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Results of Artificial Ionospheric Turbulence Studies Using the ISR and SEE Techniques at the Arecibo Low-Latitude Heating Facility

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Abstract

We report preliminary results of the Arecibo heating campaign in November 2018. Different methods for studying artificial plasma turbulence were used concurrently, namely the incoherent scattering radar (ISR) and stimulated electromagnetic emission (SEE) techniques. The aim of the experiments was analyzing HF-induced plasma turbulence evolution for short and long time of ionosphere modification above the low-latitude heating facility in view to investigate a competition between the Langmuir and upper-hybrid plasma turbulence.

1 Introduction

Results of artificial ionospheric turbulence studies at a low latitude heating facility at the Arecibo Observatory (Puerto Rico, USA) on November 7-8, 2018 using ISR technique are presented. Simultaneously, the SEE measurements were made, the results of which are presented in [1]. Note that the only experiment to date on simultaneous the SEE and ISR measurements has been carried out long time ago [8]. Since that the RF measurement technique have stepped far forward. In addition, a huge amount of results was accumulated in radar experiments, which for the most part received a fairly adequate interpretation [2]-[6]. In this regard, the conduct of new joint measurements is of undoubted interest.

2 Experimental Setup

The ionosphere was heated by powerful radio wave of ordinary (O) polarization with an effective radiated power $ERP \approx 100$ MW vertically at a pump wave (PW) frequency $f_{\rm PW} = 5095$ kHz for various radiation modes (see Fig. 1): 1) short pulses with low duty cycle ($\tau_i = 5-100$ ms, $T_i = 2-20$ s, "cold start" mode) to study the formation of Langmuir turbulence and 2) quasi-continuous pumping ($\tau_i = 165$ ms, $T_i = 200$ ms) with a pulse train duration of 1–150 s and simultaneous sounding by diagnostic pulses ($\tau_i = 0.2-10$ ms , $T_i = 0.2-1$ s) for studying the processes of transition from the Langmuir to upper hybrid plasma turbulence. The incoherent scattering radar pulses with a duration of 440 μs modulated by the long random code with a repetition period $T_r = 10$ ms at a carrier frequency $f_{\rm R} = 430$ MHz, in accordance with the scheme proposed in [2]. The delays of these pulses with respect to the pump wave start varied from 2.2 ms to 7.8 ms, which made it possible to study the evolution of the signal scattered by plasma turbulence at different stages of its development.

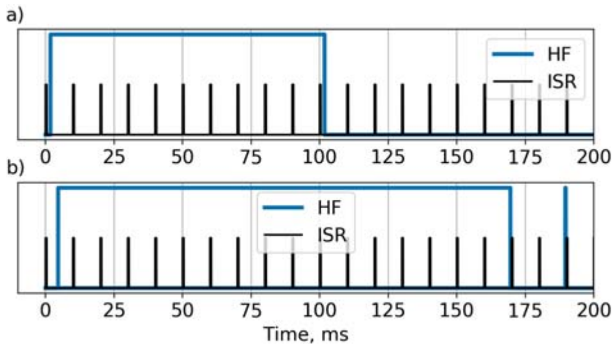

Figure 1. The example of the radiation modes of the heating facility and incoherent scattering radar used in the experiment.

3 The ISR measurements

As a result of the spectral analysis of the scattered radar signals, followed by averaging the data, the electron density profiles and artificial plasma line spectra (signals scattered by plasma waves) with a spatial resolution of 300 m were obtained. For the short PW pulse radiation modes (5-100 ms, Fig. 1, panel a), scattered signal spectra were plotted relative to the central frequencies $f_\pm = f_{\rm R} \pm f_{\rm PW}$ for the plasma lines shifted down ($-$) and up ($+$) with respect to $f_{\rm R}$. In this case, the frequency shift $\Delta f_\pm$ of the scattered signal frequency f from the central frequencies $\Delta f_\pm = f - f_\pm$ corresponds to the shift of the plasma wave frequency $f_{\rm PL}$ from $f_{\rm PW}$. In Fig. 2 the results of such an analysis for the pulse emission regime with $\tau_i = 100$ ms, $T_i = 20$ s are shown.

