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SPECTRAL FEATURES OF IONOSPHERIC PLASMA WAVES EXCITED BY POWERFUL HF RADIO WAVES RADIATED AT FREQUENCIES NEAR ELECTRON GYROHARMONICS AND F2-LAYER CRITICAL FREQUENCY

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Abstract. We present the result of the studies into characteristics of high-latitude ionospheric F-region longitudinal plasma waves (Langmuir and ion-acoustic), caused by the impact of powerful HF radio waves of ordinary (O-mode) or extraordinary (X-mode) polarization of the EISCAT/Heating facility, Tromsø, Norway. The powerful HF radio waves on October 20, 2012 and February 26, 2013 were emitted in the direction of the magnetic zenith with a step change in the effective radiation power (*ERP*). The radiation frequency f_H of the EISCAT/Heating facility on February 26, 2013 was close to the F2-layer critical frequency f_oF2 (f_H/f_oF2~1) and exceeded the electron gyroresonance frequency f_H>5f_{ce}. On October 20, 2012, the conditions f_H/f_oF2~0.85–0.95 and f_H<6f_{ce} were fulfilled. Analysis of EISCAT measurements of an incoherent scatter radar (ISR) at a frequency of 930 MHz, spatially aligned with the heating facility for radiation conditions *ERP*<200 MW, has shown that parametric decay instabilities are excited at the ionospheric heights where the pump frequency is close to the plasma Langmuir frequency, f_H≈f_{PL}. We have studied peculiarities of excitation of the decay parametric instabilities as a function of height in the ionosphere and pump wave polarization, the ratios between f_H and f_oF2, and also f_H and nf_{ce}.

Keywords: high-latitude ionosphere, F-region, powerful HF radio wave, Langmuir wave, ion-acoustic wave, incoherent scatter, EISCAT.

INTRODUCTION

The article is sequel to an earlier article [Borisova et al., 2023], in which from experiments at the HF heating facility EISCAT/Heating we have determined generation conditions and threshold (minimum) values of the pump wave electric field in the ionospheric F-region, which are necessary to form channels of enhanced electron density E_{ionNe}, to generate plasma Langmuir and ion-acoustic waves E_{ionPL} and E_{ionIL} at O- and X-mode heating. The minimum values of the electric field of a powerful HF radio wave E_{ion} were calculated taking into account the non-deflective absorption along the pump wave propagation path.

The current status of research on the excitation of various parametric decay instabilities such as periodic decay instability (PDI), oscillating two stream instability (OTSI) [Gurevich, 2007; Robinson, 1989], and thermal parametric (resonance) instability (TPI) [Vaskov, Gurevich, 1979; Grach et al., 1977; Stubbe, 1996] during experiments on the modification of the ionosphere by powerful HF radio waves is discussed in [Borisova et al., 2023]. The development of PDI and OTSI are directly identified in incoherent scatter radar spectra as HF-induced plasma lines (HFPL) and HF-enhanced ion lines (HFIL), which is a reliable indicator for the excitation of field-aligned plasma waves (Langmuir and ion-acoustic).

The purpose of this work is to study spectral features of plasma waves (Langmuir and ion-acoustic), using EISCAT radar data, and to examine the dependence of the effects of artificial ionospheric turbulence generation on height in the ionosphere. Artificial turbulence features were analyzed using experimental data on ionospheric F-region modification by powerful HF radio waves of ordinary and extraordinary polarizations given that f_H is close to f_oF2 with a stepwise change in *ERP* of the heating facility. General description of the experiments is given in [Borisova et al., 2023].

1. OBSERVATIONAL RESULTS

Using EISCAT observations made by an IS radar (930 MHz) [Rishbeth, van Eyken, 1993], we have analyzed conditions and characteristics of excitation of plasma Langmuir and ion-acoustic waves at F-layer heights in the high-latitude ionosphere during experiments carried out at the EISCAT/Heating facility on February 26, 2013 and October 20, 2012 [Rietveld et al., 2016]. On February 26, 2013, a powerful HF radio wave was emitted at a frequency f_H=7.1 MHz, close to the F2-layer critical frequency (f_H/f_oF2~1), with f_H being higher than the frequency of the fifth electron gyroharmonics (f_H>5f_{ce} by 0.26 MHz). In another experiment (October 20, 2012), the frequency f_H=7.953 MHz was used, which is below f_oF2 (f_H/f_oF2~0.89–0.94) and below the frequency of the sixth electron gyroharmonics (f_H<6f_{ce} by 0.187 MHz). In both experiments, the radiation was emitted in cycles: 10 min heating; 5 min pause. The effective radiated power *ERP* varied in a stepwise manner during the heating cycle.

Using the Grand Unified Incoherent Scatter Design and Analysis Package (GUISDAP) [Lehtinen, Huuskonen, 1996], we calculated intensities of spectral maxima of plasma Langmuir S_{PL} and ion-acoustic S_{IL} waves at t (UT) of the experiments considered and in the height range from 150 to 278 km. Integration of radar data was performed with a time step of 30 s and a height step of 3 km. Note that during the EISCAT experiments the radar in the high-frequency measurement channel detected plasma waves downshifted relative to the radar frequency (downshifted plasma lines) (in Figures, the frequencies are marked with minus ("–")). Graphical representation of the integration results was performed in MatLab.

