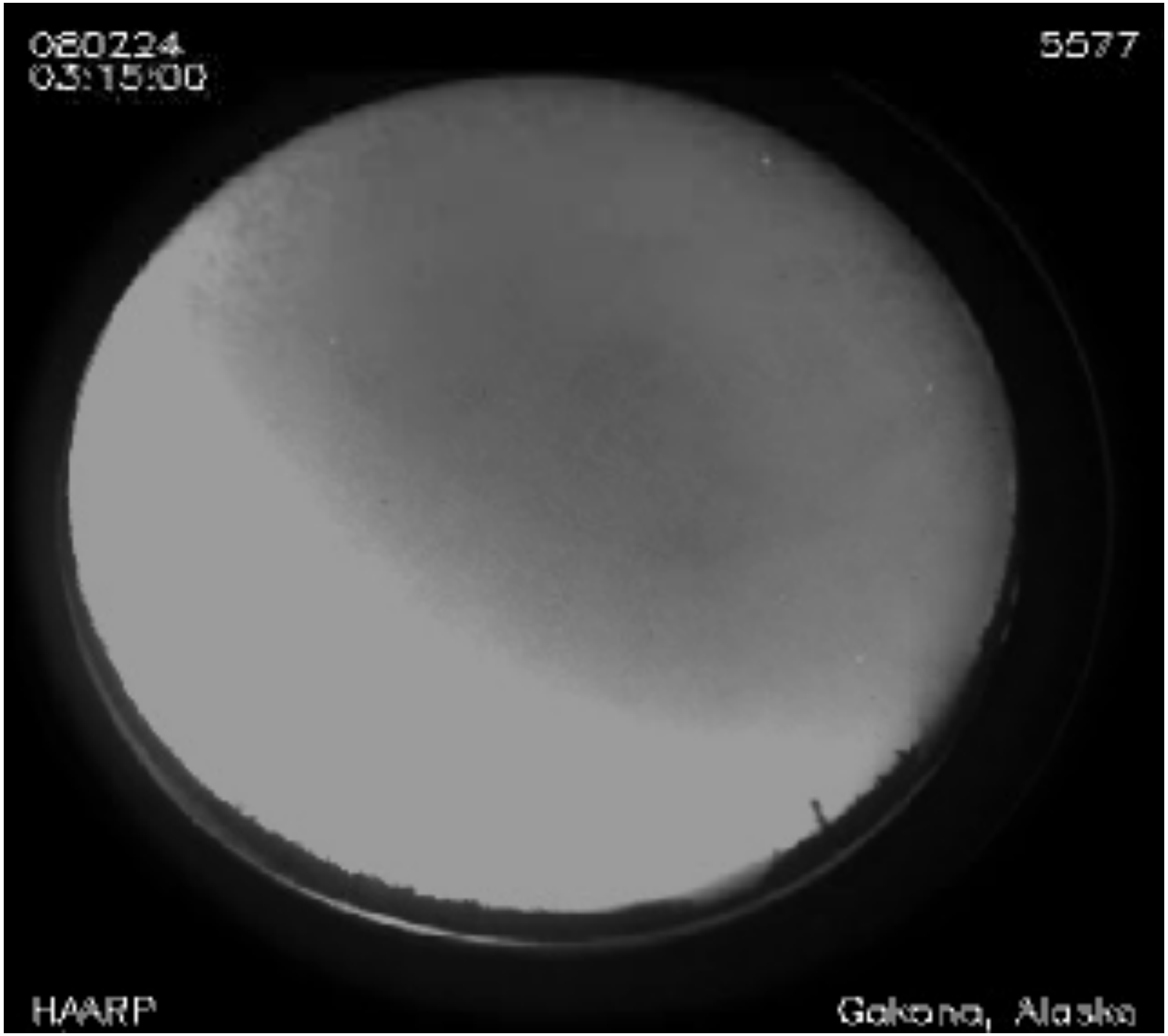

**Requires preferential excitation of 10 cm scales**

# Ionospheric Modifications
# SEE- SLT-Acceleration
# Artificial Aurora- Ionization





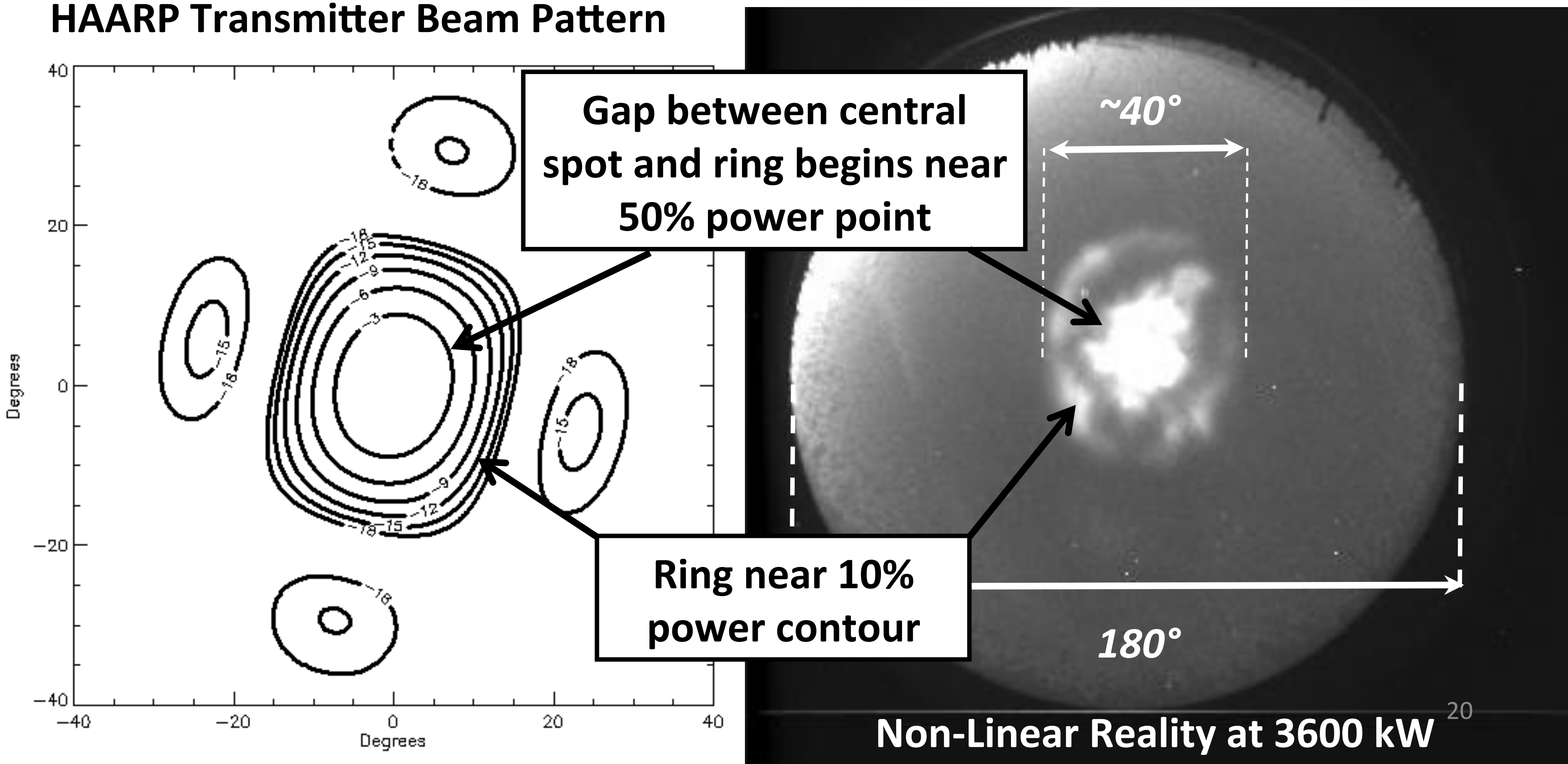
# Artificial Aurora



# Artificial Ionization – Puzzle & Discovery

- Puzzling bull's-eye patterns in optical emissions extending beyond beam edges filling ~¼ of sky. (Pedersen et al. GRL, 2009)

