Artificial small-scale field-aligned irregularities in the high latitude ionosphere F region: Comparison between O- and X-mode HF pumping at EISCAT

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Abstract

We present experimental investigations of distinctive features and behaviors of artificial small-scale field-aligned irregularities (AFAIs) in the high latitude ionosphere F-region induced by the ordinary (O-mode) and extraordinary (X-mode) polarized HF pump waves. Results are based on a large body experiments carried out at the EISCAT HF heating facility at Tromsø Norway from 2010 – 2019.

1 Introduction

One of the most prominent phenomena discovered from HF heating experiments is the generation of artificial small-scale field-aligned irregularities (AFAIs), which were investigated with profit at all HF heating facilities in the world. Such irregularities are excited by the ordinary polarized (O-mode) powerful HF pump radio waves (HF pump waves) at the upper hybrid resonance altitude due to the thermal parametric (resonance) instability. Extraodinary polarized (X-mode) HF pump waves do not reach the resonance altitudes, therefore, they are not able to excite AFAIs. However, numerous experiments carried out at the EISCAT (European Incoherent Scatter Scientific Association) HF heater facility have shown that an X-mode HF pump wave radiated towards the magnetic zenith is capable to generate AFAIs in the F-region of the high latitude [1, 2, 3]. The main goal of the paper is the comparison between behaviors and distinctive features of AFAIs in the F-region of the high-latitude ionosphere excited by O- and X-mode HF pump waves.

2 Description of experiments

HF heating facility located near Tromsø, Norway (69.6° N, 19.2° E), was used for the ionosphere modification of the high latitude F-region. The O/X-mode HF pump waves were radiated at frequencies in the range of f_H = 4.0404 – 7.953 MHz towards the magnetic zenith by 10 min on, 5 min off pulses. At low pump frequencies (4 – 5 MHz) the Phased Array 2 having a beam width of 12 – 14° and the effective radiated power ERP = 130 -200 MW was utilized in the course of experiments. At high pump frequencies (5.5 – 8 MHz) the Phased Array1 with a beam width of 5-6°, resulting in the ERP of 450 – 750 MW, was used. Experiments were conducted in day and evening hours under quiet magnetic conditions.

The features of the O/X-mode AFAIs were found by using the CUTLASS (Co-operative UK Twin Located Auroral Sounding System) HF radar at Hankasalmi, Finland (62.3° N, 26.6° E). Observations were performed in a nonstandard mode simultaneously at three frequencies from 10 to 20 MHz, which allowed diagnostics of AFAIs with spatial scale perpendicular to the magnetic field of 7.5–15 m. The CUTLASS radar operated on the only beam (beam 5) directed to the artificially disturbed region over Tromsø. The temporal resolution of 3 s and the range gate of 15 km were utilized in the course of experiments. The EISCAT UHF incoherent scatter radar (930 MHz) at Tromsø was used to interpret and analyze the CUTLASS radar data.

3 Results of observations

The consideration of the entire volume of the CUTLASS data clearly demonstrated that the features and behaviors of the O- and X-mode AFAIs radically differed. In addition the features of the X-mode AFAIs at low (f_H = 4 – 5 MHz) and high (f_H = 5.5 – 8 MHz) pump frequencies are also different.

3.1 AFAIs at high pump frequencies ($f_H \geq$ 5.5 MHz)

Figure 1 shows the EISCAT UHF radar and the CUTLASS measurements on 3 November 2013 in the course of alternating O/X-mode HF pumping towards the magnetic zenith (MZ) at f_H = 6.2 MHz. As seen from Fig. 1, in the course of the experiment, foF2 dropped from 6.7 MHz at 15:30 UT to 5.2 MHz at 18 UT. It makes possible to analyze the behavior of the X-mode AFAIs at pump frequencies both below and above the foF2 ($f_H \leq$ foF2 and $f_H >$ foF2). From 15:30 to 17 UT, when $f_H \leq$ foF2, AFAIs could be excited both upon O- and X- mode heating. An O-mode pumping was accompanied by strong Te enhancements. By a contrast, as seen from Fig. 1a, in the course of the X-mode pulses strong Ne enhancements were observed, but up to present their origin is not clear. The X-mode AFAI intensity was by 4–6 dB lower as compared to O-mode heating. From 17 to 18 UT, when f_H > foF2, only X-mode AFAIs were excited. Backscatter power from X-mode FAIs at frequencies of 13 and 16 MHz was higher by 5-10 dB as compared with their intensities under $f_H \leq foF2$.