Together with the ionograms obtained by the unperturbed ionosphere sounding before start of the heating, the Figure shows the artificial plasma lines shifted up and down near the frequencies $f_{\rm R} = 430$ MHz, $f_+ = 435.095$ MHz and $f_- = 424.905$ MHz, respectively.

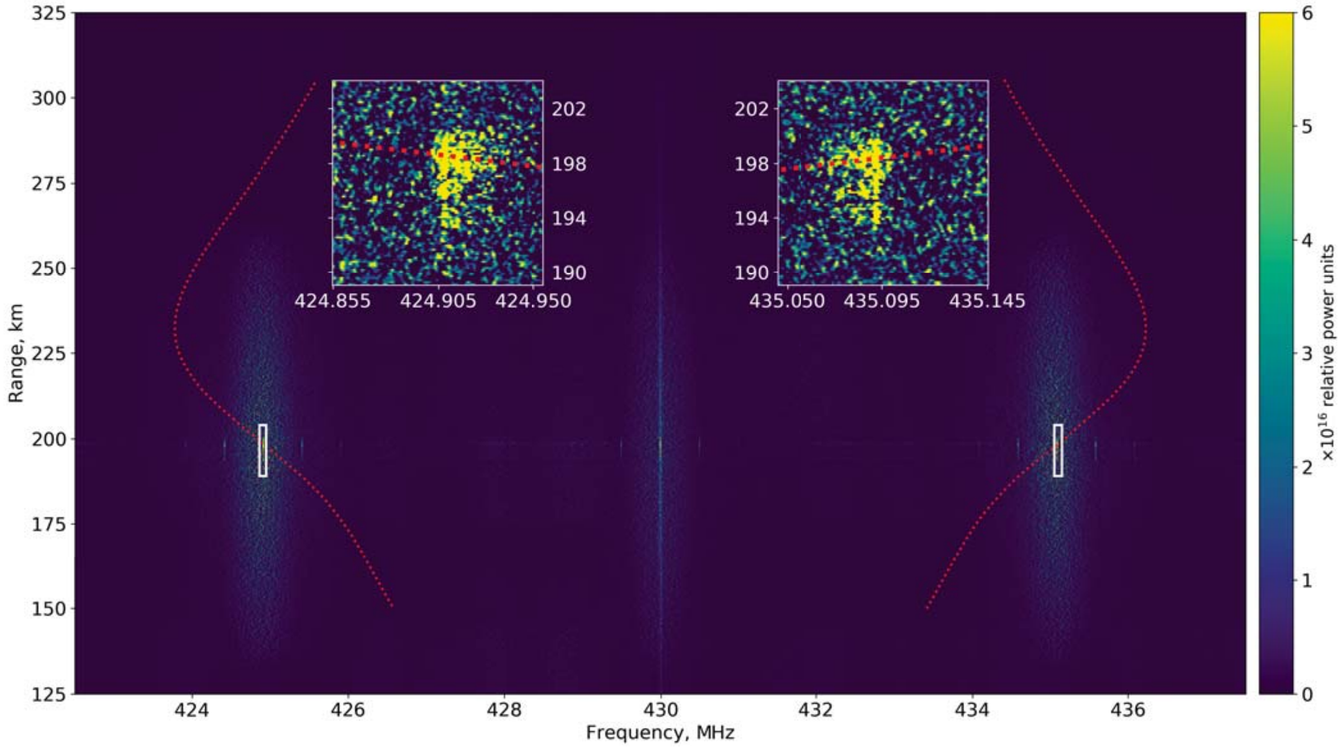

Figure 2. Electron density profile and spectrogram of artificial ion and plasma lines (downshifted plasma line on the left, upshifted plasma line on the right for 98.2 ms of pumping). Separate panels show the region of generation of the plasma line with a high frequency-altitude resolution. 11/08/2018, 15:51:00-16:11:30 LT.

In Fig. 3 the results of more detailed analysis of the plasma line spectra evolution for different heights and times the pump pulse beginning for low duty cycle program with $\tau_i = 100$ ms and $T_i = 20$ s are presented.