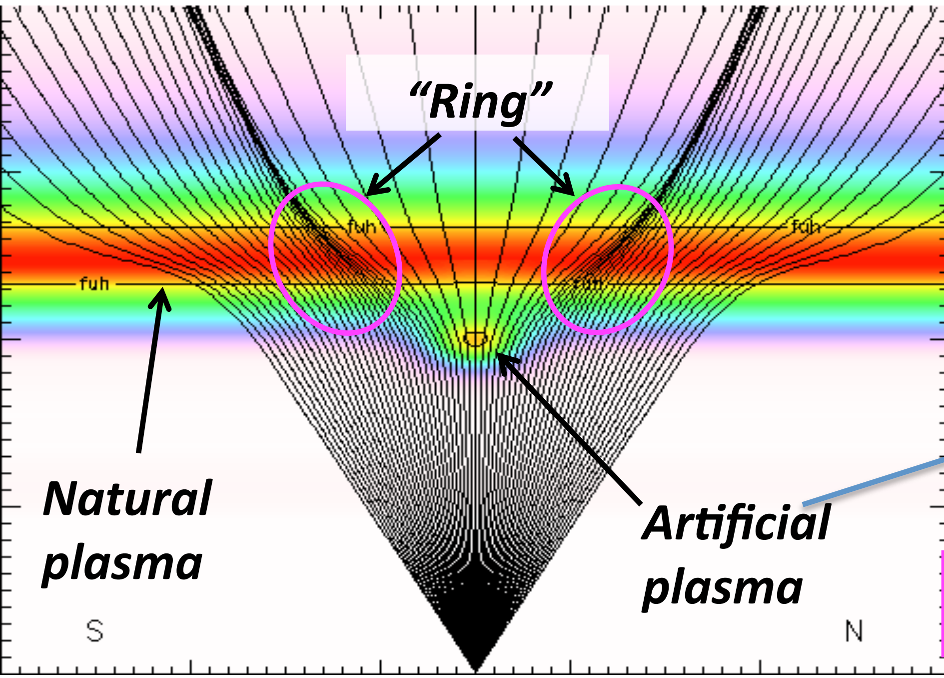
**HAARP Transmitter Beam Pattern**




**Non-Linear Reality at 3600 kW**

# HYPOTHESIS – ARTIFICAL PLASMA LAYER

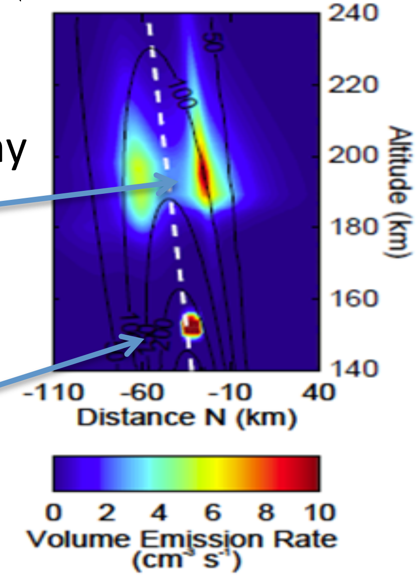
PEDERSEN ET AL, GRL 2009,2010,2011

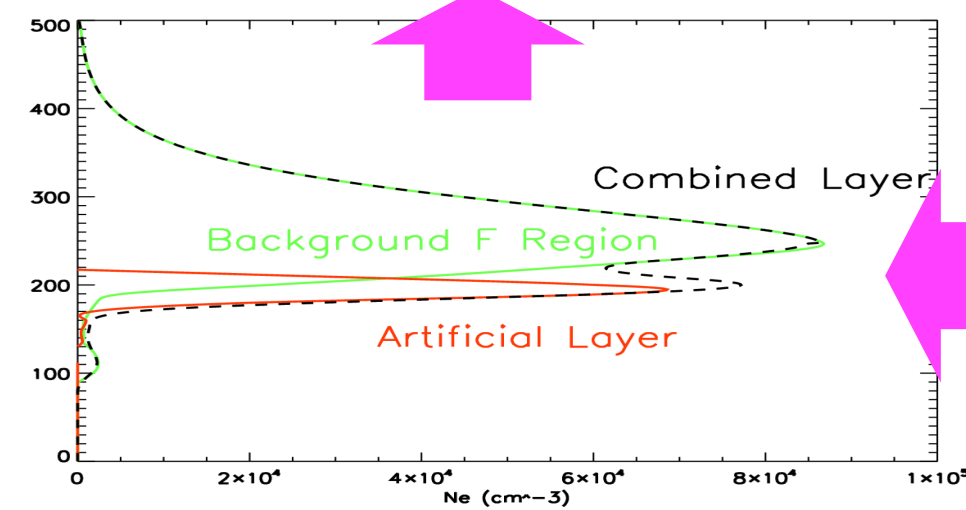


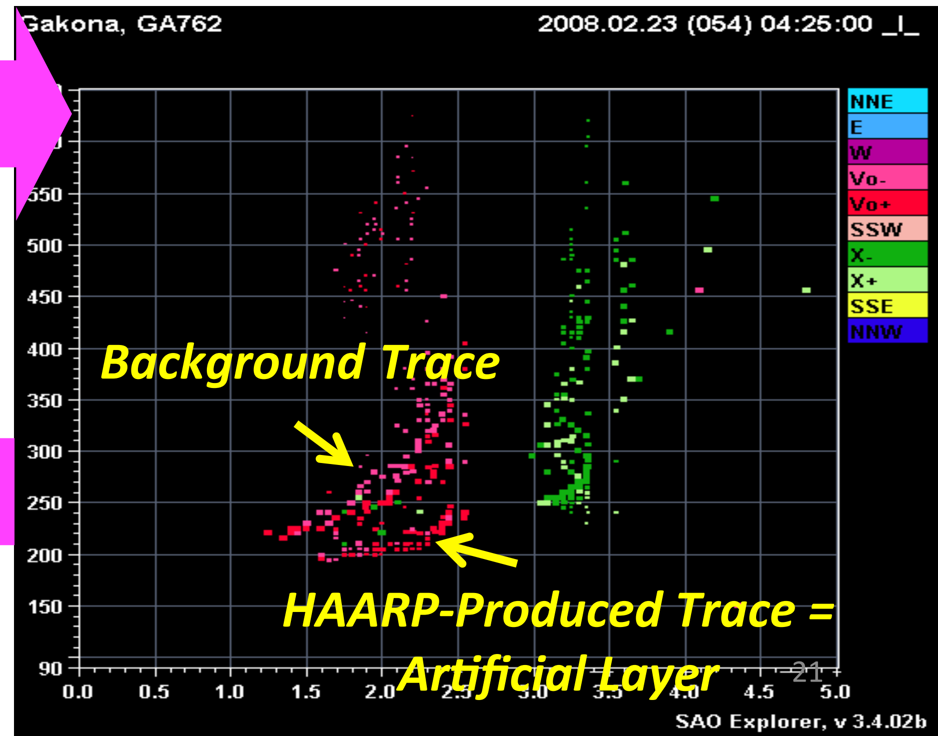

Cartoon

Tomography

Reflection

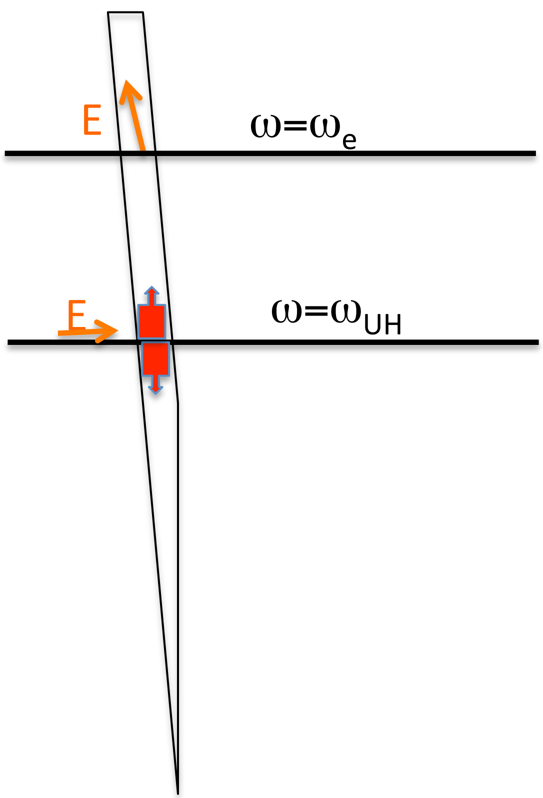


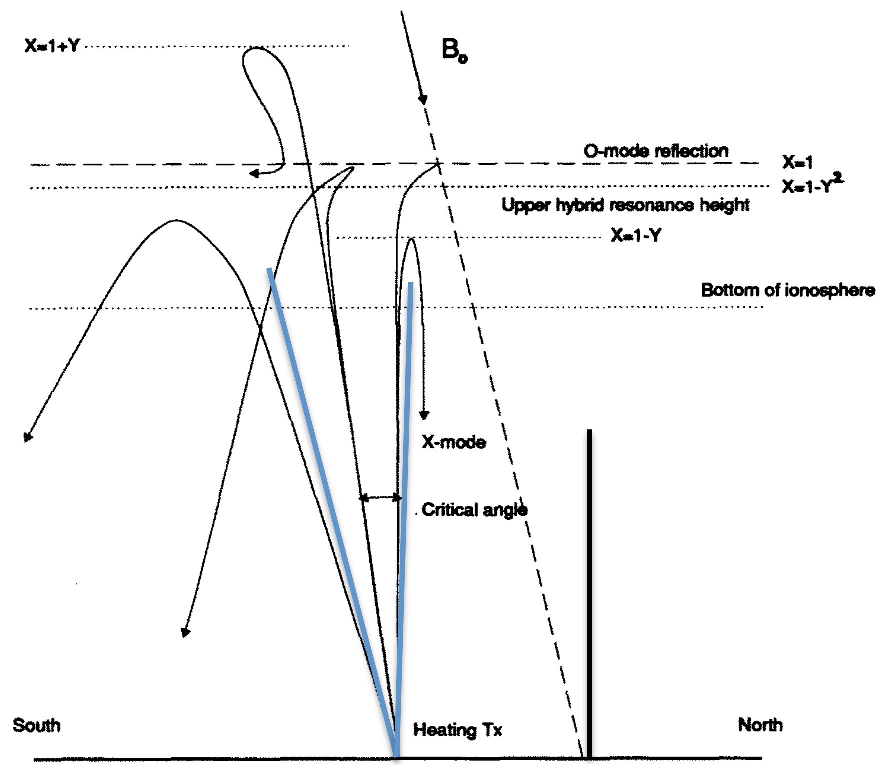



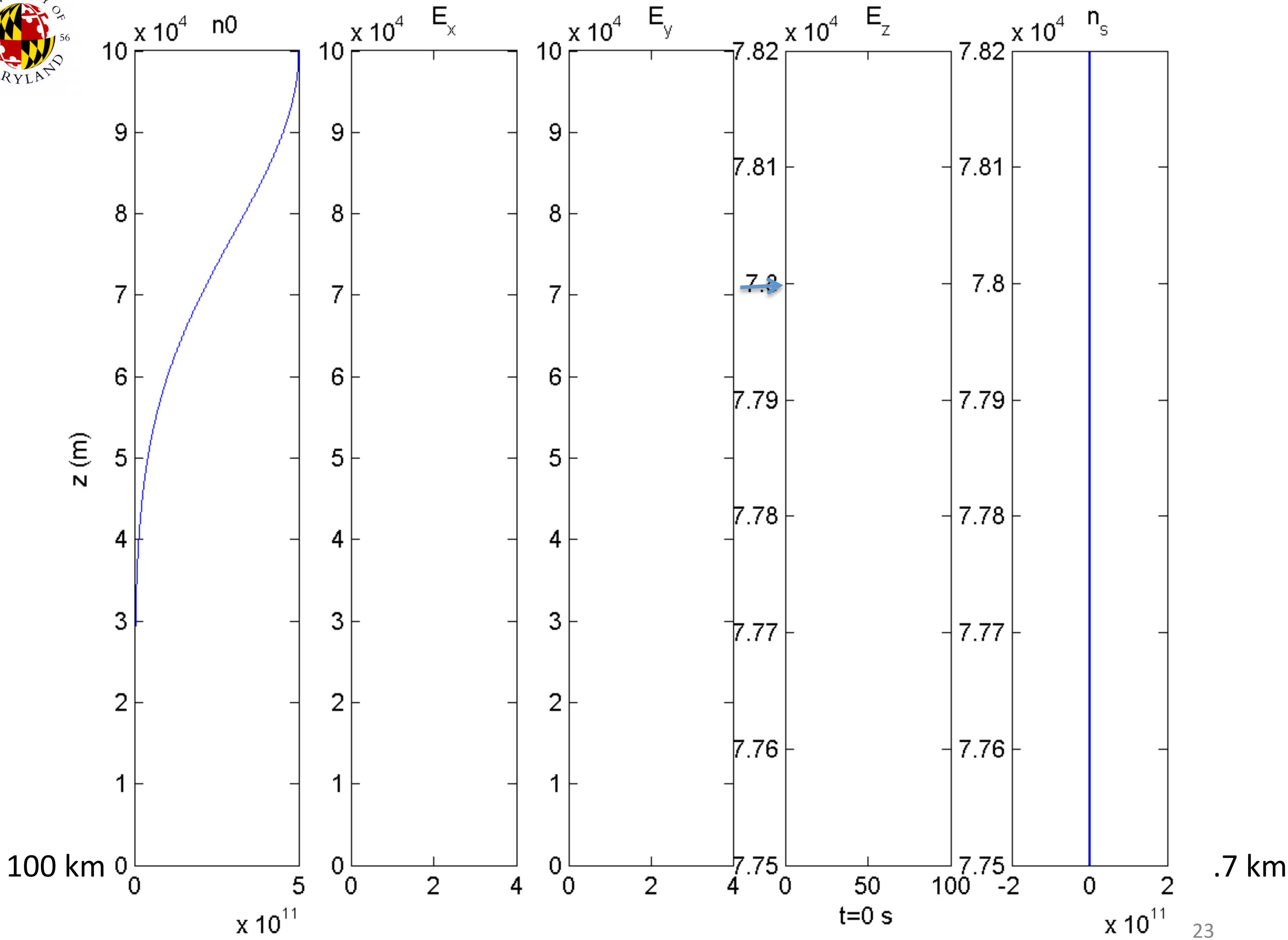