The development of PDI and OTSI at ionospheric heights near the reflection altitude of a powerful HF radio wave is accompanied by the occurrence of ion-acoustic and Langmuir turbulences. The IS radar through spectral measurements in the low-frequency range detects HF-enhanced ion-acoustic lines (HFIL); and in the high-frequency range, HF-induced plasma lines (HFPL). For a plasma in thermal equilibrium, the signal spectrum in a low-frequency region generally has two spectral intensity maxima S_{IL}: downshifted ion lines S_{ILD} and upshifted ion lines S_{ILU}, which correspond to ion-acoustic waves shifted from the radar frequency to positive and negative sides. Under conditions of OTSI excitation, nonshifted ion lines S_{IL0} increase. The Doppler shift of S_{IL} relative to zero in the spectrum $S_{IL}(f)$ depends on radar radiation frequency and ion sound velocity. The Doppler shift for the EISCAT radar at F-region heights is approximately $f_{IA}=\omega_{IA}/(2\pi)\approx 10$ kHz. For ionospheric parameters characterizing average background conditions of the ionospheric F layer over the heating facility during the daytime (for example, T_e=1700 K and T_i=1000 K), we have f_{IA}~9.5 kHz. During heating experiments, T_e rises are observed in the F layer. Under these conditions, for the ionospheric parameters (T_e=2500 K and T_i=1200 K) f_{IA} increases to ~10.8 kHz.

Figure 1 presents the results of spectral processing of IS radar signals registered on October 20, 2012 from 13.30 to 14.30 UT in the form of altitude-temporal distributions of spectral maxima of Langmuir waves $S_{PL}(t, h)$ (Figure 1, *a*) and ion-acoustic waves $S_{ILD}(t, h)$, $S_{IL0}(t, h)$, $S_{ILU}(t, h)$ (Figure 1, *b*, c, *d*). The EISCAT/Heating facility emitted powerful HF radio waves at f_H=7.953 MHz of O or X polarization into the high-latitude F-region toward the magnetic zenith with a stepwise change in *ERP*. The values of S_{PL} and S_{IL} are given in relative units (r.u.) on a logarithmic scale. Variations in the pump wave electric field in the ionosphere E_{ion}, calculated taking into account absorption in underlying layers [Borisova et al., 2023], and polarization of a heating signal are shown in Figure 1, *e*. During X-mode HF heating cycles, the HFPL excitation altitude increases (Figure 1, *a*). A feature of X-mode heating was an enhancement of S_{IL0} (Figure 1, *c*), which indicates the excitation of OTSI in the resonance region. This effect has previously been observed in [Blagoveshchenskaya, 2020]. The intensities S_{ILD}, S_{IL0}, S_{ILU}, and S_{PL} during X-mode heating cycles are by an order of magnitude higher than S_{IL} and S_{PL} during O-mode heating cycles. Analysis of Figure 1 indicates that at the moments when the heater was switched on for the O-mode pump wave there were "overshoot" effects — short-term bursts of intensities of scattered signals S_{IL} and S_{PL} (<200 ms), which are a typical manifestation of PDI according to the IS radar data at O-mode heating [Kuo, Lee, 2005]. No overshoot effects were observed during X-mode heating. Previous studies have shown that even at a maximum effective radiated power of X-mode pump wave, manifestations of HFIL and HFPL began only 10–20 sec after a transmitter of the heater was switched on [Borisova et al., 2017; Blagoveshchenskaya, 2020].

Figure 2 illustrates intensity distributions of plasma wave spectral maxima in the ionosphere for the heating experiment on February 26, 2013 at 12.30–13.30 UT. The heater emitted radio waves at f_H=7.1 MHz. Altitude-time distributions $S_{PL}(t, h)$ (*a*), $S_{ILD}(t, h)$ (*b*), $S_{IL0}(t, h)$ (*c*), and $S_{ILU}(t, h)$ (*d*) are given in the altitude range 190–265 km. Heating cycles, variations in the pump wave field in the ionosphere E_{ion} with *ERP* changing every minute, and wave polarization are shown in Figure 2, *e*.

In the experiment on February 26, amplitudes of natural Langmuir waves at altitudes near the F2-layer maximum were S_{PL}~1.0–1.5 r.u. When analyzing high-frequency radar data under conditions f_H~f_oF2, we took S_{PLfon}~1.6 r.u. as a background value. Background values for the low-frequency range were S_{ILfon}~70–80 r.u.

Analysis of S_{IL} and S_{PL} (Figure 2) suggests that at the moments when the heater was switched on there were very weak overshoot effects for the O-mode pump wave, the spectral amplitudes of S_{IL} and S_{PL} were comparable to S_{PLfon} and S_{ILfon}. S_{PL} signals were recorded at altitudes close to the F2-layer maximum and had amplitudes S_{PL}~1.8–1.9 r.u. There no overshoot effects at X-mode heating.

Particularly noteworthy is the behavior of the altitude of Langmuir wave excitation at O-mode heating. After the initial manifestation of S_{PL}, as *ERP* increased to ERP_{max}, the height h_{PL} of excitations of S_{PL} decreased; and, as *ERP* decreased in the second half of the cycle, h_{PL} increased more slowly. The values of S_{PL} with an increase in *ERP* during the 12.31–12.41 UT cycle increased from 3 to 200 r.u.; and during the 13.01–13.11 UT cycle, from 7 to 450 r.u. With a decrease in *ERP*, S_{PL} decreased.

A special character of excitations of S_{IL} and S_{PL} was observed during the 13.01–13.11 UT O-mode heating cycle, when the conditions $f_o\mathrm{F2}<f_H<f_x\mathrm{F2}$ (f_oF2~7 MHz) were met, where f_xF2 is an extraordinary critical frequency of the F2 layer. During this cycle, the S_{ILD}, S_{ILU}, and S_{PL} amplitudes increased sharply. Another characteristic feature of the 13.01–13.11 UT cycle at maximum radiated power ERP_{max} was the excitation of HFPL at h_{PL}~247–255 km (above the F2-layer maximum, h_mF2~237–242 km) with amplitudes S_{PL}~20–100 r.u.

