Narrowband Stimulated Electromagnetic Emissions (SEE) spectra: a new ionospheric diagnostic technique

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Abstract

Use of high frequency (HF) heating experiments has been extended in recent years as a useful methodology for plasma physicists wishing to remotely study the properties and behavior of the ionosphere as well as nonlinear plasma processes. Our recent work using high latitude heating experiments has lead to several important discoveries that have enabled assessment of active geomagnetic conditions, determination of minor ion species and their densities, ion mass spectrometry, electron temperature measurements in the heating ionosphere, as well a deeper understanding of physical processes associated with electron acceleration and formation of field aligned irregularities. All of these diagnostic capabilities have been made possible for the first time by utilizing the narrowband Stimulated Electromagnetic Emission SEE spectrum. Narrowband SEE spectra from the High Frequency Active Auroral Research Program (HAARP) facility are presented with theoretical models to demonstrate these new capabilities along with other supporting diagnostic measurements including, range-time-intensity of FAIs (field aligned irregularities) using SuperDARN HF radar, enhanced ion lines detected by MUIR radar, DMSP satellite observations over HAARP, and coordinated observations of pump induced optical emissions.

1. Introduction

Stimulated Electromagnetic Emissions (SEEs) are secondary electromagnetic waves excited by high power electromagnetic waves transmitted into the ionosphere. A new era of ionospheric remote sensing techniques was begun after the recent update of the HF transmitter at High Frequency Active Auroral Research Program (HAARP). Increasing the maximum transmitter power up to 3.6 MW (ERP 1 GW) has allowed studying some of the parametric decay instabilities responsible for SEE which was not possible a few short years ago. The classical SEE features with frequency offset of 1 kHz up to 100 kHz have been observed and studied in detail in the 1980s and 1990s. But recent observations of narrowband SEE emission lines (within 1 kHz of pump frequency) have caused a renaissance in the field of space science and remote sensing. Sideband emissions of unprecedented strength have been reported during recent campaigns at HAARP, reaching up to 10 dB relative to the reflected pump wave which are by far the strongest spectral features of secondary radiation that have been reported. The emissions were shifted by only up to a few tens of Hertz from radio waves transmitted at several megahertz. Measuring the low frequency SEE emission line excited in the ionosphere may cause a break through in the space science field and result in the development of new remote sensing techniques.

2. New narrowband SEE diagnostic capabilities

a. Magnetized Stimulated Brillioun Scatter (MSBS): Parametric decay of ordinary mode electromagnetic wave into an electrostatic wave and a scattered electromagnetic wave by a process called Magnetized Stimulated Brillouin Scatter (MSBS) was observed for the first time in recent observation at HAARP [1-3]. Depending on the angle between the wave normal direction and the background magnetic field vector, the excited electrostatic wave could be either Ion Acoustic (IA) or Electrostatic Ion Cyclotron (EIC). These experiments have provided additional quantitative interpretation of the SEE spectrum produced by MSBS to yield diagnostic measurements of the electron temperature and ion composition in the heated ionosphere. IA emission lines appear with a frequency offset 10-30 Hz and EIC emission lines with frequency shift 50 Hz from the pump frequency. It should be noted that emission lines excited at the reflection of UH altitude appear with different frequency offset in the SEE spectra which is consistent with the MSBS matching condition. The matching conditions are applied to give a relation between the electron temperature and the SBS emission spectra. With this relation, the electron temperature in the modified ionosphere can be measured using the ion acoustic wave shifts in the SEE data. The frequency offset of EIC lines relative to the pump frequency also demonstrates a sensitive method for determining ion species. Therefore, MSBS emission lines in the SEE spectra could be used to determine ion species in the altitude rage 90-400km along with their densities, which could be a reliable complement for LIDAR and incoherent scatter radar under certain conditions. Our observations of MSBS at HAARP have shown that the growth rate for the EIC waves is much lower than the growth rate for the IA waves in the plasma near the reflection or upper-hybrid altitudes which is consistent with the theory [1, 3]. Our experiments have been designed to better characterize the conditions for initiating MSBS. In one series of experiments, the power was varied in an effort to determine the threshold for the onset of MSBS [3]. Additional experiments were designed to determine if there was any aspect sensitivity for MSBS to proximity of pump frequency to the third electron gyro-frequency [3-4]. The spectrum was experimentally found to be highly dependent on the proximity of the pump frequency to the harmonics of the electron cyclotron frequency f_{ce} which has not been investigated by current theory. The suppression of MSBS and transition to (Stimulated Ion Bernstein Scatter) SIBS lines as the heater pump frequency approaches the gyro-harmonic was observed for the first time during frequency sweeping experiments near the electron gyro-harmonics.