# Theory/Modeling - Key Physics Ideas

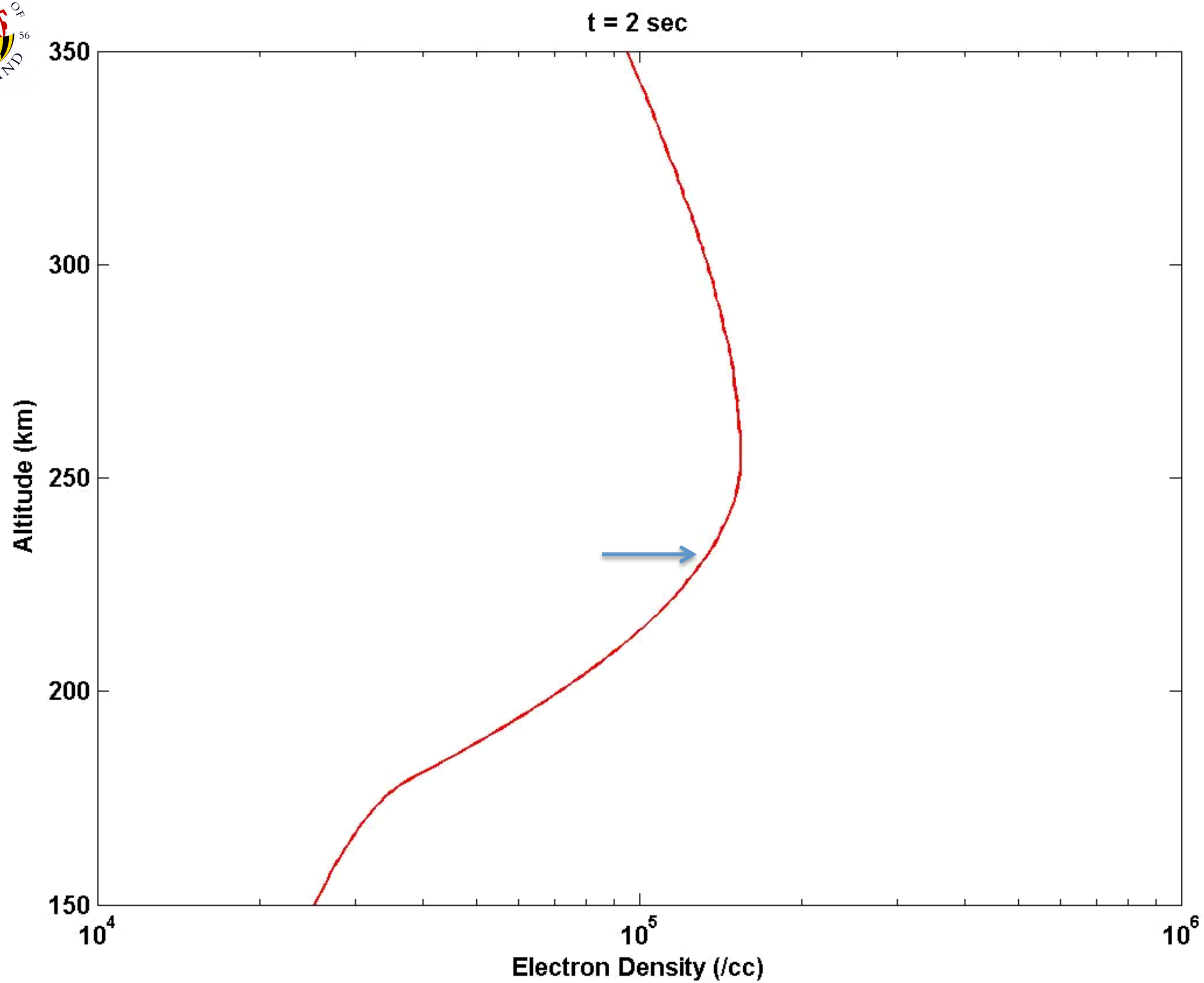
- Electron acceleration controlled by Langmuir turbulence at the reflection height
- Electron heating controlled by upper hybrid heating including dual resonance
- Field aligned heat transport of heated plasma and energetic electrons




Ray paths for HF radio waves



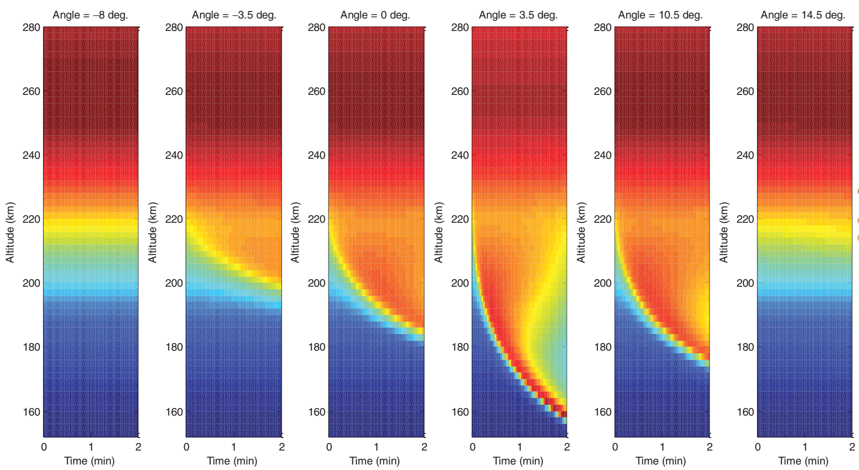

n0
E_x
E_y
E_z
n_s
x 10^4
z (m)
x 10^11
t=0 s
100 km
.7 km

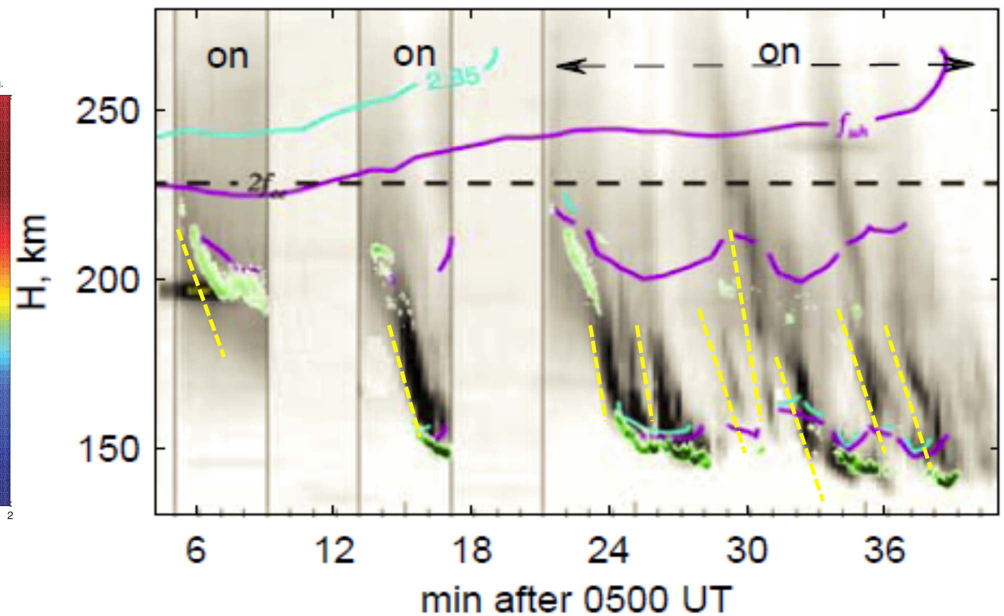


