White Paper for Frontiers of Plasma Science Panel

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Turbulence and Transport	**S**
Interaction of Plasma and Waves	**P**

Oral	**X**

Title:	**HAARP: an Open Plasma Laboratory (OPL) in Space**
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***1. Introduction*:** Active experiments, where the environment can be perturbed with controlled injections of particles, waves, beams, ionized or neutral gases and then diagnosed to determine the response of the space plasma, provided the opportunity to perform laboratory-style, cause and effect experiments in space. Such experiments were very valuable understanding basic plasma physics processes due to the controlled nature of the injected perturbation and, when diagnosed properly, provided answers to critical questions. In the past experiments, such as electron and ion beam, neutral gas and wave injection provided answers to key space plasma physics issues. Unfortunately, with the exception of small rocket experiments, such active experiments have been eliminated, due to the high cost and risk associated with such one-shot type experiments.

The advent of and extreme sophistication and high power associated with the first "phased-array" type ionospheric heater associated with the *High Frequency Active Auroral Research Program (HAARP)* heater, its supporting ground instrumentation, and diagnostics provided by overflying microsatellites ushered the active experiments and the use of space as an "open" plasma laboratory into a new era. This white paper argues that HAARP, with its associated ground and space based diagnostic instrumentation, is a unique tool for plasma physics studies in a truly collisionless, magnetized, multi-ionic inhomogeneous environment without the complications of walls or impurities and with a variety of conditions that depend on season, solar activity and solar illumination. It is a facility that will permit exploration and understanding of scientific challenges associated with the frontiers of basic plasma science and its impact on understanding the geo-space environment including the radiation belts, the magnetosphere and the ionosphere.

I should note that the HAARP facility is currently temporarily closed, while transferred from AFRL to the State of Alaska and will be operated by the University of Alaska. It is anticipated that the transfer will take place by July 30, 2015.

***2. Research Frontiers*:** Quoting from a recent NAS report[1] active HAARP experiments "*provide scientists with a qualitatively new laboratory in the sky to excite input-response discoveries that span 12 orders of magnitude of scale size. This capability enables-wide ranging studies such as the flow of energy in matter, cascading in excited of atoms and molecules; ionizing matter to probe aspects of the very nature of particle, collective-gas, and wave-particle energy exchange; and exploring fundamental plasma processes, which bear directly on attempts to realize controlled plasma fusion. All of the above*

[1] *Opportunities for High-Power, High-Frequency Transmitters to Advance Ionospheric/Thermospheric Research*, **National Academy of Sciences Report**, **2014**

is also highly relevant to understanding the geospace response to solar storms and the development of space weather near Earth." Particular research frontiers addressed in this white paper include:

(i) Physics of Radiation Belts (RB): Exploration in the area relies in the capability of HAARP to inject in controlled fashion whistler, Shear Alfven (SA) and Magnetosonic waves in the RB a capability known as "***Virtual Antennae***" (Figs. 1,2). While major progress has been achieved by multi-spacecraft passive measurements, the physics interpretation suffers from the traditional "***chicken and egg"*** problem, since the source causing the observed is not controlled, difficult to identify and the wave-particle interactions complex and coupled. Using virtual antennas to inject waves with frequencies from .1 Hz to kHz will among others allow quantitative understanding of: stimulated emissions and their relation to chorus, noise-like and discrete emissions; Pc 1 pulsations; SA and EMIC wave propagation, attenuation, reflection and mode conversion; pitch angle scattering rates of electrons and protons by the injected low frequency waves; operation of the Alfvenic Resonator and duct; characteristics and stimulation of the Alfven maser and excitation of field resonances. Controlled duct formation will allow for the possibility of guiding the injected waves. Complementing the HAARP facility with dedicated diagnostics on micro or cube satellites on magneto-synchronous orbit, orbit that allows the instruments to stay on the HAARP field line for 30-40 minutes, will revolutionize space plasma science.