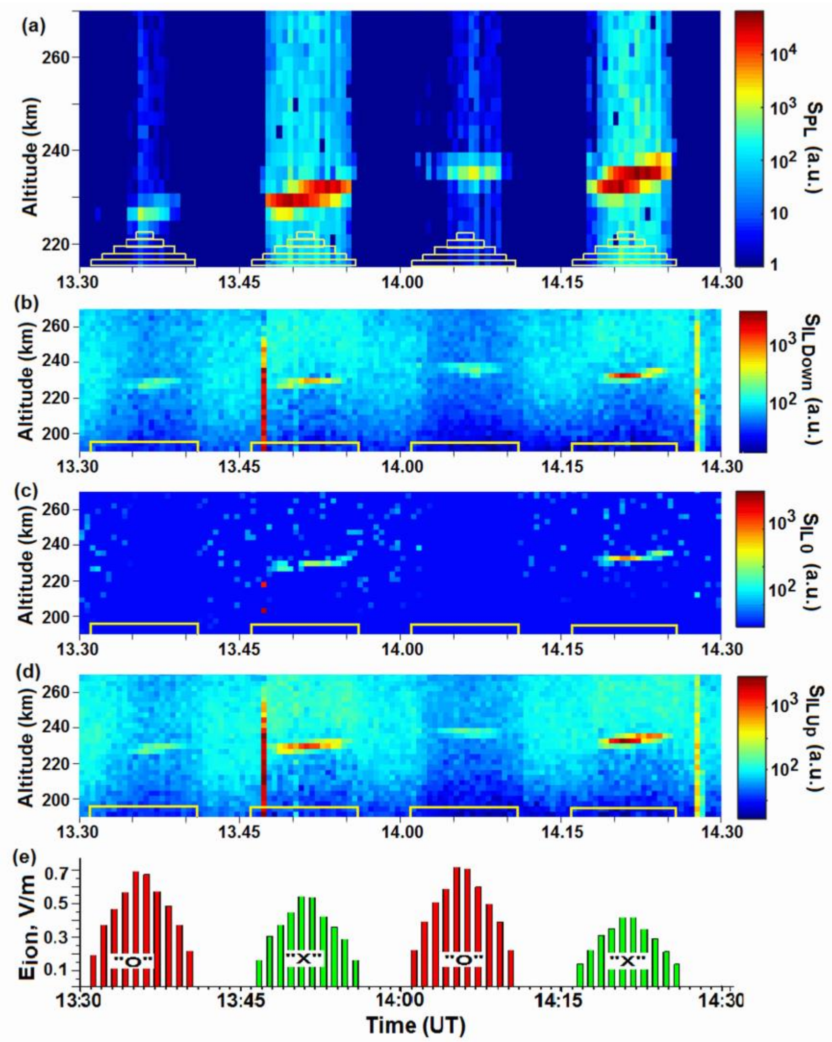

Figure 1. Altitude-time distributions of intensity maxima of plasma (Langmuir) and ion-acoustic spectral lines on October 20, 2012: S_{PL} (*a*); S_{ILD} (*b*); S_{IL0} (*c*); S_{ILU} (*d*) in the altitude range of 190 to 270 km; variations in the calculated pump wave electric field in the ionosphere E_{ion} and heating signal polarization (*e*)

Figure 3 plots variations in height $h_{\mathrm{PL}}(t)$ and spectral intensities $S_{\mathrm{PL}}(t)$ of Langmuir waves generated by heating by powerful HF radio waves of the EISCAT/Heating facility on February 26, 2013.

Another difference at O-mode heating under conditions f_{H}~f_{o}F2 (in both cycles) was also the excitation of spectral maxima S_{PL} at frequencies shifted from f_{H} toward an increase in frequency by 200–400 kHz (see Figure 4, *a3* and Figure 1, *d* in [Borisova et al., 2023]). The S_{PL} intensities at the outshifted frequencies were comparable or exceeded S_{PL} near pump frequencies.

At X-mode heating (see Figure 2, *b*) there were two S_{ILdown} tracks spaced by 10–20 km apart. The lower altitude is close to the reflection altitude of the X-mode pump wave; the upper altitude, to the altitude of the upper hybrid resonance h_{UH}, at which the condition holds

$$f_{\mathrm{H}} \approx f_{\mathrm{UH}} = \sqrt{f_{\mathrm{pe}}^2 + f_{\mathrm{ce}}^2},$$

where f_{UH} is the frequency of the upper hybrid resonance; f_{pe} is the local frequency of ionospheric plasma; f_{ce} is the electron gyrofrequency. The effect has previously been observed in [Blagoveshchenskaya, 2020]. During the X-mode heating cycles at ERP_{max}, S_{IL0} values were recorded which indicated the excitation of OTSI. The Langmuir wave amplitudes S_{PL} at X-mode heating varied from 4 to $4{\cdot}10^4$ r.u., as *ERP* increased during the cycle, and were recorded at a constant altitude. The S_{PL} and S_{IL} intensities at X-mode heating were by an order of magnitude higher than during O-mode heating cycles. No S_{PL} maxima were observed at outshifted frequencies during X-mode heating cycles.

Figure 4, *a*, *b* displays VS ionograms obtained on February 26, 2013 for the time moments before the start of O- and X- mode heating cycles 12.31–12.41 UT and 13.16–13.26 UT respectively. Distributions of ionospheric Langmuir frequencies with height $S_{\mathrm{PL}}(f, h)$, plotted from measurements made in the high-frequency channel of the IS radar on February 26, 2013, are given for 12.31.00 UT (undisturbed ionosphere before the start of O-mode heating, *ERP*=0 MW) (panel *a1*) and 12.33.00 UT (during the radiation period *ERP*=190 MW, E_{ion}~0.34 V/m) (panel *a2*). Panels *b1* and *b2* show distributions $S_{\mathrm{PL}}(f, h)$ of the undisturbed ionosphere at 13.15.58 UT before the start of an X-mode heating cycle