t = 2 sec
Altitude (km)
350
300
250
200
150
$10^4$
$10^5$
$10^6$
Electron Density (/cc)

# Descending APL

2GH, 440 MW, MZ




Eliasson et al. JGR 2014

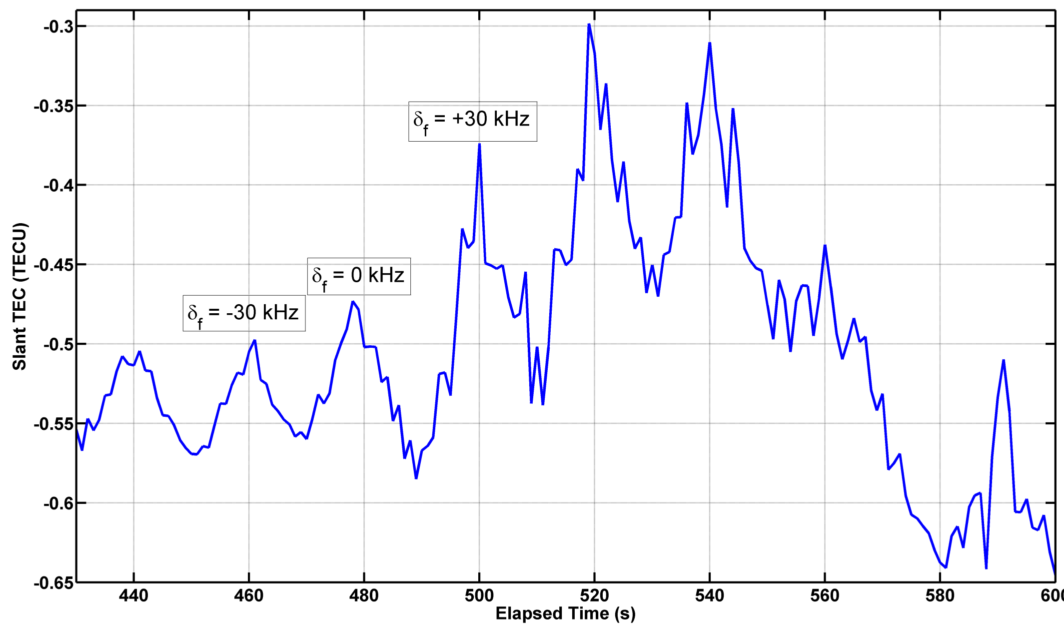
Time-vs-altitude plot of 557.7 nm optical emissions along *B* with contours showing the altitudes where *fp =2.85 MHz (blue), UHR= 2.85* MHz (violet), and 2$f_{ce}$ *= 2.85 MHz (dashed white). Horizontal blips* are stars. Green is the Ion Acoustic Line intensity.