(ii) Artificial Ionospheric Turbulence (AIT) and its impact on HF/VHF/UHF trans-ionospheric propagation: Naturally excited turbulence, such as spread-F, has major impact on trans-ionospheric communications including GPS reception. Understanding ionospheric turbulence and its impact on communications is of major scientific and societal importance. The power and flexibility of HAARP has created major breakthroughs in exciting and controlling AIT scale lengths. Breakthrough studies of Langmuir and Upper Hybrid (UH) turbulence including electron acceleration, artificial aurora and artificial ionization have been conducted (Figs 1). Mode conversion and Stimulated EM Emissions (SEE) revealed new ways of controlling turbulent spectra including the important role of double resonance, when the UH frequency is close to a multiple of electron gyro-frequency (Figs 3-6). In addition to controlling the spectrum and amplitude of the turbulence HAARP was capable for the first time to open a new space plasma regime where the transmitter-generated plasma dominate over the natural plasma Figs (7,8). Descending plasma layers as well as stationary plasmas maintained over several hours were created. The artificial plasma layers are highly turbulent and can be used to inhibit as well as to promote long-path HF/VHF/UHF propagation. Understanding the physics controlling the new regime and exploring the possibility of becoming an active component of communications, navigation, radar and other systems is of paramount importance.

(iii) Plasma Physics under Subauroral and Auroral conditions: HAARP is located in a region where depending on the prevailing geospace conditions research can be conducted under different ambient plasma conditions. HAARP is within the auroral zone under storm, maps in the plasma sphere during quite times and is in the subauroral region during substorms. As a result experiments can explore the effects of HF heating under different and often dynamic conditions. The modification of the ionospheric conductivity resulting from electron heating and plasma density increase/decrease allows studies of the role of HF heating on the evolution of substorms as well as studies of electrojet instabilities. Furthermore when in the subauroral region one can study of the role of temperature and plasma density in plasma outflows related to ion drifts and polarization streams, as well as high electron temperature plasma chemistry and density troughs. Finally there is evidence that heating can drive artificial gravity waves offering a novel way of exploring satellite drag issues in the lower ionosphere.

3. Research Tools and Approach: In this section (Fig.1) we summarize the plasma physics chain of processes and energy involved in ***Ionospheric Modifications (IM)*** using the HAARP heater and its diagnostic instrumentation and present some examples of past research emphasizing the unique capabilities of HAARP as an advanced OPL. The ionospheric heater injects HF radio waves (red box in Fig.1) in the D/E or F region of the ionosphere increasing the temperature of the plasma electrons. Collisional electron heating in the D/E region (80-100 km altitude) modulates the plasma conductivity thereby modulating existing currents (electrojet currents) when present. Alternatively collisionless F-region (200-250 km altitude) heating modifies the pressure creating modulated diamagnetic currents (green boxes). The modulated currents act as virtual antennae (orange boxes) injecting ELF/VLF waves in the earth-ionosphere waveguide and whistler, magnetosonic and shear Alfven waves in the radiation belts and the magnetosphere (Fig. 2). Additionally the induced pressure gradients drive magnetic Field Aligned Irregularities (FAI), known as Artificial Ionospheric Turbulence (AIT) that can affect the performance of trans-ionospheric VHF/UHF signals, including GPS signals, and can act as Bragg reflectors providing ground-to-ground paths for signals with frequencies up to GHz (blue boxes). The lower path (lavender boxes) describes ponderomotive force phenomena driven by the interaction of the radio waves with F-region plasma in the vicinity of the critical (f_p) and Upper Hybrid (f_{UH}), where the HF frequency $f=f_p$ (f_p is the plasma frequency) or $f=f_{UH}$. Depending on the intensity of the radio waves including the Airy function amplification near the reflection point, the interaction drives three or four wave parametric instabilities that generate a host of electrostatic (ES) plasma waves, natural modes of the local magneto-plasma. These modes are detected on the ground when are back converted to EM waves. These waves, whose frequency is shifted from the pump wave, are known as Stimulated Electromagnetic Emissions (SEE) and represent an outstanding diagnostic of the HF/plasma interaction. Figure 3 shows the SEE generated by mode converting the HAARP pump at 4.95 MHz (on a static FAI) to an ES UH wave that decays (by Plasma Decay Instability – PDI) to an ES Lower Hybrid (LH) wave and an EM wave observed on the ground downshifted by 8 kHz (the LH frequency). The observed line at 4.93 MHz is due to the decay of the EM pump to an electron plasma oscillation (EP) and IA, followed by mode conversion of EP to a downshifted EM. Figure 4 shows an outstanding example of Stimulated Ion Bernstein (SIB) signals generated by HAARP operating at precisely twice the electron cyclotron frequency. The SEE spectrum shows strong lines between the 3rd and 6th ion cyclotron harmonic with the spectrum extending to the 16th. As demonstrated by Bernhardt et al., the SIB processes appears to involve EM to Electron Bernstein (EB) modes followed by multiple decay of the EB to EB and IB waves. Figure 5 shows parametric instability measurements measured by the HAARP MUIR radar at 446 MHz showing multiple order EP and IA lines. The next three figures, Figs 6-8, are unique to the high ERP (>2 GW) of the HAARP heater. They describe processes corresponding to the lower bottom of Fig.1 (**gold** and **light green boxes**). It has been found that the strongest HF-plasma interaction is strongest for O-mode heating in the direction of the magnetic zenith and incidence between the reflection height, where the HF frequency matches the plasma frequency, and the UH resonance height (typically 4-5 km below the reflection height). The combination of electron heating at the UH layer and strong Langmuir turbulence at the reflection height results in electron acceleration to tens of eV, that cause artificial aurora (visible with naked eye) and artificial ionization. It was also found that the interaction is maximum near double resonance, i.e. when $f=f_{UH}=nf_{ce}$ (n integer). Furthermore the double resonance is a demarcation point of the resultant SEE and AIT spectra. This is seen in Fig.6 that shows that if f is slightly below double resonance the SEE spectrum is indicative of 3 wave interaction with the downshifted maximum (DM) shifted by the LH frequency (8 kHz), while above it indicates a 4 wave interaction with upshifted maxima, in which case L-band GPS scintillations indicate the presence of 10 cm structures associated with EB modes. Fig. 7 shows optical emission and a strong filamentary structure associated with AIT. Finally Fig. 8 descending plasma layers associated with artificial ionization.