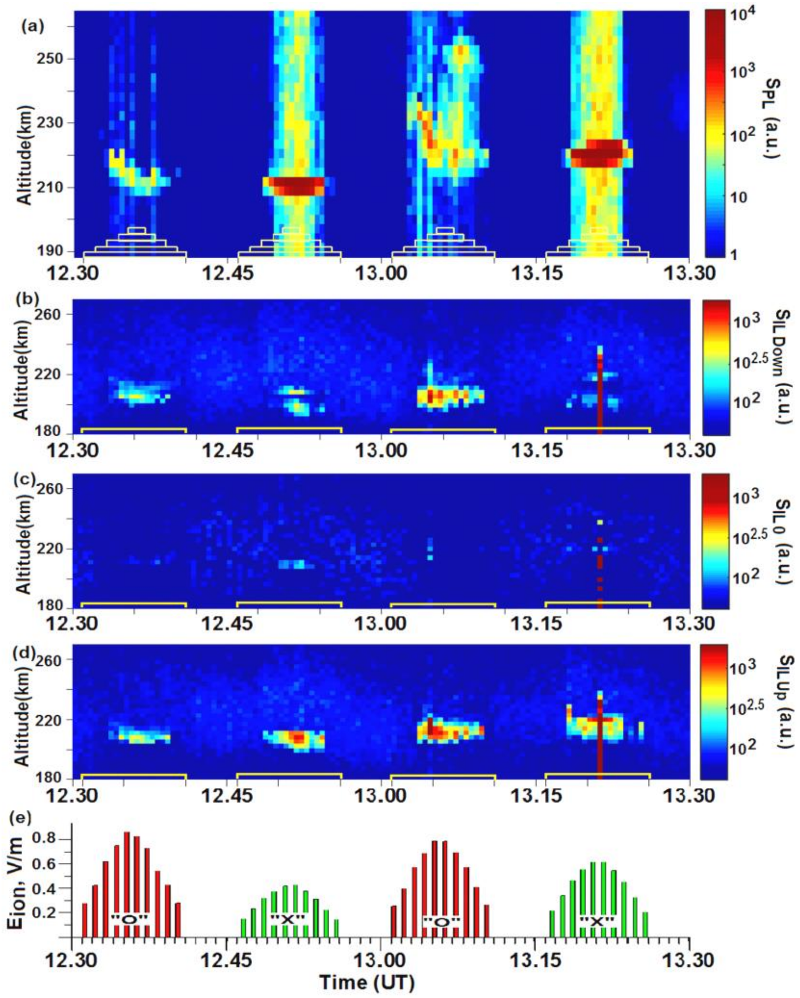

Figure 2. Altitude-time distributions of intensity maxima of plasma (Langmuir) and ion-acoustic spectral lines on February 26, 2013: S_{PL} (*a*); S_{ILD} (*b*); S_{IL0} (*c*); S_{ILU} (*d*) in the altitude range 180–270 km; histogram (*d*)

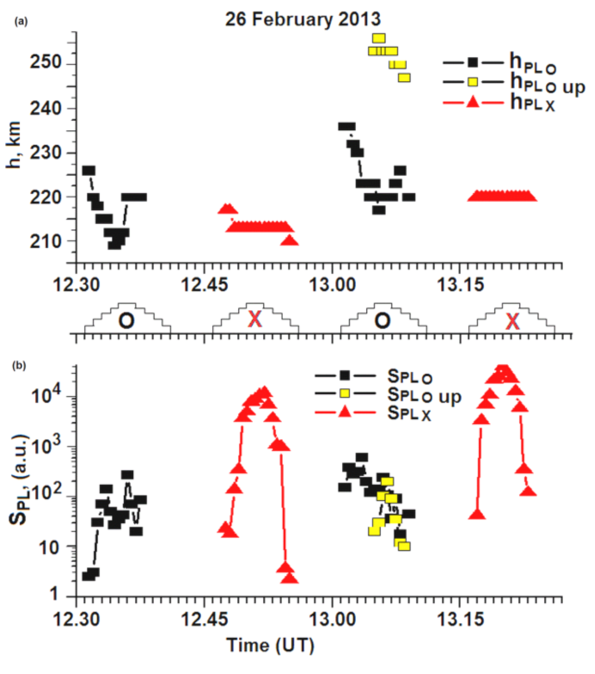

Figure 3. Variations in altitude $h_{\mathrm{PL}}(t)$ (*a*) and spectral intensities $S_{\mathrm{PL}}(t)$ (*b*) of Langmuir waves caused by heating on February 26, 2013

and at t=13.17.30 UT at *ERP*=27 MW, E_{ion}~0.24 V/m. Panels *a1*, *b1* exhibit vertical distribution profiles of Langmuir frequency maxima of the F2-layer background ionosphere $f_{\mathrm{PLfon}}(h)$. Panels *a2* and *b2* illustrate the simultaneous observation of $f_{\mathrm{PLfon}}(h)$ and S_{PL} caused by HFPL excitation near f_{H}. If S_{PL} becomes over 5–7 times higher than S_{PLfon}, $f_{\mathrm{PLfon}}(h)$ in $S_{\mathrm{PL}}(f, h)$ during the heating period is not visible in spectral data processing, and only S_{PL} at f_{H} is observed in $S_{\mathrm{PL}}(f, h)$. On panels *a1*, *a2*, *b1*, *b2*, the frequency variations are marked with minus, but toward increasing values. The distributions $S_{\mathrm{PL}}(f, h)$ are shown for the height range 210–270 km when f_{PL} varies from –6.9 to –7.5 MHz. On VS ionograms (panels *a*, *b*) along the frequency axis, a rectangle indicates the variation range of f_{PL} for $S_{\mathrm{PL}}(f, h)$. Panels *a3*, *b3* exhibit $S_{\mathrm{PL}}(f)$ for t=12.33.00 UT of O--mode heating at a given altitude of 216 km and for t=13.17.29 UT of X-mode heating at a given altitude of 219 km corresponding to $S_{\mathrm{PL}}(f, h)$, presented on panels *a2*, *b2*.