✓the artificial plasma near $h_{min}$ was quenched several times.

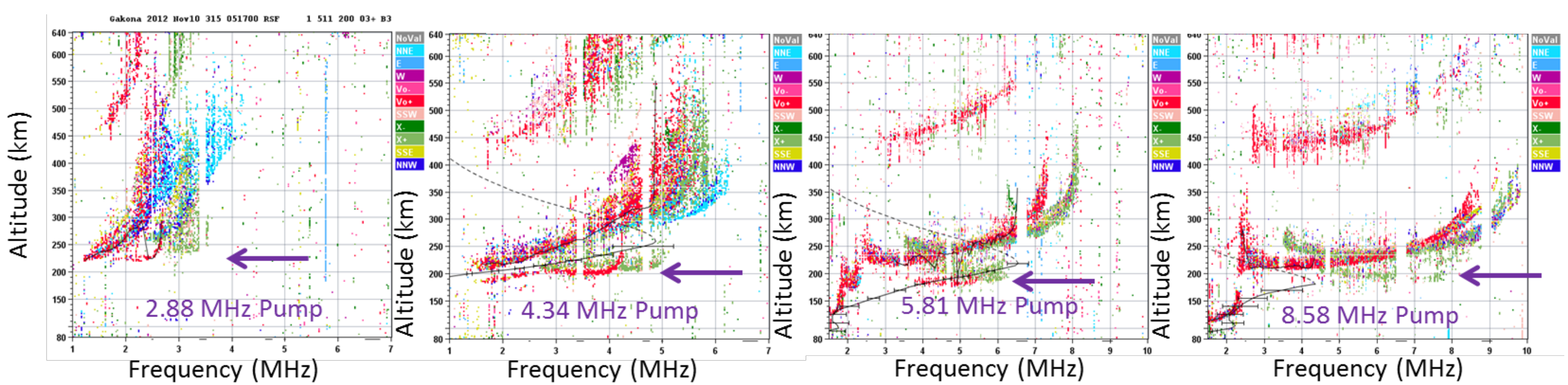
Mishin & Pedersen , GRL 2011

# The Role of the Double Resonance

$\omega \approx \omega_{UH} \approx n\Omega_e$

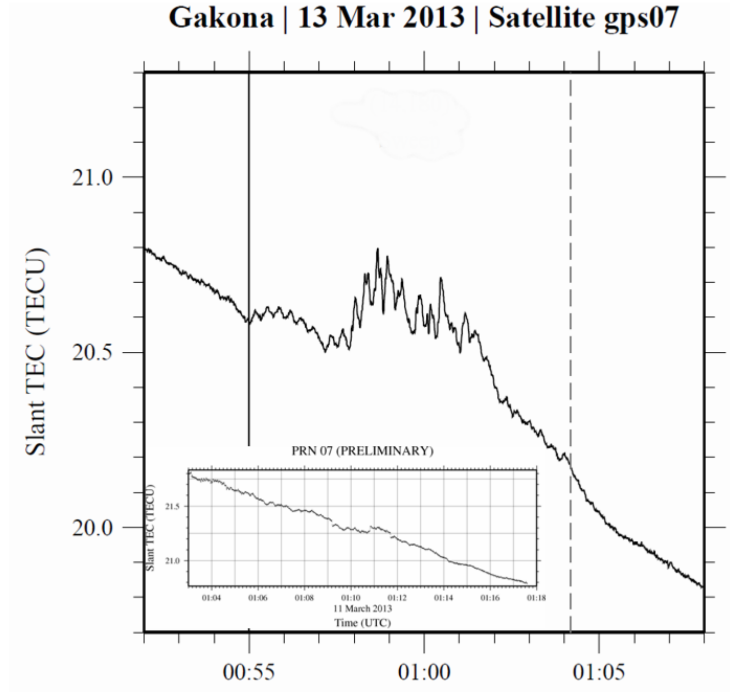



P. BERNHARDT



# The Role of the Double Resonance

$\omega \approx \omega_{UH} \approx n\Omega_e$

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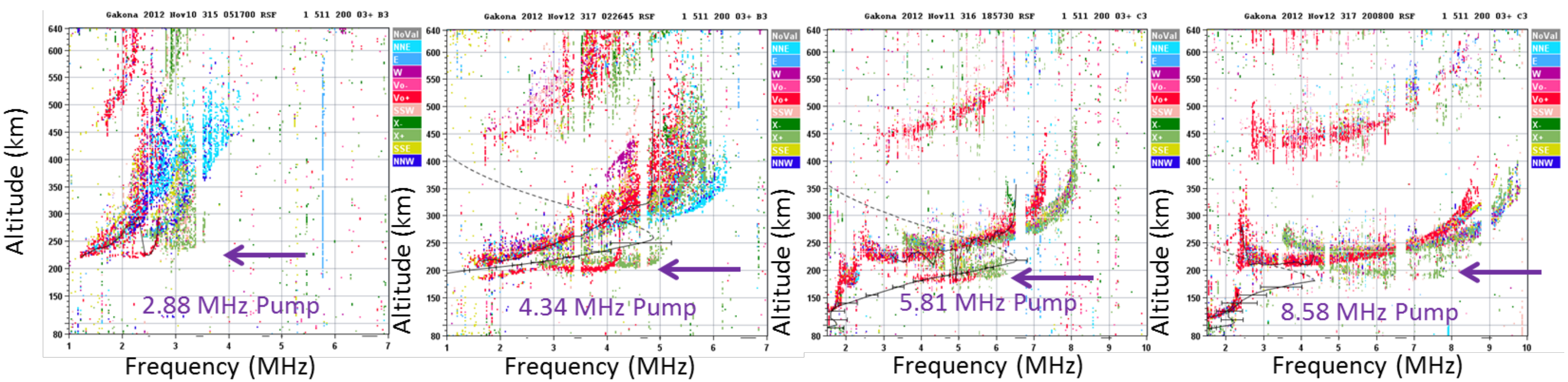
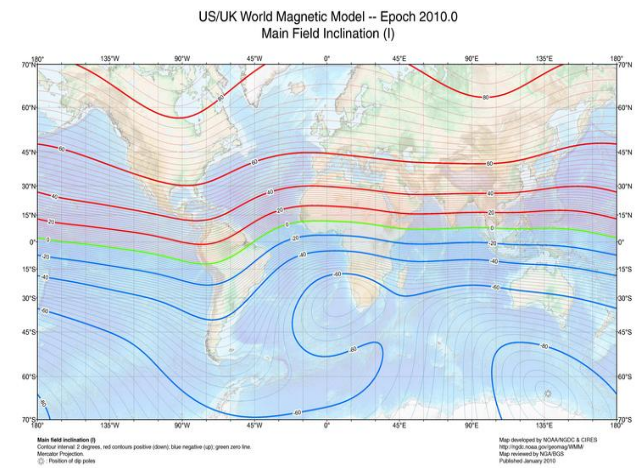
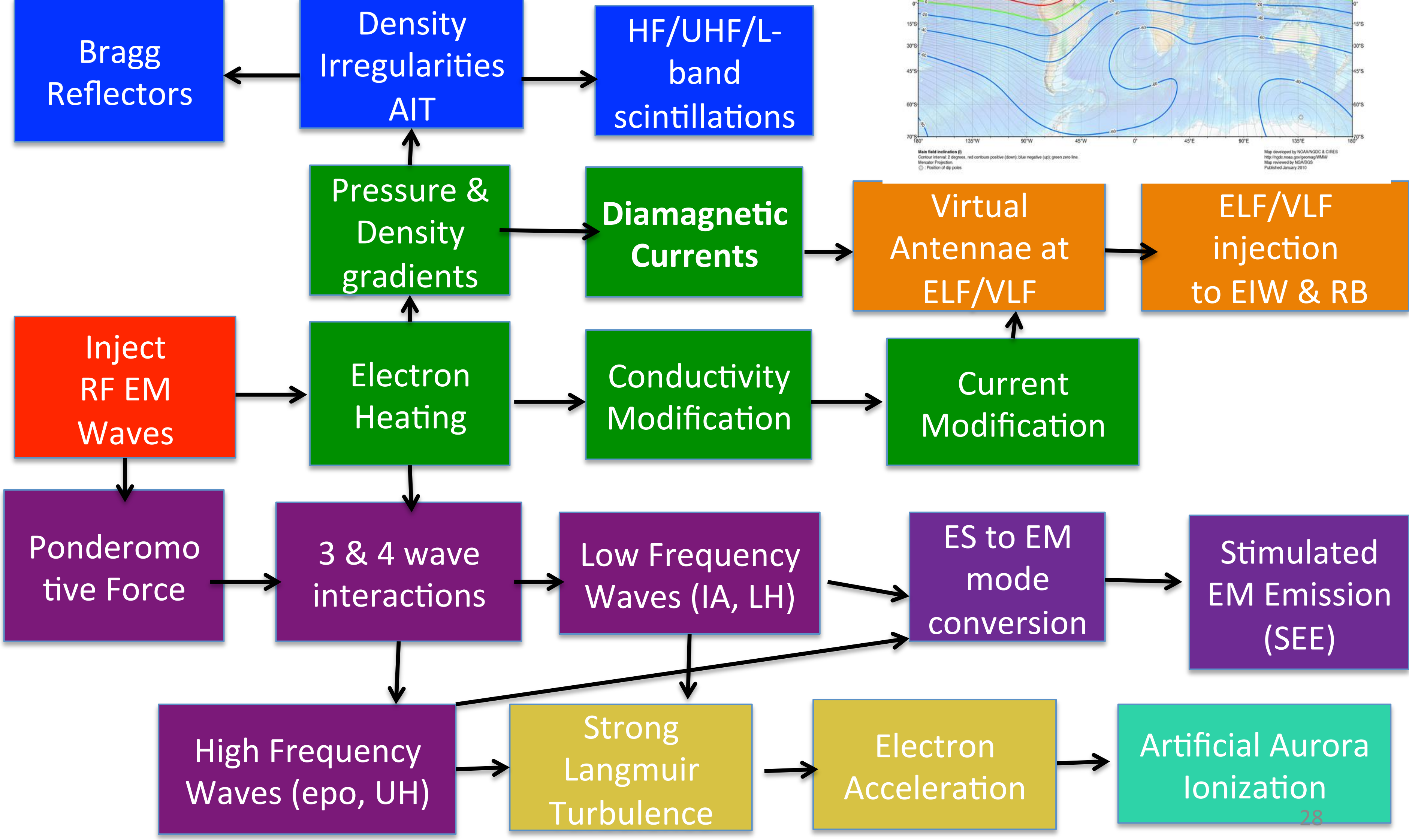


# Concluding Remarks



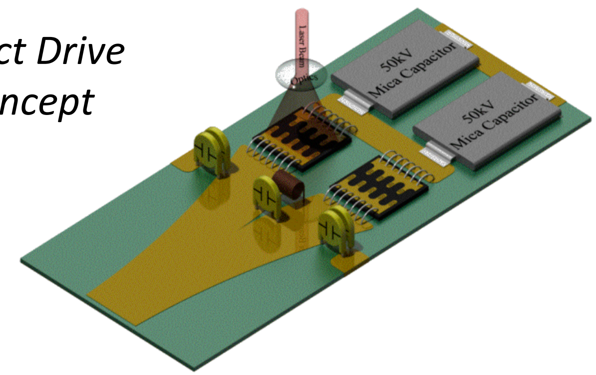
# SUPPLEMENTARY SLIDES

# Technology Drivers – PCSS

- **Photo-conducting switches (PCSS) enable direct synthesis of RF signal from HV DC sources by using high-rep rate UV light sources to modulate switching. 20 kV at 200 A demonstrated – Study physical mechanisms that limit switch efficiency (trap levels and concentration for HV holdoff e.t.c.)**

**PCSS –** Photoconductive Semiconductor Switching
- Achieved 700 kV/cm switching field
- Demonstrated repetition rates of up to 65 MHz at 20 kV switching amplitude