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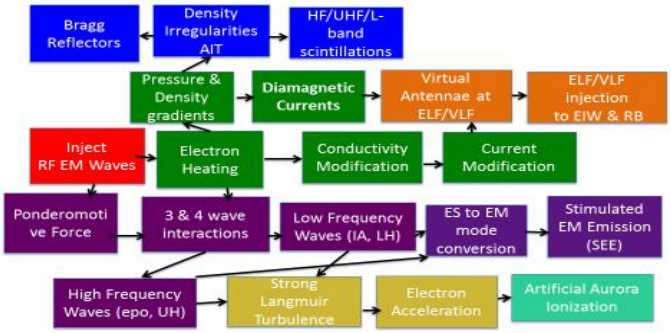

Figure 1: Schematic of plasma physics driven processes

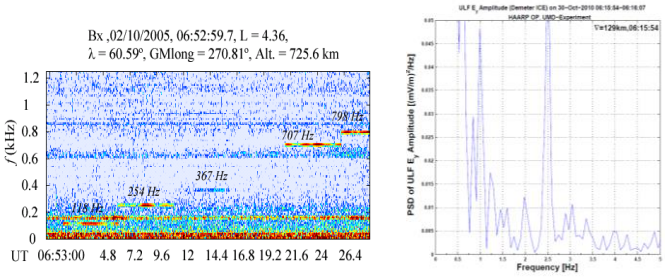

Figure 2: Virtual antenna injected whistler (left) and SA (right) waves measured by the DEMETER satellite overflying HAARP at 700 km

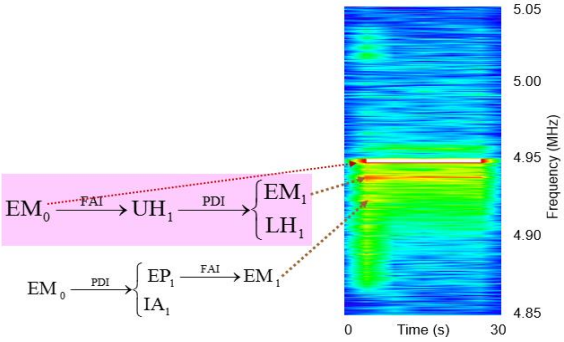

Figure 3: Parametric UH and PDI instabilities and their SEE signatures

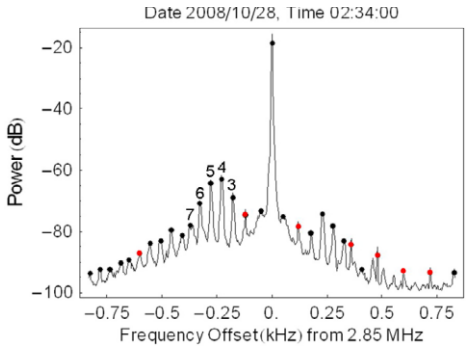

Figure 4: Stimulated Ion Bernstein SEE when HAARP was tuned to twice the electron gyro-frequency. Red dots are interference (Benhardt et al. 2011,)