Enhancement of the HF pump-induced plasma line measured with a UHF diagnostic radar at HAARP shows a close agreement with narrowband SEE feature. The correlation of enhanced ion lines observed by MUIR incoherent scatter radar and narrowband SEE spectra (IA lines produced by MSBS process) as well as correlation of the DM in the SEE spectra (which is produced by upper hybrid UH waves) and SuperDARN echoes are shown in Fig.1. When persistent enhancements of the radar backscatter power appear, two case studies show that the local plasma frequency at the reflection height of the O-mode polarization wave is close to the second or third electron gyroharmonic frequencies. Therefore SEE measurement could be a good candidate for locations that ISR facilities are not available or as a complementary measurement for the waves and irregularities that cannot be observed by ISR. Broadband SEE spectra also have shown good agreement with SuperDARN echoes and could be employed to study the excitation and time evolution of FAI [4].

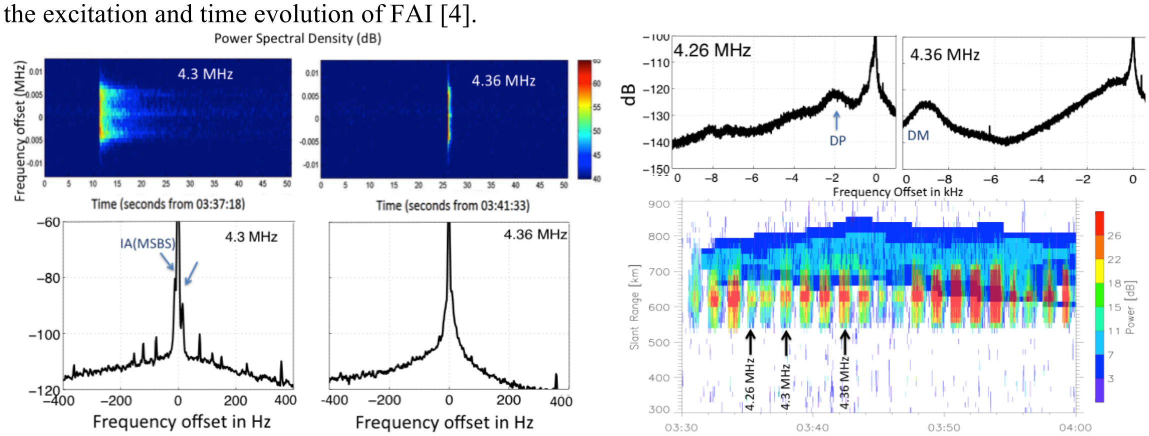

Fig. 1. a) Enhanced ion lines observed by MUIR b) Narrowband SEE spectra c) Broadband SEE spectra d) Artificial backscatter generated in the Kodiak SuperDARN radar during the heating experiment on 7 August 2012. Pump frequency was swept from 4.26 to 4.38 MHz in 0.2 MHz steps.

Artificial airglow is another phenomenon associated with ionospheric heating experiments and creation of visible artificial optical emissions. High frequency plasma waves parametrically excited during pump heating may cause acceleration of electrons. Superthermal electrons may enhance airglow emissions through the collisional excitation of neutral species or even create new plasma when their energy exceeds the ionization potential of gasses. Our recent joint SEE and airglow observation at HAARP (illustrated in Fig.2) have shown the possible role of IA MSBS waves in electron acceleration and optical emissions. Packets of short-scale (1–20 m) due to IA MSBS waves formed near the height of the upper hybrid resonance are believed to be contained within the large-scale structures. Most likely, electron acceleration and electron thermal heating inside these striations give rise to the observed 630.0 nm and 557.7 nm emissions.. Also our recent work has shown that IA waves produced through a parametric decay instability saturate in electron heating along the magnetic field. The electron kinetic energy along the magnetic field grows significantly while the IA parametric decay is developing and causes tail heating in the electron velocity distribution along the magnetic field.

b. Stimulated Ion Bernstein Scatter (SIBS): Recently there has been considerable interest in SEE with structures near harmonics of the ion gyro-frequency observed in the spectrum. O^+ gyro-harmonic structuring (~50Hz) within 1 kHz of the pump frequency has been observed for second electron gyro-harmonic heating [5] and various aspects have been explained in terms of parametric instabilities in a single component plasma [4,5]. The first observation of stimulated ion Bernstein scatter (SIBS) during the third electron gyro- harmonic heating was first reported by [4]. These emissions are attributed to Stimulated Ion Bernstein Scatter SIBS [4] which involves parametric decay of the pump field, upper hybrid/electron Bernstein and O^+ Bernstein waves at the upper hybrid layer. Characteristics of the spectrum are predicted to change from discrete harmonics to more broadband involving parametric decay into broadband oblique IA mode depending on the orientation angle of the pump field relative to the background geomagnetic field.