For *ERP*=190 MW of O-mode heating (panel *a2*), we can simultaneously see the profile $f_{\mathrm{PL}}(h)$ of the F2-layer Langmuir frequency maxima and the excitation of a cascade of plasma lines near f_{H}=7.1 MHz. A small maximum at this frequency (panels *a2*, *a3*) suggests the occurrence of a standing Langmuir wave, i.e. the excitation

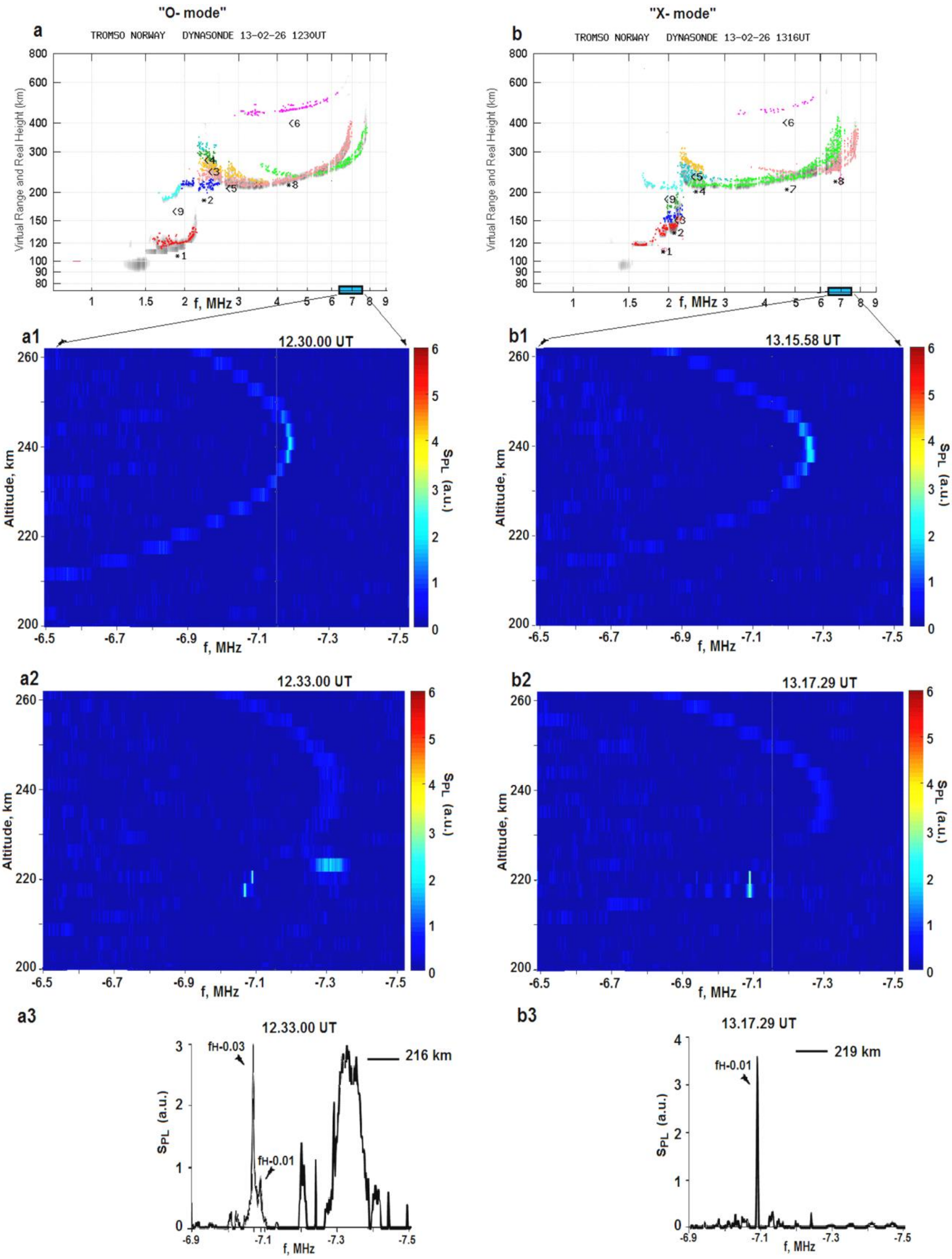

Figure 4. VS ionograms (Tromsö) obtained on February 26, 2013 before heating cycles at f_H=7.1 MHz of O- (*a*) and X-modes (*b*). Distributions of plasma (Langmuir) frequencies of the ionosphere $S_{PL}(f, h)$, plotted from EISCAT IS radar data, for 12.31.00 UT (*ERP*=0 MW before the start of O-mode heating) (*a1*) and 12.33.00 UT (during an O-mode heating cycle, *ERP*=190 MW) (*a2*); $S_{PL}(f)$ spectrum for *t*=12.33.00 UT at 216 km (*a*3); at X-mode heating at 13.15.58 UT (*ERP*=0 MW before heating) (*b1*); 13.17.29 UT (during an X-mode heating cycle, *ERP*=27 MW) (*b2*), and $S_{PL}(f)$ for *t*=13.17.29 UT at 219 km (*b3*)

of OTSI. S_{PL} at f_H–0.01 MHz corresponds to a mother Langmuir wave; and at f_H–0.03 MHz, a daughter one. There is also an increase in the intensity of S_{PL} near the 7.3 MHz frequency.

At X-mode heating (panel *b2*), S_{PL} are excited near f_H–0.01 MHz, shifted from f_H.

Panels *a2, b2* indicate that the HFPL instability is excited in the ionosphere, where the condition $f_H \approx f_{PL}$ of the background plasma is satisfied.

Figure 5 illustrates frequency distributions of ionospheric parameters with height for the October 20, 2012 experiment. The VS ionograms obtained before O- and X- mode heating at 13.30.30, 13.45.30 UT are presented on panels *a*, *b* respectively. $S_{PL}(f, h)$ for the same time points without heating are shown on panels *a1*, *b1*. The frequency range of $S_{PL}(f, h)$ is marked with a rectangle along the frequency axis of the VS ionograms (panels *a*, *b*). Panels *a2*, *b2* show $S_{PL}(f, h)$ in the disturbed ionosphere for O- and X-mode heating, provided that $f_{PLfon}(h)$ and maxima of Langmuir waves S_{PL} were simultaneously observed when HFPL was excited near f_H=7.953 MHz for 13.34.30 and 13.46.30 UT of O- and X-mode heating. The pumping wave field in the ionosphere E_{ion}~0.56 V/m at t=13.34.30 UT of the O-mode heating cycle and E_{ion}~ 0.28 V/m at t=13.46.30 UT of the X-mode heating cycle.