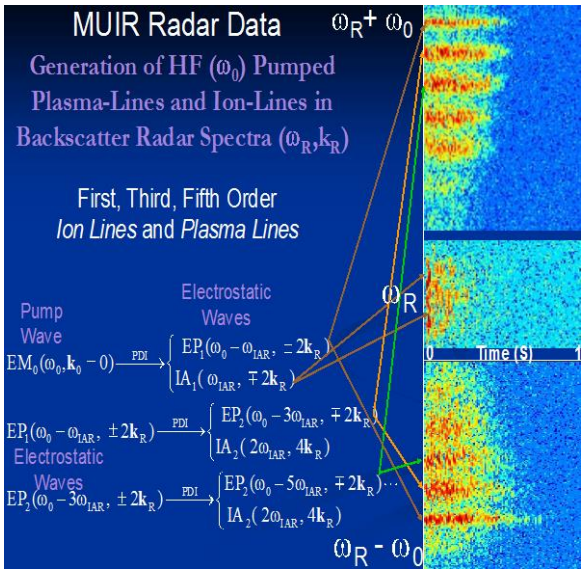

Figure 5: Example of parametric instabilities of pump (EM), plasma (EP) and Ion Acoustic(IA) . (Watkins UAF)

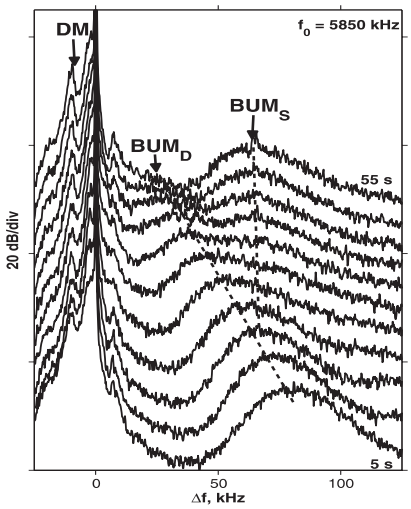

Figure 6: SEE spectra showing transition from below double resonance (DM) to above (BUM) (Sergeev et al., 2013)

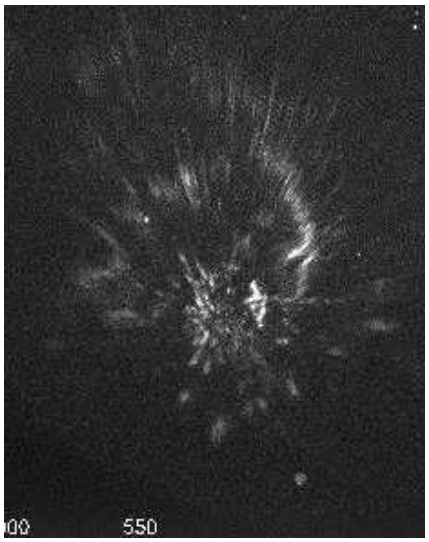

Fig. 7: Artificial aurora (Kendall SRI)

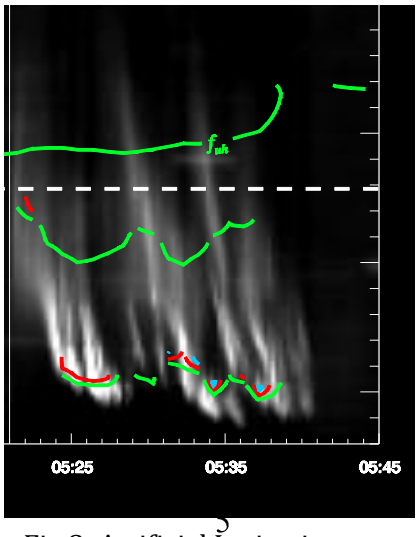

Fig.8: Artificial Ionization (Pedersen, et al. 2010)