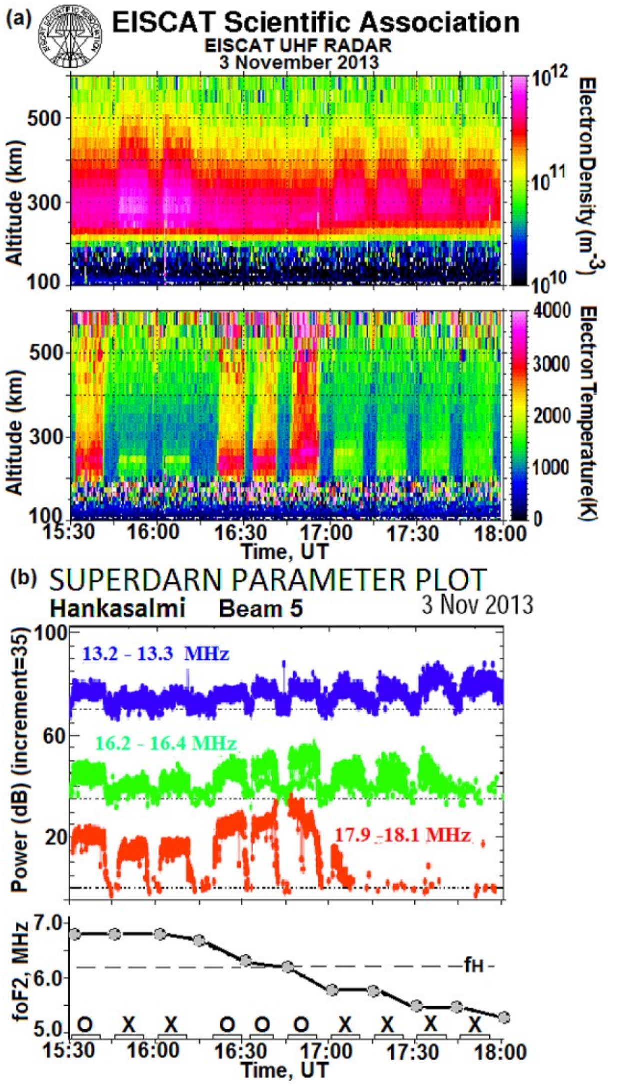

Figure 1. Electron density Ne and temperature Te from EISCAT UHF radar observations (a) and the CUTLASS backscatter power (beam 5) at operational frequencies of about 13, 16, and 18 MHz averaged over an artificially disturbed ionospheric region and the behavior of the critical frequency of the F2 layer, foF2, and heater frequency f_H (b) in the course of the experiment on 3 November 2013. A powerful HF radio wave was radiated towards MZ at a pump frequency of frequency 6.2 MHz, ERP = 450 MW. The pump cycles and polarization are marked on the time axis.

Figure 2 demonstrates the CUTLASS (SuperDARN) radar data received on 28 October 2013 under an X-mode HF pumping towards MZ at high pump frequency of f_H = 6.96 MHz, when the critical frequency foF2 decreased in a wide range from 7.6 to 5.1 MHz. It is a typical example of the behavior of X-mode AFAIs at high pump frequencies below (from 15:30 to 16:30 UT) and above (from 16:30 to 18 UT) the critical frequency of the F2 layer. It is important that X-mode AFAIs on 28 October 2013 at f_H = 6.96 MHz were excited when f_H exceeded foF2 up to 2 MHz. This clearly demonstrated that HF pump wave was not reflected from the ionosphere.

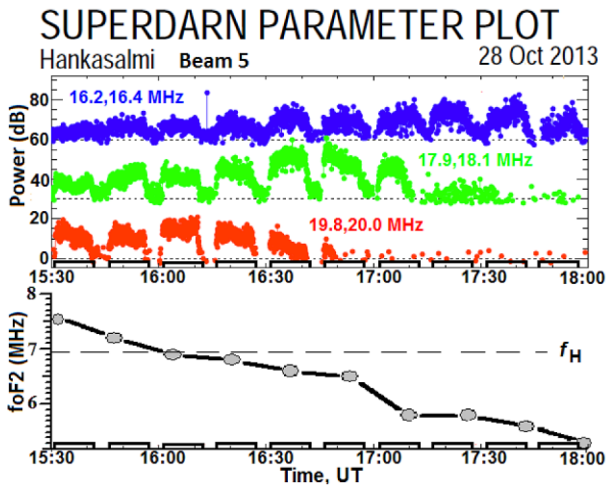

Figure 2. CUTLASS backscatter power (beam 5) at operational frequencies of about 16, 18, and 20 MHz averaged over an artificially disturbed ionospheric region and the behavior of the critical frequency of the F2 layer, foF2, and heater frequency f_H on 28 October 2013. An extraordinary polarized powerful HF radio wave was radiated towards MZ at a pump frequency of 6.96 MHz, ERP = 550 MW. The X-mode pump cycles are marked on the time axis.