- Direct rf drive approach

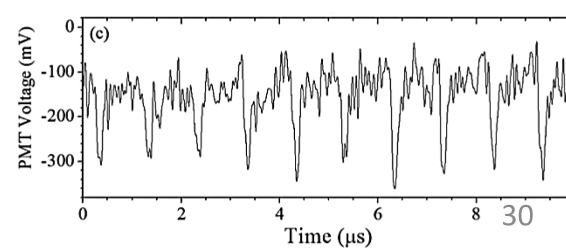
*Direct Drive Concept*




- **Need to develop small, high rep-rate UV sources to modulate PCSS**
  - **MHz rep-rate at deep UV, 121.5 nm, demonstrated**
  - **Study limitations of high-power pulsed UV micro-discharges**
  - **Increase UV output power and match output wavelength with PCSS energy/distribution**

**Highly repetitive light sources**
- Driver for PCSS
- Modulated UV narrowband light source with high power (~ 100 W) at RF frequencies

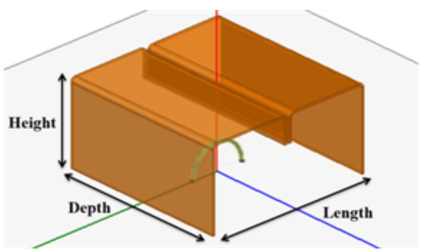
*1 MHz light pulse train*



# Technology Drivers - ESA

**Electrically Small Antennae (ESA) with footprint five to seven times smaller than traditional dipole are under development. Challenges include**

- **Bandwidth**
- **Tunability**
- **Power handling**




*4 to 10 MHz antenna*

**ESA** – Electrically Small Antenna to interface with UMD 50 Ohm impedance RF source.

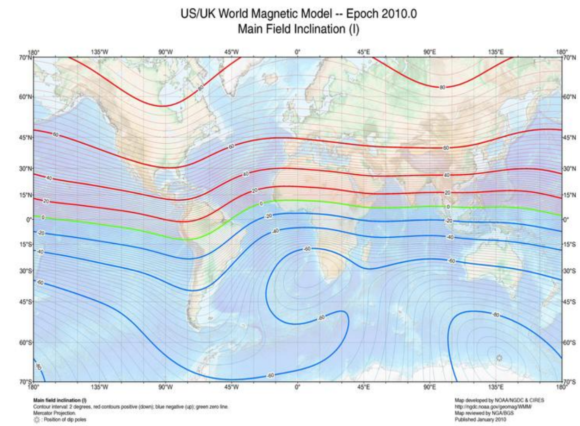
- Factor of several smaller than dipole
- Frequency tunability demonstrated