At the stage of the Langmuir turbulence development, it was found that the maximum intensity in the spectrum of plasma waves is observed at zero shifts from $f_{\rm PW}$, $\Delta f_{\rm PL} = f_{\rm PL} - f_{\rm PW} = 0$ at 2-6$^{\rm th}$ ms of pumping, and the spectra themselves are of the "continuum" type in the negative shift range, $\Delta f_{\rm PL} = f_{\rm PL} - f_{\rm PW} < 0$ at heights near the PW reflection level. With an increase in the heating duration to 12–20 ms, the decay type spectra with pronounced maxima (satellites) at – 12 kHz< $\Delta f_{\rm PL}$ < – 2.5 kHz are developed.

A comparison of the integral intensity of the plasma line for $\tau_i = 10$ and 50 ms with one in 2.2 ms after the PW pulse switching off made it possible to determine the plasma line relaxation time, which amounted to $\tau_{\rm rel} \sim 0.5$ ms. This indicates that damping of plasma waves in colissionless with a rate $\gamma = \tau_{\rm rel}^{-1} \sim 2000\ {\rm s}^{-1}$, since the collisional damping rate does not exceed $\nu_{\rm e} \sim 500 - 1000\ {\rm s}^{-1}$. Note that the relaxation of different spectral components occurs with different rates, slowing down with an increase of the $|\Delta f_{\rm PL}|$. As a result, at the relaxation stage, flattening and even inversion of the plasma wave spectrum can be observed.

With an increase in the PW pulse duration, the altitude range occupied by the generation of Langmuir plasma waves increases from 1 km for $\tau_i = 5$-–10 ms to 2.5 km for $\tau_i = 100$ ms. In general, the data for the stage of the Langmuir turbulence development are consistent with the previous results at the Arecibo facility [3]-[5].

According to [5]-[6], with an increase in the pumping duration to seconds or minutes, the plasma turbulence region expands downward from the PW reflection level up to the heights of the upper hybrid resonance and lower. In our experiments, for long ($\sim$ 2.5 min.) pumping, an expansion of the altitude region of plasma wave generation up to 5-7.5 km (up to 15 km for pumping near the critical frequency of the F2 layer) and its stratification are observed. The time-altitude dynamics of downshifted plasma line development during the first 15 seconds of quasi-continuous pumping is shown in the Fig. 4. Two regions of plasma line excitation were observed with the intensity maxima at the heights $h_1 = 214$ km and $h_2 = 210.8$ km. In the upper region, near the PW reflection level, the decay-type spectra with intensity maxima were observed at 1$^{\rm st}$-2$^{\rm d}$ seconds of pumping. Intensity of such spectra weakened to 14-15$^{\rm th}$ seconds of pumping. In the lower region (at the heights near and below the upper hybrid resonance), the plasma line was amplified to 14-15$^{\rm th}$ s. Here the spectra look as broadband maxima in the range ($-40 < \Delta f_{\rm PL} < +10$) kHz with a peak intensity at $\Delta f_{\rm PL} \approx -10$ kHz.