Panels *a2*, *b2* also show that S_{PLfH} near f_H=7.953 MHz was excited at an altitude in the ionosphere at which f_H and f_{PL} of background plasma are close.

Figure 6 for the October 20, 2012 experiment gives examples of the spectra of HF-enhanced plasma Langmuir waves at altitudes with maximum amplitudes S_{PL} for emitted O- (*a*) and X-mode (*b*) pump waves. Panel *a* illustrates the spectra $S_{PL}(f)$ for 13:31–13:36 and 14:01–14:06 UT (O-mode heating); panel *b*, for 13.46–13.51 and 14:16–14:21 UT (X-mode heating) during the *ERP* growth phase in the range from f_H=7.953 to f_H–0.05 MHz. The spectra are calculated without the "switch-on moment".

At O-mode heating, there is a sequence of several maxima. A low maximum near f_H=7.953 MHz indicates that OTSI is excited there. The next maximum shifted by the ionic oscillation frequency (~0.01 MHz) indicates the occurrence of a mother Langmuir wave caused by excitation of an electromagnetic parametric decay instability PDI. The spectral maximum with a shift of ~0.02 MHz from the frequency of the mother Langmuir wave is associated with the development of electrostatic PDI, in which a daughter Langmuir wave arises due to the decay of the main Langmuir mode. The feature of the S_{PL} behavior made itself evident in the fact that the intensities of daughter Langmuir waves were significantly higher than the amplitudes of the mother wave. This feature, according to [Mishin, et al., 1997; Kuo, Lee, 2005], distinguishes the nonresonant mechanism (NRM) of Langmuir wave excitation. NRM of excitation of Langmuir wave cascades accounts for the effects of ion Landau damping; the excitations occur at the same altitude as the pump wave decay. In this case, when daughter Langmuir waves (cascade) are generated, the dispersion relations are not fulfilled.

At X-mode heating (panel *b*), the amplitude maxima S_{PL} are much higher (10–15 times) compared to O-mode heating. The spectra show the presence of the maxima at f_H and f_H–0.01 MHz, which suggests excitation of OTSI and PDI.

2. DISCUSSION

Analysis of the data presented in Figure 4, *a*, *a1*, *b*, *b1* shows that the critical frequency f_oF2 differs from the Langmuir frequency f_{PLmax} at the F2-layer maximum height, measured simultaneously before heating at 12.30 or 13.16 UT. The difference is attributed to the Langmuir wave dispersion in plasma with a finite electron temperature. The dispersion relation for Langmuir waves in plasma has the form [DuBois et al., 2001]

$$f_{PL}^2 = f_{pe}^2 + f_{ce}^2 \sin^2\theta + \frac{3k^2 k_{Blz} T_e}{(2\pi)^2 m_e}, \tag{1}$$

where f_{pe} is the plasma frequency of the ionosphere; f_{ce} is the electron gyrofrequency; θ is the angle between magnetic field direction and radar beam orientation (θ=0° for February 26, 2013); k is the Langmuir wave vector; k_{Blz} is the Boltzmann constant; T_e, m_e are the electron temperature and mass; for the EISCAT radar at a frequency of 930 MHz, k=38.23 m^{-1}.

When calculating f_{PL} at the F2-layer maximum height, using (1) and radar measurement data (electron temperature and plasma frequencies) (see Figure 1 in [Borisova et al., 2023]) for t1=12.30 UT T_e=1550 K, f_{pe}=f_oF2=7.0 MHz; for t2=13.15:58 UT T_e=1600 K, f_{pe}=f_oF2=7.1 MHz, we have obtain numerical values of f_{PLmax}=7.18 MHz and f_{PLmax}=7.28 MHz for t1 and t2, close to the maximum Langmuir frequencies measured by the IS radar (see Figure 4, *a1*, *b1*) f_{PLmax}~7.18 and 7.27 MHz respectively for O- and X-mode heating cycles.

The data presented in Figures 4, *a2*, *b2* and 5, *a2*, *b2* was acquired during periods of radiation by the EISCAT/Heating facility at low effective power, when it was possible to simultaneously observe profiles of Langmuir frequencies of the ionosphere $S_{PL}(f, h)$ and effects of HFPL instability excitation near the pump frequency, induced by plasma wave heating S_{PLfH}. The HFPL instability (see Figures 4, *a2*, *b2* and 5, *a2*, *b2*) is excited at an altitude in the ionosphere, where the condition $f_H \approx f_{PL}$ for background plasma is satisfied. An increase in HFPL excitation altitudes on October 20, 2012 (f_H/f_oF2<1) (see Figure 1) is observed during X-mode heating cycles; the HFPL excitation occurs at a constant altitude with an increase in *ERP* at O-mode heating. In the February 26, 2013 experiment (f_H/f_oF2~1) (see Figure 2) the HFPL excitation altitudes decrease as *ERP* increases during O-mode heating cycles and remain constant at X-mode heating. The variations in the HFPL excitation altitudes during the heating cycles can be explained by the change in the distribution of ionospheric Langmuir frequencies f_{PL} due to the T_e and N_e variations caused by powerful HF radio waves $f_{pe} \sim \sqrt{N_e}$.