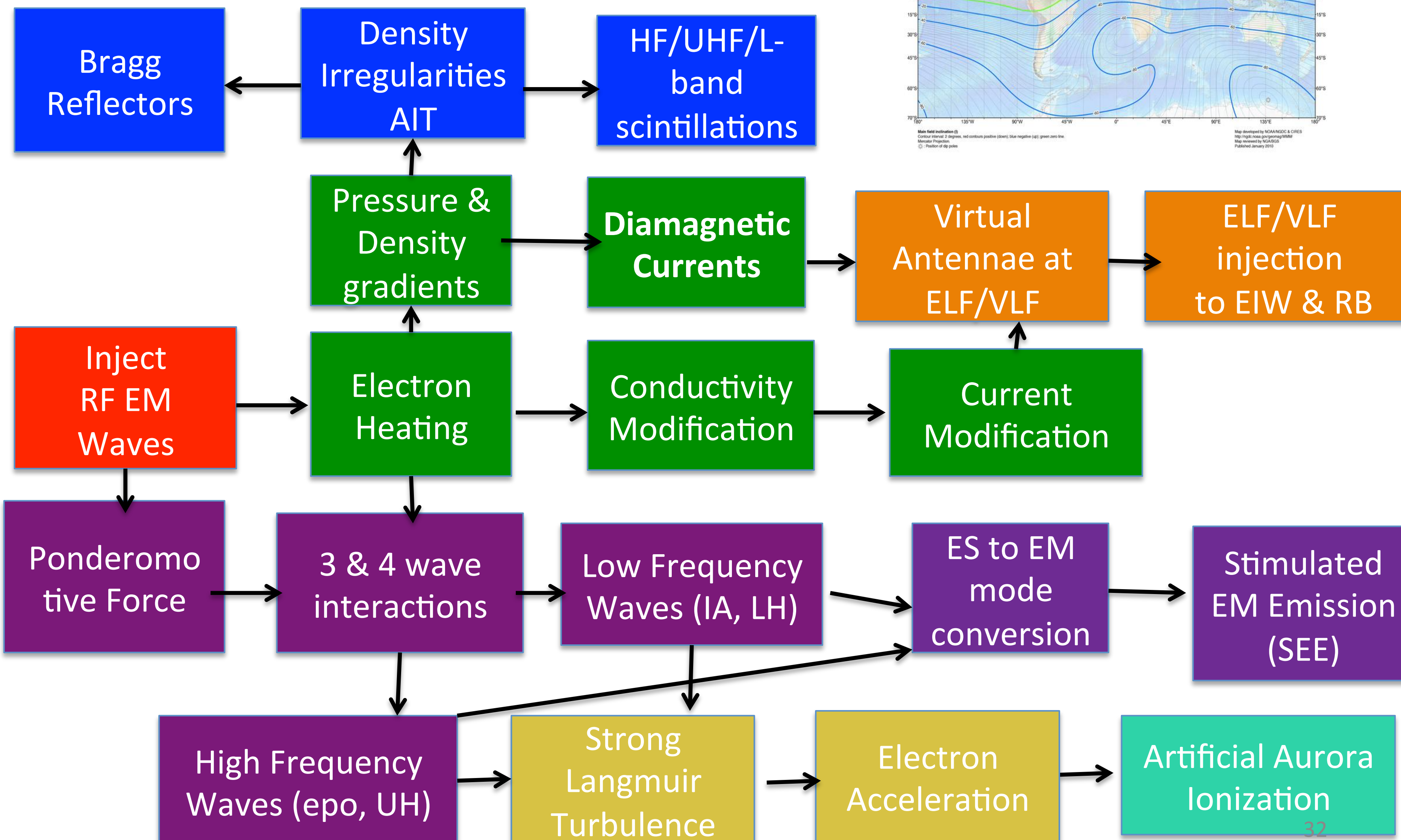
**Overall Challenges**

- Optimize tradeoff between antenna efficiency/size/tunablity
- Improve PCSS photonic efficiency
- Increase output power of light source