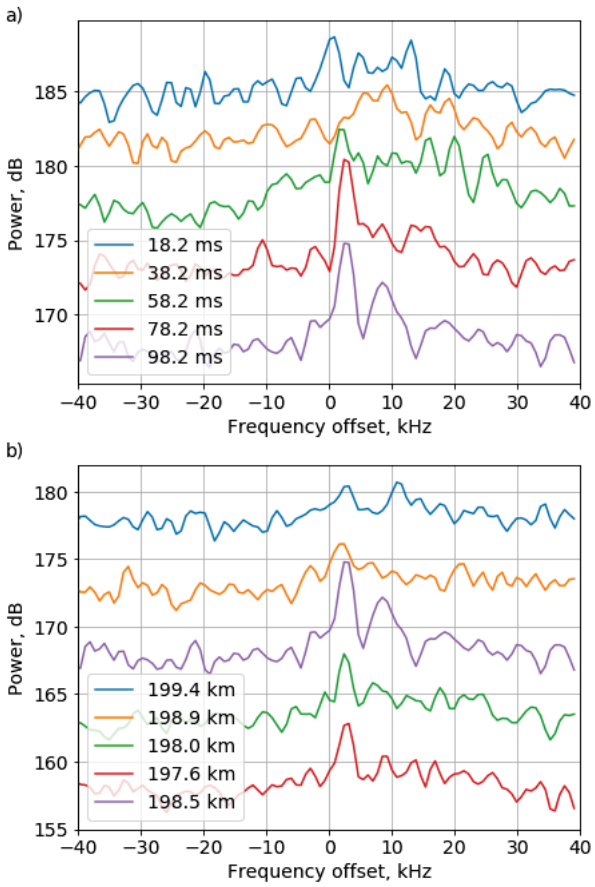

Figure 3. The dynamics of the downshifted plasma line spectra at the stage of Langmuir turbulence development for different pumping times with a step of 20 ms at a fixed height $h = 198.5$ km (panel a)) and the altitude distribution with a step of 450 m of spectral intensity towards the end of the PW pulse $t = 98.2$ ms (panel b)). Averaging over 50-55 PW pulses was carried out. An additional shift of each of the spectra by 5 dB was used. 11/08/2018, 15:51:30-16:11:30 LT.

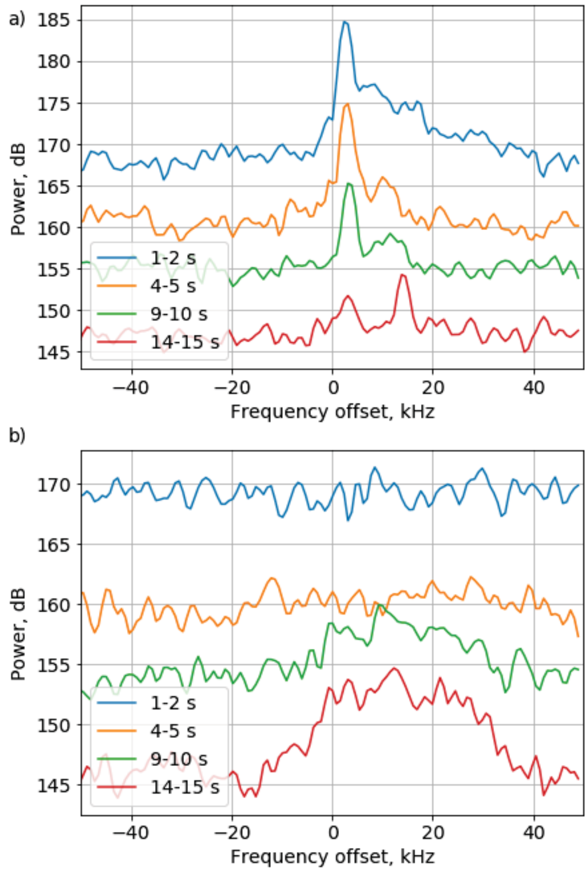

Figure 4. The dynamics of the development of the downshifted plasma line spectra during prolonged quasi-continuous heating for different exposure times (time shift ~ 5 s) at two fixed heights $h_1 = 214$ km (panel a)) and $h_2 = 210.8$ km (panel b)). Averaging over 50-55 PW pulses was performed out. An additional shift of each spectra by 5 dB was used. 11/08/2018, 17:46:00-17:46:15 LT.

4 The SEE measurements

An analysis of the concurrent measurements of the SEE and signals of incoherent scattering can substantially clarify details of ionosperic plasma turbulence excitation. Such experiments were performed at Arecibo [1, 8], HAARP [7] and EISCAT [9] heating facilities.