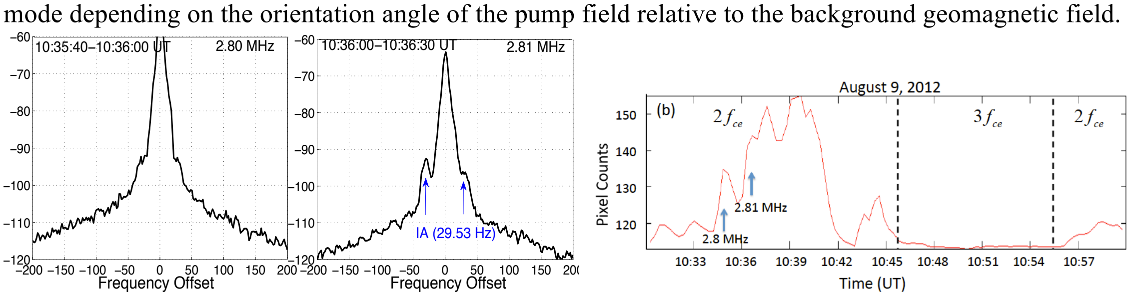

Fig. 2. a) SEE Spectra showing MSBS for P_{heater} = 3.6 MW and f_0 being tuned near $2f_{ce}$ ~ 2.76 MHz. b) average 630.0 nm intensities for the central region of the 19 FOV images over time.

c. First observations of minority ion structuring in stimulated radiation: The first observations of structuring near the H+ (proton) gyro-frequency in the SEE spectrum during second electron gyro-harmonic heating has been observed during the active ionospheric conditions (shown in Fig. 3) [6.7]. They are relatively short lived and are observed to last for as long as tens of seconds during the heating cycle, however, on occasion only for a few seconds. This is quite unusual since H^+ is a minority species and is much less than a percent of the plasma ion density under quiet conditions at heating altitudes of 160 km. However the observations were made during a period of a relatively disturbed ionosphere as indicated by disturbed magnetogram and elevated absorption thought to be associated with proton precipitation. Fig. 3(b) shows the fluxgate magnetogram and 3(c) riometer readings around the heating period with the dashed line indicating heater turn-on time. Proton precipitation was also detected during by DMSP satellite near the HAARP coordinate during this experiment as shown in Fig. 3d. Therefore, observations of ion gyro-structures ordered by the hydrogen gyro frequency (800 Hz) are postulated to be the ultimate result of proton precipitation effects at the heating interaction altitude. The new observations have shown that SEE can be employed even during proton precipitation events and active conditions as a powerful technique to asses space weather. Narrowband SEE spectra provide possibilities for further diagnostics for determining the density of minority plasma species in ionospheric plasma that have not been considered before with such SEE measurements. A three-wave parametric decay instability (PDI) of the pump wave into high-frequency upper hybrid UH/electron Bernstein and low-frequency H^+-O^+ hybrid waves in a multi- ion plasma with minority H^+ ions is proposed as a possible process for the generation of the narrowband emission lines in the SEE at the upper hybrid interaction altitude [4,6,7]. Numerical solution of the dispersion relation and growth rate of H^+-O^+ hybrid mode PDI is shown in Fig 3.e and for different percentages for H^+ ions. As can be seen, hydrogen densities (n_H/n_i) 4-5% appear to produce a reasonably consistent with the frequency shift in the experimental observations.

3. Conclusion

Data from four recent research campaigns at the HAARP facility is presented in this paper. These experiments have provided additional quantitative interpretation of the SEE spectrum produced by MSBS to yield diagnostic measurements of the electron temperature and ion composition in the heated ionosphere. The sensitivity of IA and EIC lines with different parameters was investigated in this work to get a better estimation of electron temperature and ion composition using emission lines produced by the MSBS process. The correlation of MSBS IA lines with enhanced ion lines in ISR spectra has been observed. Evidence of good correlation between SuperDARN backscatter and SIBS is observed when the pump frequency is in the vicinity of $3f_{ce}$ which implies UH waves as a driving source for SIBS. Simultaneous observation of MSBS and airglow during heating near $2f_{ce}$ is presented which shows a correlation with the strength of optical emissions. This could shed light on the physical processes associated and role of IA waves in electron precipitation and formation of artificial field alighted irregularities FAIs. Narrowband emissions ordered near the H^+ (proton) gyro-frequency (f_{cH}) were reported in SEE spectrum during active geomagnetic conditions. Impact of active geomagnetic conditions on the SEE spectrum and capabilities of SEE spectra for interrogation of possible proton precipitation is discussed. The frequency offset of hydrogen emission lines along with the theory were used to estimate the density of minor ion species. All of the examples discussed here underscore the tremendous future potential of Narrowband SEE as a powerful untapped ionospheric diagnostic.