3.2 AFAIs at low pump frequencies (f_H <5.5 MHz)

Figure 3 depicts the CUTLASS (SuperDARN) radar data received on 20 October 2016 under HF pumping towards MZ at low pump frequency of f_H = 4.543 MHz. The values of foF2 gradually decreased from 5.5 MHz at 1415 UT to 4.1 MHz at 16 UT, i.e., heating at a frequency of 4.543 MHz was made at frequencies at first below, then from 15:30 UT above the critical frequency. Comparing the O- and X-mode HF pump pulses, it is seen that intensity of signals backscattered from O-mode AFAIs was greater than was X-mode AFAIs. It is similar to case of high pump frequencies (see Fig. 1). Backscatter power from X-mode FAIs increased with dropping foF2. After 15:30 UT the smallest irregularities (9.3 m) observed at the CUTLASS operational frequency of 16 MHz disappeared, but larger scale X-mode AFAIs (11.5 and 12.5 m) intensified. Similar behavior was observed at high pump frequencies (see Figs. 1 and 2).

Let's further consider the AFAI growth and decay times (τ_1 and τ_2) for O-and X-mode HF pumping. The CUTLASS backscatter power on 20 October 2016, starting 1 min before and during the first 2 min after the onset of HF pumping, is shown in Figure 4. Figure 5 presents the CUTLASS backscatter power for the same

O- and X- mode pulses during the last minute of a pump pulse and the first 2 min after the EISCAT/Heating was turned off. Remind that signals at CUTLASS operational frequencies of about 16 and 13 MHz are backscattered from 9.3-m and 11.5-m irregularities. The AFAI growth and decay times significantly differ for O- and X-mode HF pumping. Upon the O-mode pumping τ_1 = 6 - 9 s and τ_2 = 30 – 50 s. Moreover, the AFAI decay occurred in two stages. The fast stage lasted about 9 – 12 s, and the slow stage up to 40 s duration. The growth and decay times for an X-mode pumping greatly depend on the precondition history. From the "cold" start (the first X-mode pulse) $\tau_1 \approx$ 60–70 s (it can even reach 150 s at f_H > foF2) and $\tau_2 \approx$ 100–130 s. In X-mode cycles with history, when the aftereffects of previous heating cycles act, τ_1 decreased and τ_2 increased.

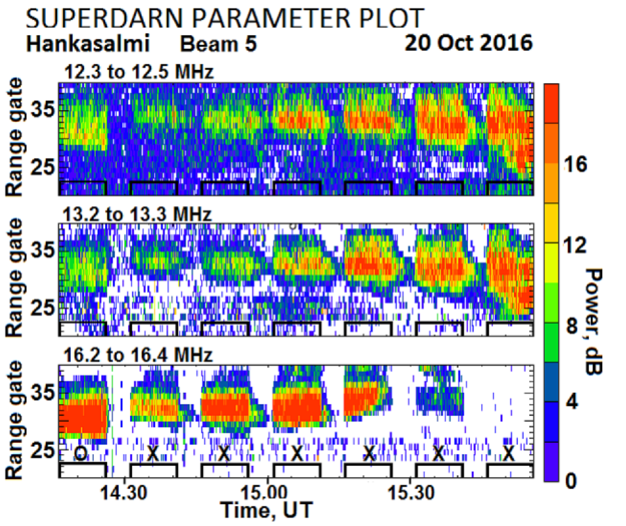

Figure 3. CUTLASS backscatter power (beam 5) at operational frequencies of about 12, 13, and 16 MHz in the range gate – universal time UT coordinates on 20 October 2016. A powerful HF radio wave was radiated towards MZ at a pump frequency of 4.543 MHz, ERP = 130 MW. The pump cycles and polarization are marked on the time axis.

4 Discussion and Summary

We presented results of investigations of features and behaviors of AFAIs with a size across the geomagnetic field of 7.5–15 m excited by the ordinary (O-mode) and extraodinary (X-mode) polarized HF pump waves in the F-region of the high latitude ionosphere. It was found that X-mode AFAIs are generated under quiet conditions (no precipitation of particles, longitudinal currents, and electrojet) By a contrast to the O-mode FAIs generated when $f_H \leq$ foF2, the X-mode AFAIs were excited when a HF pump is radiated towards MZ at frequencies that are both lower and much higher (up to 2 MHz) than the critical frequency of the F2 layer.