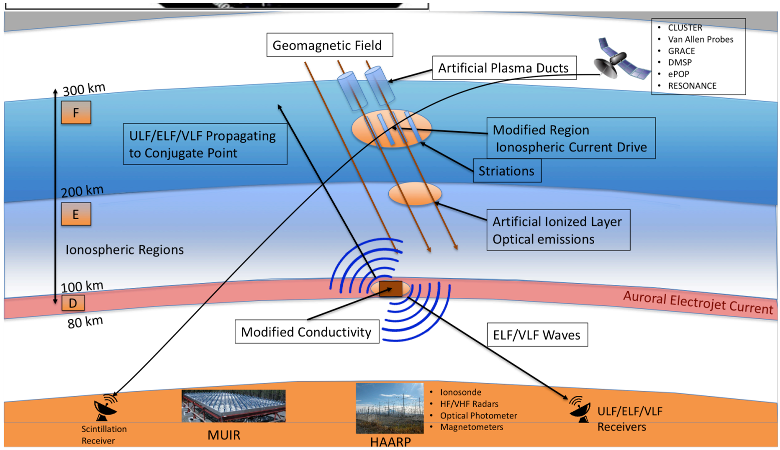
*PCSS die for size comparison*

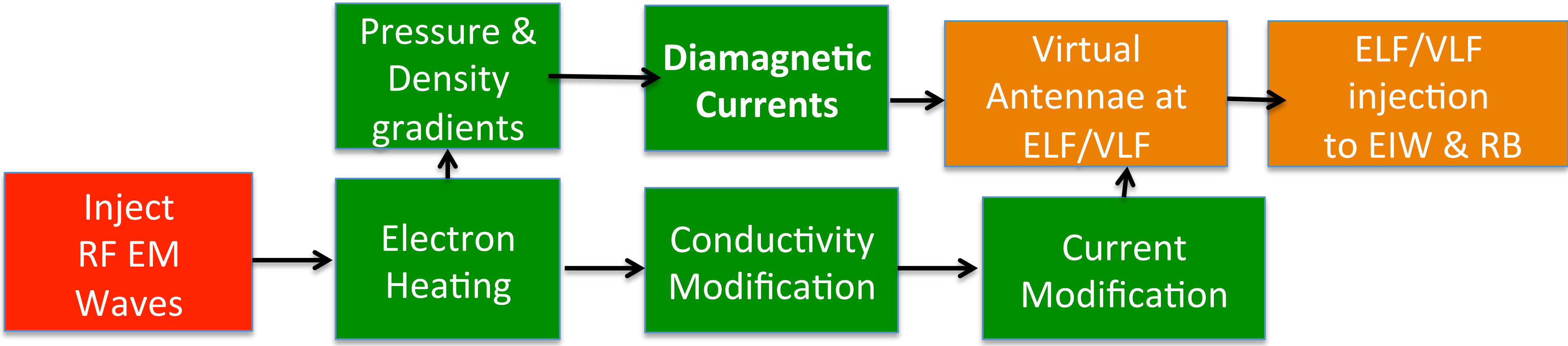
# Ionospheric Modifications



# Ionospheric Modifications

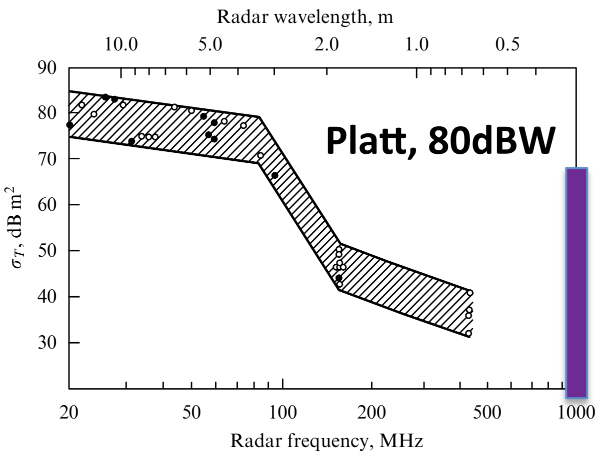


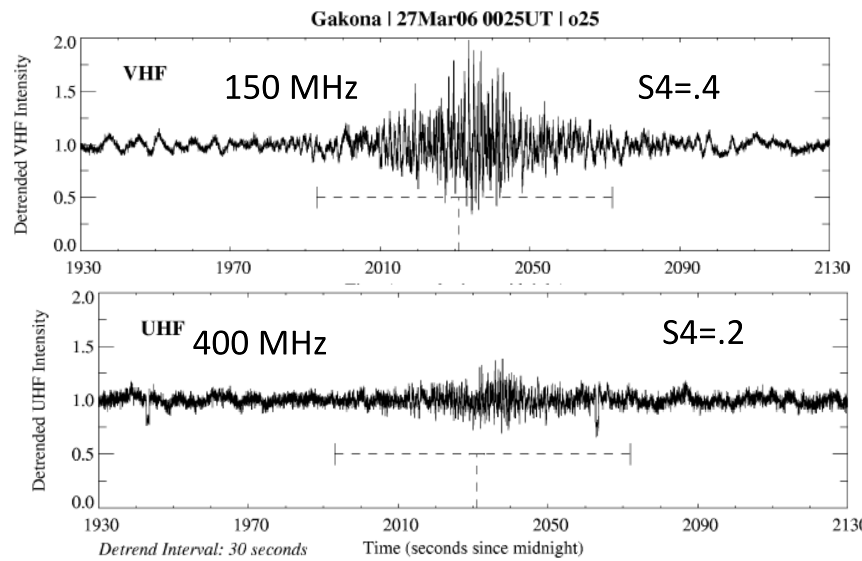



# Artificial Ionospheric Turbulence AIT

## Inspiration & Challenge

**HAARP @ .96 MW**




**Requires preferential excitation of 10 cm scales**

**HF heating generates Field Aligned Striations (FAS) ($L_z$> 1 km, $L_T$≈ 10 m) at ERP> 70 dBW**

**MUF at GHz**

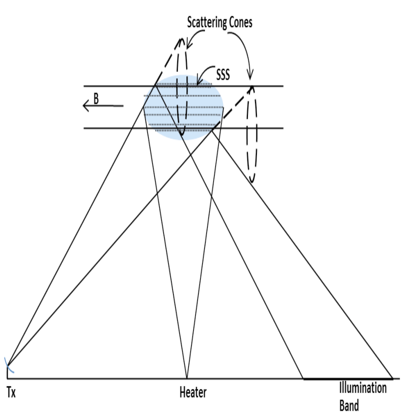
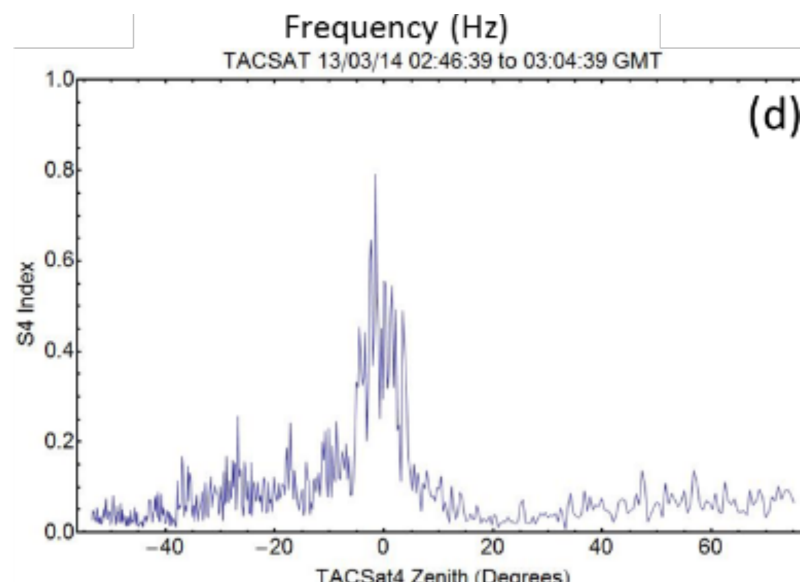
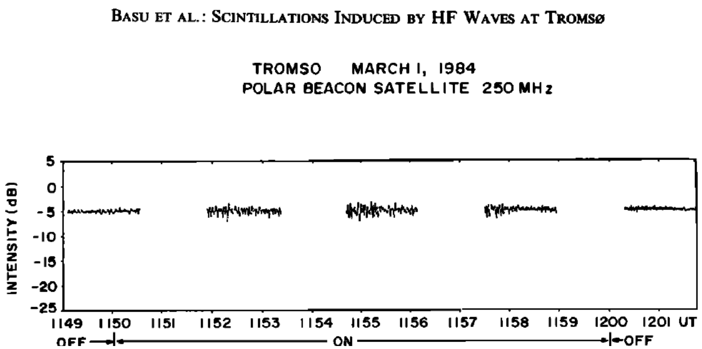


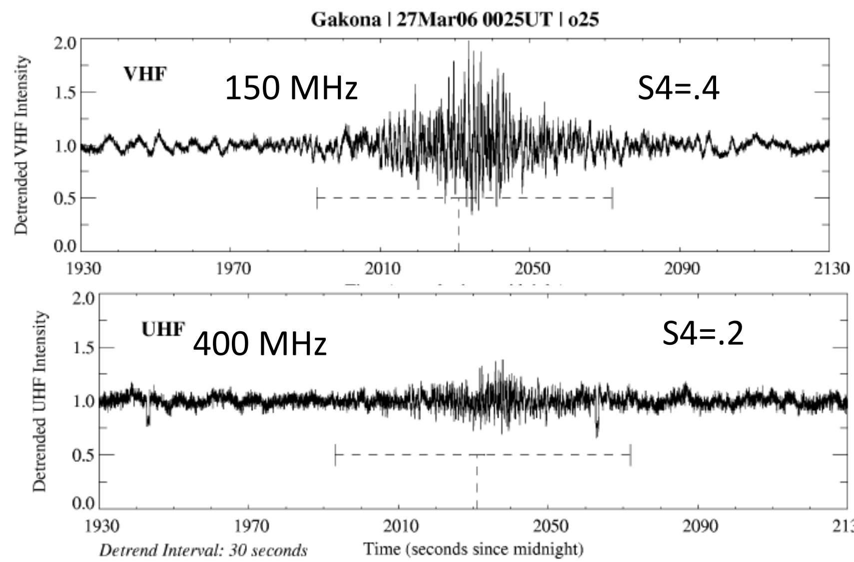

Fig. 1: Schematic of SSS FAS system at GHz.

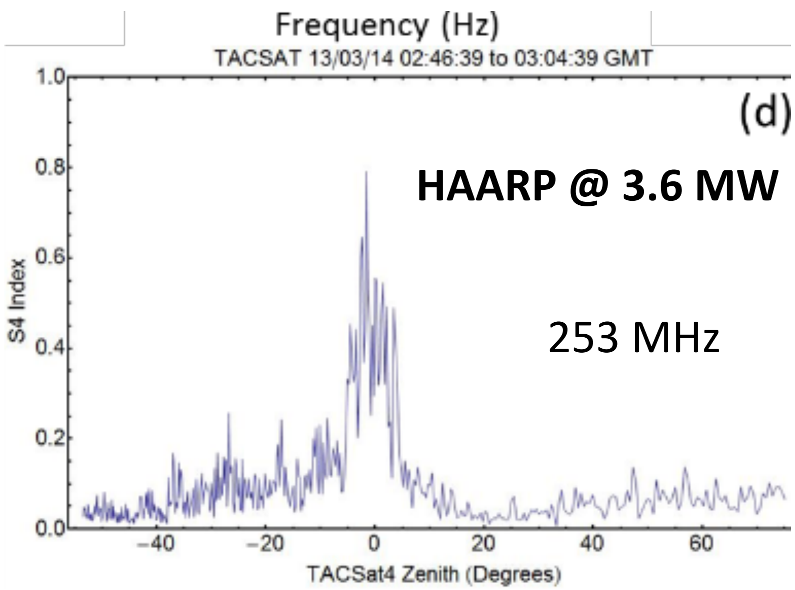


# HF Driven Scintillations




**HAARP @ .96 MW**




1m @ 300