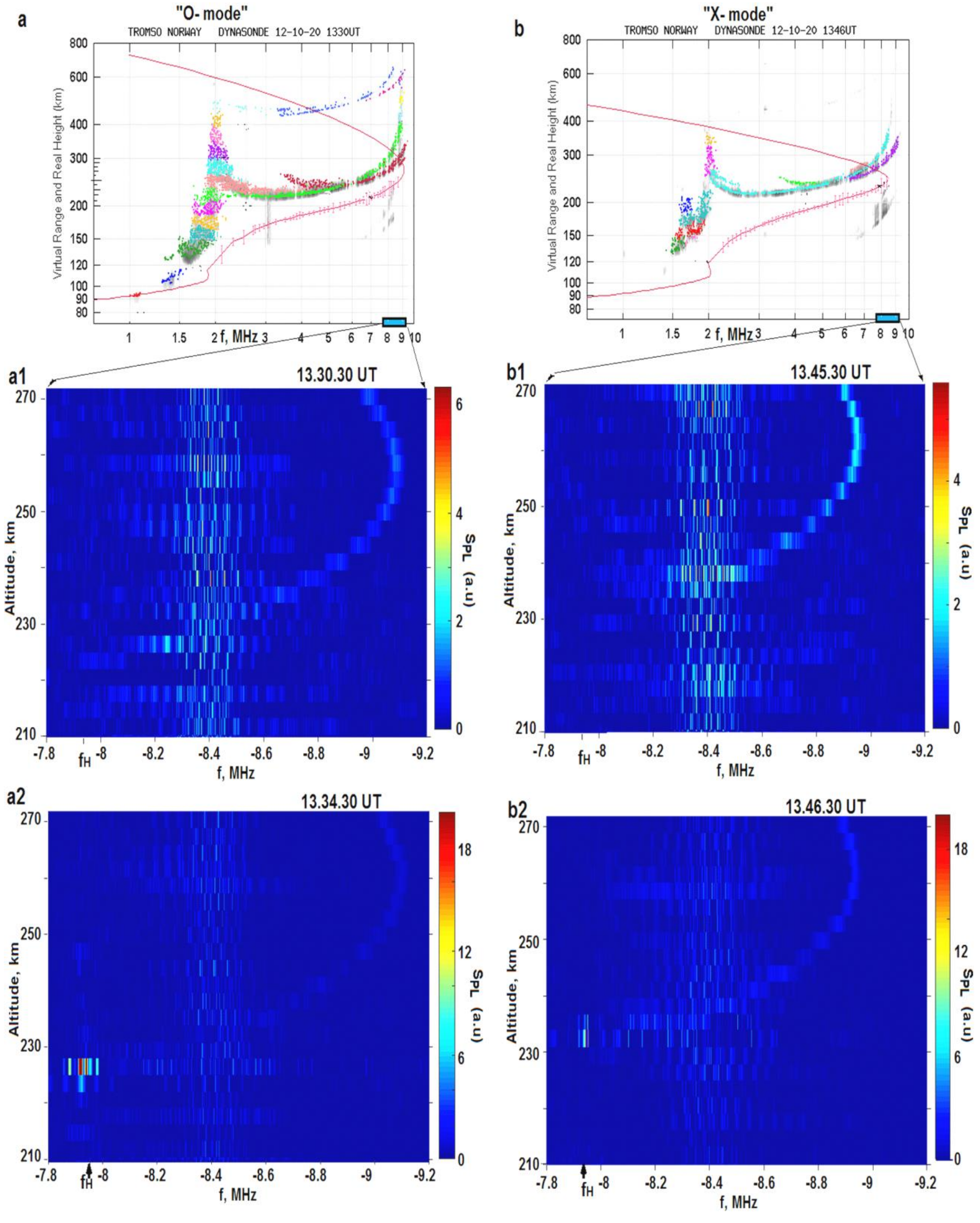

Figure 5. VS ionograms (Tromsö) obtained on October 20, 2012 before the start of heating cycles at a pump frequency f_H=7.953 MHz of O- (*a*, left) and X-modes (*b*, right). Distributions of plasma (Langmuir) frequencies of the ionosphere $S_{PL}(f, h)$, plotted from EISCAT IS radar data, for the time points (*a1*) 13.30.30 UT (*ERP*=0 MW before the start of O-mode heating) and (*a2*) 13.34.30 UT (during an O-mode heating cycle, *ERP*=190 MW); at X-mode heating (*b1*) of 13.45.30 UT (*ERP*=0 MW before heating); (*b2*) 13.46.30 UT (during an X-mode heating cycle, *ERP*=27 MW)