The first such comparison was performed in [8] for $f_{\mathrm{PW}} =$ 3125 kHz at the initial stage pumping and had shown a similarity of the plasma line and SEE spectra up to 50 ms. Examples of SEE spectra at the initial (short pulse) stage of pumping and during long heating for experiments presented are shown in Fig. 5. Our measurements of the plasma line and SEE also show a similarity of the main spectral characteristics of the plasma line and SEE (the continuum shape of spectra with a widths up to 30-40 kHz) at the stage of Langmuir turbulence development during first 100 ms. During longer quasi-continuous heating, the formation of the main upper hybrid SEE feature, such as the Downshifted Maximum (DM) at $\Delta f_{\mathrm{DM}} = f_{\mathrm{DM}} - f_{\mathrm{PW}} \approx -(8...11)$ kHz, correlates with the observed characteristics of the development of the broadband maximum of the plasma line in the lower part of the plasma turbulence region. However, the spectral shape of the SEE and scattered signals differ noticeably. Since the data of radar sensing provide information on only one of the components of the spatial spectrum of plasma waves, (wavelength $\lambda_{\mathrm{PL}} = 35$ cm for Arecibo radar), it is difficult to expect full compliance with the SEE measurements, since SEE generation and ground based reception are determined by the integral influence of the entire spatial spectrum of plasma waves.

5 Summary

During concurrent measurements of the pump-induced plasma line and SEE it was established the following.

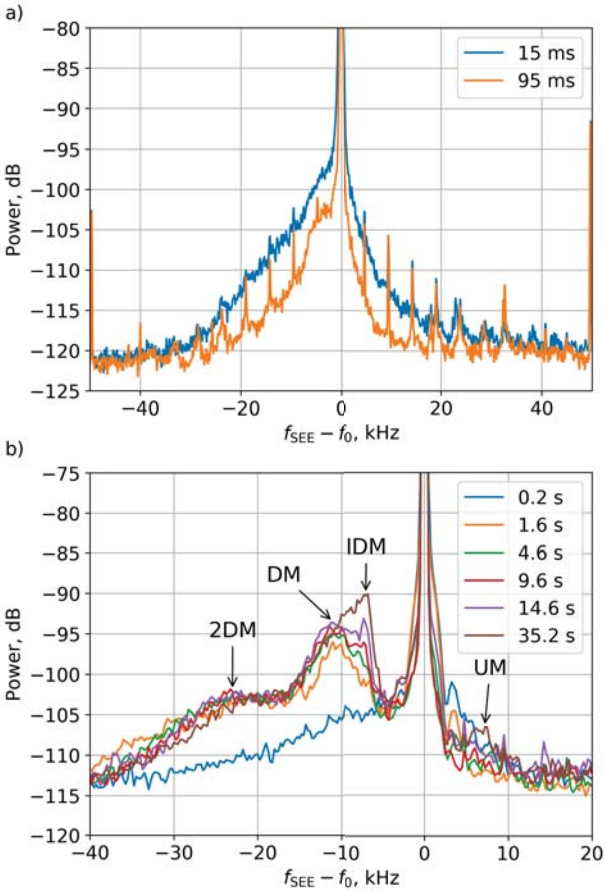

Figure 5. The panel (a): an example of the narrow-band ponderomotive narrow continuum SEE feature for the 15th and 95th ms of pumping, 55 pulses are averaged, the frequency resolution is 100 Hz. The panel (b): an example of the SEE spectra dynamics for a quasi-continuous radiation mode, the frequency resolution of 250 Hz. The sequential development of the Downshifted Maximum DM ($\Delta f = -11$ kHz), the second DM (2DM), and, after 30 s, intermediate DM (IDM) ($\Delta f = -8$ kHz) SEE components is clearly visible. The data of 11/08/2018. For nomenclature of the SEE features see [7].

1. With increasing pump time from milliseconds to hundred of milliseconds, a transition from the continuum plasma line spectra to decay type spectra is observed while the SEE is kept in continuum shape, and the SEE intensity decreases.
2. From 1st–2d to 10th seconds the plasma line decay spectra generated near the PW reflection point weaken and even drop till 15th second. In the same time the broadband plasma line maximum at lower (by ~ 3) km altitudes and well structured SEE spectra with well pronounced upper hybrid components develop. This points, most probably, for shielding the region of Langmuir turbulence generation near the PW reflection point by upper hybrid turbulence.
3. The relaxation process of plasma waves and SEE is accompanied by a flattening of their spectra and, as a rule, is collisionless with rates $\gamma > \nu_e$.

6 Acknowledgements

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