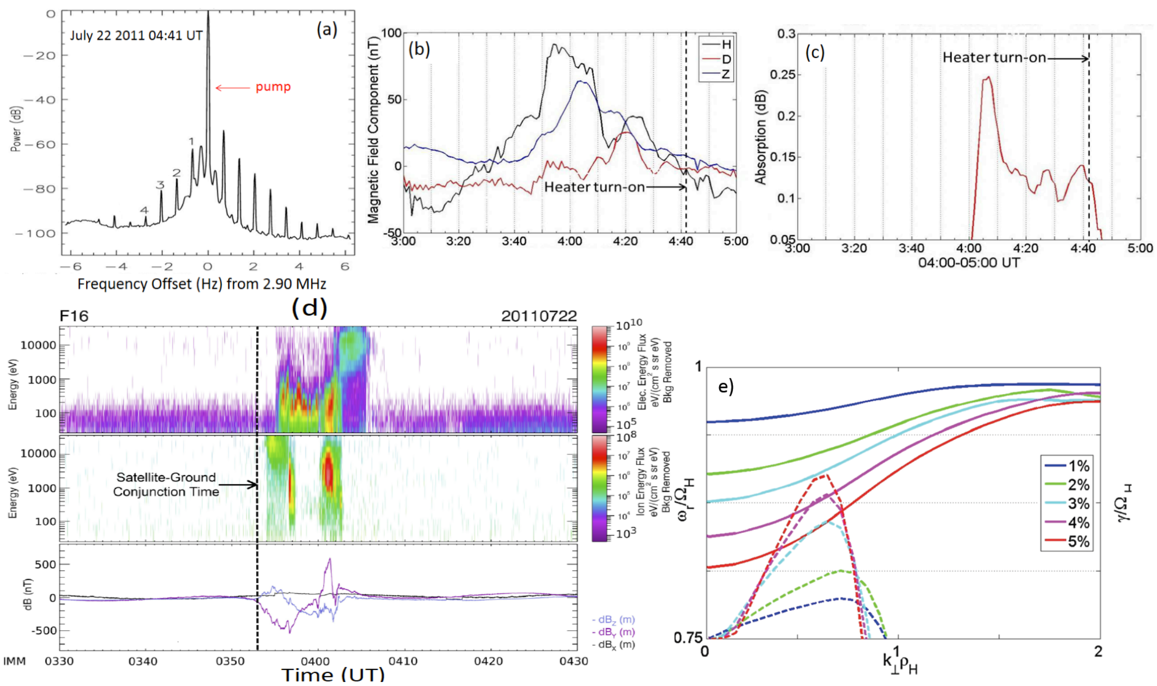

Fig. 3. (a) SEE spectrogram showing emissions lines at harmonics of a frequency slightly less than Ω_H. (b) fluxgate magnetometer and (c) riometer located at Gakona, AK on July 22, 2011. (d) DMSP-16 satellite data. (e, f) PDI growth rate and dispersion relation.

4. References

1. Bernhardt, P. A., et al., (2010), "Stimulated Brillouin scatter in a magnetized ionospheric plasma", Phy. Rev. Lett., 104, doi: 10.1103/Phys-RevLett.104.165004.

2. Fu, H., W. A. Scales, P. A. Bernhardt, A. Samimi, A. Mahmoudian, (2013), "Stimulated Brillouin scatter and stimulated ion Bernstein scatter during electron gyroharmonic heating experiments", Radio Sci., 48.

3. Mahmoudian, A., et al., (2013), "Investigation of ionospheric stimulated Brillouin scatter generated at pump frequencies near electron gyroharmonics", Radio Sci., 48, doi:10.1002/2013RS005189.

4. Mahmoudian, et al., (2013), "Ion gyro-harmonic structuring in the stimulated radiation spectrum and optical emissions during electron gyro-harmonic heating", J. Geophys. Res. Space Physics, 118,1270-1287.

5. Bernhardt, P. A., et al., (2011), "Electron and ion Bernstein waves excited in the ionosphere by high power EM waves at the second harmonic of the electron cyclotron frequency", Geophys. Res. Lett., 38.

6. Bordikar, M. R. et al. (2013), "First observations of minority ion (H^+) structuring in stimulated radiation during second electron gyroharmonic heating experiments, Geophysical Research Letters", 40.

7. Bordikar, M. R., W. A. Scales, A. Mahmoudian, et al. (2014), "Impact of active geomagnetic conditions on stimulated radiation during ionospheric second electron gyroharmonic heating", J. Geophys. Res., 119.