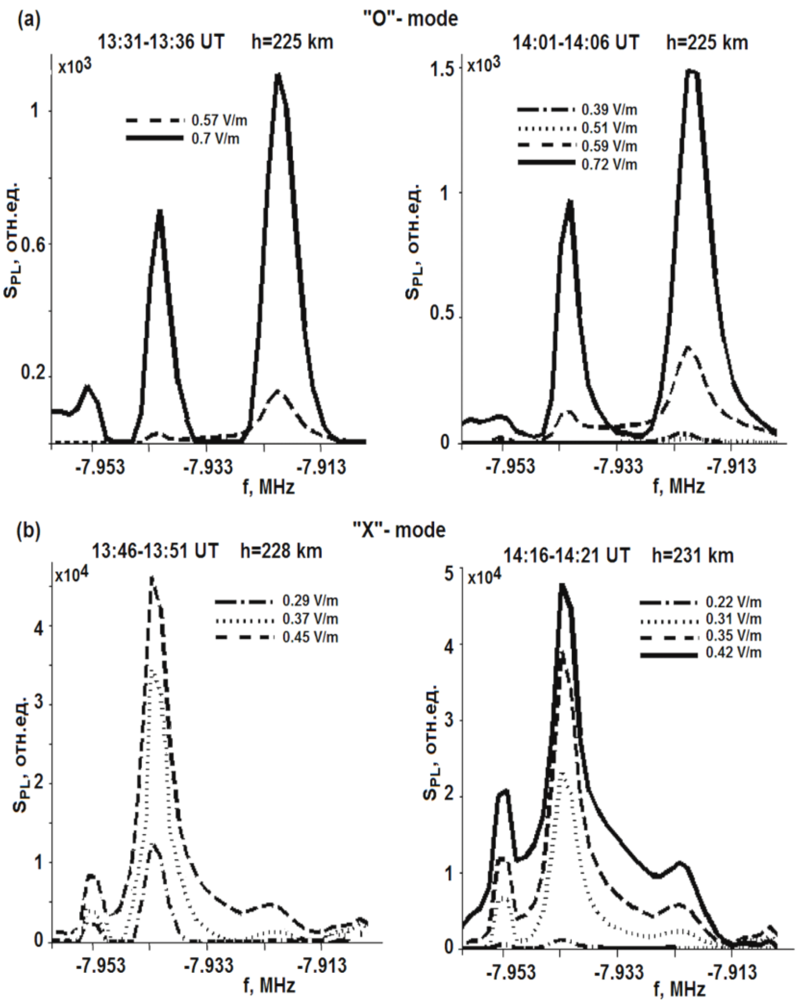

Figure 6. Spectra of plasma waves $S_{PL}(f)$ induced by HF heating in the ionosphere by a pump wave with f_H=7.953 MHz on October 20, 2012 for f_H/f_oF2<0.95 are shown for the first half of the radiation cycles of the EISCAT/Heating facility (*ERP* growth phase): O-mode heating (*a*); X-mode heating (*b*). Different lines indicate $S_{PL}(f)$ when the pump wave field level E_{ion}, calculated taking into account damping along the wave propagation path, changes

Borisova et al. [2018] have examined the excitation of Langmuir waves during periods of long-term heating at frequencies shifted from f_H by hundreds of kHz toward an increase. The authors discussed possible explanations for the generation of spectral maxima of Langmuir waves S_{PLout} at the outshifted frequencies due to dispersion features of Langmuir waves in plasma when the finite electron temperature (free mode) was taken into account [DuBois et al., 2001], as well as due to the four-wave interaction of Bernstein waves with ionospheric plasma and upper hybrid waves, generated by the transformation of a pump wave. For the conditions of February 26, 2013 and the time 12.33 UT at an altitude of 220 km, f_{pe}=6.62 MHz, f_{ce}~1.395 MHz, T_e=3700 K. Using (1), we get f_{PL}~7.1 MHz.

The frequency f_H=7.1 MHz is higher than the fifth harmonic of gyrosonance $5f_{ce}$. Let us explore the possibility of explaining the generation of plasma waves at f_{PLout} when three plasma waves interact at the PDI excitation altitude: an elongated Langmuir wave with f_{PL}, a transverse upper hybrid wave at $f_{UH}=\sqrt{f_{pe}^2+f_{ce}^2}$, and a transverse Bernstein wave with $f_B=5f_{ce}$. Suppose that the interaction of the three waves gives rise to the fourth elongated plasma wave with f_{PLout}. Assume that for the four frequencies of high-frequency waves f_B, f_{UH}, f_{PL}, and f_{PLout} the relation holds

$$f_B + f_{PL} = f_{UH} + f_{PLout}. \qquad (2)$$

In this case, the wave-synchronism condition takes the form

$$\mathbf{k}_B - \mathbf{k}_{PL} = \mathbf{k}_{PLout} - \mathbf{k}_{UH}$$

or

$$\mathbf{k}_B + \mathbf{k}_{UH} = \mathbf{k}_{PL} + \mathbf{k}_{PLout},$$

where $\mathbf{k}_{PL}$, $\mathbf{k}_{PLout}$ are wave vectors of elongated ionospheric plasma waves; $\mathbf{k}_B$, $\mathbf{k}_{UH}$ are wave vectors of the Bernstein and upper hybrid waves transverse to the magnetic field.

For the conditions of February 26, 2013, using the ionospheric data at h~220 km: f_{pe}=6.62 MHz, f_{ce}=1.395 MHz, f_B=6.975 MHz, f_{UH}~6.765 MHz, f_{PL}=7.1 MHz, and relation (2), we obtain f_{PLout}~7.3 MHz.

Note that the question about excitation of the maximum at f_{PLout} remains controversial and call for further investigations into generation of Langmuir waves in heating experiments.

CONCLUSION

We have reported the results of experiments carried out at the EISCAT/Heating facility on February 26, 2013 (f_H/f_oF2~1 and $f_H>5f_{ce}$ by 0.26 MHz) and October 20, 2012 ($f_H/f_oF2<1$ and $f_H<6f_{ce}$ by 0.187 MHz) at an alternative O-/X-mode heating of the high-latitude F-region in the direction of the magnetic zenith with a stepwise change in the effective radiated power *ERP*. The spectral features of ionospheric plasma waves, excited by powerful HF radio waves at radiation frequencies near electron gyroharmonics and the F2-layer critical frequency, were studied using data from the incoherent scatter radar EISCAT (930 MHz), spatially aligned with the heater.

We have shown that when *ERP*<200 MW an HFPL excitation was recorded at altitudes in the ionosphere, where the condition of proximity of the pumping frequency and the Langmuir frequency $f_H \approx f_{PL}$ is fulfilled. The value of f_{PL} is determined by the electron temperature and ionization of both the background ionosphere and the additional one caused by a pump wave during O-/X-mode heating cycles.

For $f_H/f_oF2<1$, an increase was observed in the HFPL excitation altitude during X-mode heating cycles, with HFPL being excited at a constant altitude as *ERP* increased at O-mode heating.

In the case of f_H/f_oF2~1, the HFPL excitation altitudes decreased with increasing *ERP* during O-mode heating cycles and remained constant at X-mode heating.

The HFIL excitation was observed at altitudes close to those of the excitation of HFPL up to the measurement interval of the IS radar (3 km).

When O-mode powerful HF radio waves affected the high-latitude F-region in the direction of the magnetic zenith on February 26, 2013 under the conditions f_H/f_oF2~1 and $f_H>5f_{ce}$, we noted the following:

- excitation of plasma Langmuir waves HFPL simultaneously at two altitudes (below and above the F2-layer maximum);
- recording of spectral maxima S_{PL} not only at f_H=7.1 MHz, but also at f_{out}, shifted from f_H toward an increase by Δ~0.2–0.4 MHz, $f_{out}=f_H+\Delta$.

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