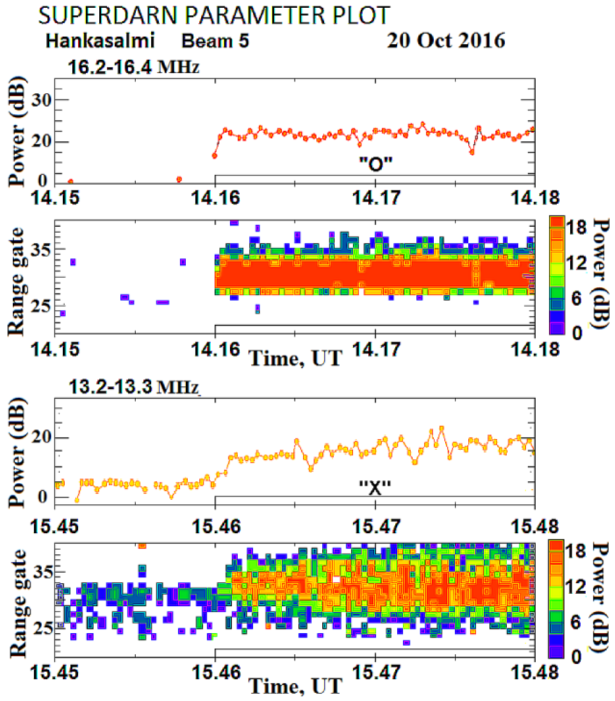

Figure 4. CUTLASS backscatter power (beam 5) at operational frequencies of about 16 and 13 MHz on 20 October 2016 for O- and X-mode pump cycles starting 1 min before and during the first 2 min after the onset of HF pumping.

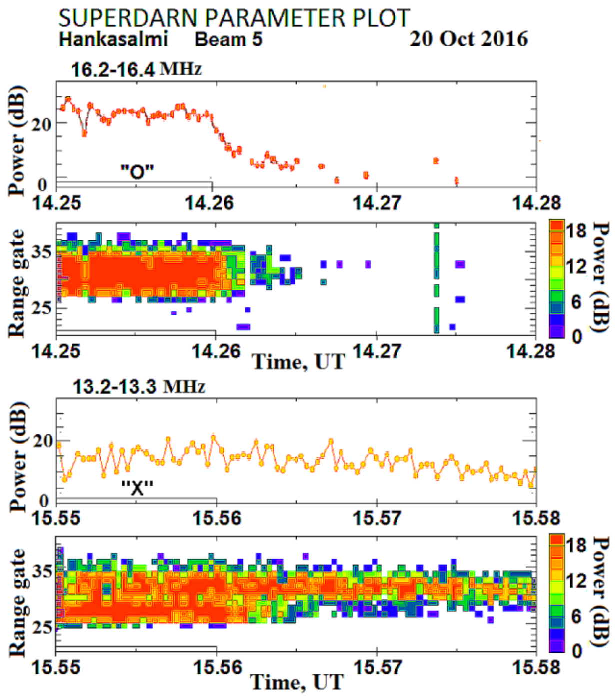

Figure 5. CUTLASS backscatter power (beam 5) at operational frequencies of about 16 and 13 MHz on 20 October 2016 for O- and X-mode pump cycles during the last minute of a pump pulse and the first 2 min after the EISCAT/Heating was turned off.

The AFAI growth and decay times significantly differ for O- and X-mode HF pumping. There is also a significant difference in the decay times for X mode AFAIs excited at high and low heater frequencies. The AFAI decay time at high pump frequencies did not exceed 3 min in the evening hours, whereas it can reach the unusually long values exceeding the 5 min pause between the pump pulses at low heater frequencies.

It was found that the features and physical driving mechanisms of AFAIs with the spatial scale across the geomagnetic field of 7.5 – 15 m are significantly different for O- and X-mode HF pumping, presenting challenges for understanding the relevant processes. By a contrast to the O-mode AFAIs excited by a thermal parametric (resonance) instability at the upper hybrid resonance altitude, the X-mode FAIs are generated via two-step process. In the first step the generation of elongated large-scale irregularities (with the spatial scale across the geomagnetic field of the order of 1 - 10 km depending on the background geophysical conditions and the pump frequency) is occurred. As a second step, we suggest that the filamentation instability can be responsible for the generation of small-scale AFAIs. As is found from EISCAT UHF radar measurements AFAIs greatly impact on the development of strong artificial turbulence such as Langmuir and ion-acoustic plasma waves.

5 Acknowledgements

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6 References

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