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ОРИГИНАЛЬНАЯ СТАТЬЯ **ORIGINAL ARTICLE**

Disturbances of electron density in the high latitude upper (*F*-region) ionosphere induced by X-mode HF pump waves from EISCAT UHF radar observations

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Summary

The paper presents experimental results concerning disturbances of electron density in the high latitude ionosphere *F*-region, induced by powerfulHF radio waves (pump waves) with extraordinary (X-mode) polarization. The experiments were carried out at the EISCAT/Heating facility at Tromsø, Norway. The EISCAT UHF incoherent scatter radar (ISR), running at 930 MHz, co-located with a heating facility, was used to detect the disturbances of electron density. In the course of the experiments, the X-mode HF pump waves radiated into the *F*-region towards the magnetic zenith at different pump frequencies and ratios of the pump frequency to the critical frequency of the *F*2 layer.The effective radiated power was ERP = 360–820 MW. An increase in electron densities was found in a wide altitude range, giving rise to field-aligned ducts with enhanced electron density. The features and behavior of the ducts were investigated. It was revealed that the ducts are formed under quiet background geophysical conditions in a wide altitude range up to the upper altitude limit of EISCAT ISR measurements, when the pump frequencies were both below and above the critical frequency of the *F*2 layer ($f_H \le f_oF2$ or $f_H > f_oF2$). A plausible formation mechanism of the ducts is discussed.

Keywords: duct, electron density, EISCAT, experiment, polarization, *F*-region, high-latitude ionosphere, HF pump wave, incoherent scatter radar.

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INTRODUCTION

Controlled injection of powerful HF radio waves into the high latitude upper (*F*-region) ionosphere allows investigating various ionospheric disturbances, nonlinear phenomena, the excitation of plasma waves, plasma and cyclotron resonances and the mechanisms of electron acceleration. Powerful HF radio waves with ordinary (O-mode) polarization at frequencies below the critical frequency of the *F*2 layer ($f_H \leq f_oF2$) are commonly used for the modification of the upper ionosphere (*F*-region) at all HF heating facilities in the world. This is due to the fact that powerful HF radio waves with extraordinary polarization in the background undisturbed ionosphere are reflected from altitudes significantly below the reflection altitude of the O-polarized HF pump wave and the altitude of the existing electrostatic plasma waves (Langmuir and upper hybrid). Because of that, the X-mode pump waves are not able to generate electrostatic plasma waves and, as a consequence, the excitation of the artificial plasma turbulence and accompanying phenomena [1–4].

However, results from a large number of experiments, carried out by scientists from AARI at the EISCAT/Heating facility (Tromsø, Norway), have shown for the first time that an X-polarized HF pump wave, injected into the high latitude ionosphere *F*-region towards the magnetic zenith, is able to produce the excitation of various artificial disturbances such as small-scale field-aligned artificial irregularities, optical emission, narrowband stimulated electromagnetic emission and Langmuir and ion acoustic plasma waves [5–9]. Moreover, the artificial ionosphere turbulence (AIT) may be much stronger compared with the AIT induced by an ordinary polarized HF pump wave [8]. In contrast to artificial ionospheric disturbances induced by ordinary (O-mode) polarized powerful HF radio waves, ionospheric disturbances in the upper (*F*-region) high latitudinal ionosphere under X-mode HF pumping are far from being sufficiently investigated, and the mechanisms of their formationare not well understood. Therefore, investigations of artificial ionospheric disturbances in the *F*-region induced by X-mode HF pump waves require further serious experimental and theoretical studies.

The present paper is aimed at investigating the features and the formation conditions of ducts with an enhanced electron density in the high latitude ionosphere F-region induced by extraordinary polarized (X-mode) HF pump waves injected towards the magnetic zenith at frequencies both below and above the critical frequency of the *F*2 layer ($f_H \leq f_oF2$ or $f_H > f_oF2$) under very high effective radiated power (ERP > 250 MW) from the direct measurements of the EISCAT UHF incoherent scatter radar co-located with the EISCAT/Heating facility.

EXPERIMENTAL SETUP AND METHODS

The experiments were conducted using the EISCAT/Heating facility (69.6º N, 19.2º E, L = 6.2, I = 78º) located near Tromsø, Norway [10] under quiet magnetic conditions in the morning, afternoon and evening hours. Powerful HF radio waves with extraordinary (X-mode) polarization radiated towards the magnetic zenith (the HF heater beam was tilted to the south from the vertical direction by 12°) at fixed frequencies from 5.4 to 8 MHz in 10 min on — 5 min off cycles. A phased array with a bandwidth of 5–6° (at –3 dB level), providing the effective radiated power ERP = 360–820 MW, was utilized in the course of the experiments. The choice of the heater frequency was made in the real time from the Tromsø dynasonde [11].

The EISCAT UHF incoherent scatter radar (ISR) at 930 MHz [12], co-located with the EISCAT/Heating facility, was used for observations of HF-induced effects in a wide altitude range. It provides the detection of plasma turbulence with a wavelength L = 0.16 м ($L = c/2f_{rad}$, where c is the velocity of light and frad is the radar frequency). In the course of the experiments, the ISR operated in the altitude range from 70 to 700 km using “beata” code [13] with an altitude resolution of 3 km and temporal resolution of 5 s. In most of the experiments, the EISCAT ISR runs in the same direction as the radiation of the

HF pump wave (towards the magnetic zenith). However, in some of our experiments, in determining the spatial scale in the horizontal plane of artificial disturbances, the stepping of the elevation angles was used in the following sequence: 72–74–76–77–78–79–80–82–84–86° (2 min for each angle). The magnetic zenith at Tromsø corresponds to the elevation angle of 78°. EISCAT ISR data were processed by the Grand Unified Incoherent Scatter Design and Analysis Package (GUISDAP) software [13].

RESULTS AND DISCUSSION

First, we consider the behavior and features of the plasma parameters under X-mode HF pumping towards the magnetic zenith at different pump frequencies f_H and ratios of f_H to the critical frequency of the $F2$ layer ($f_H \leq f_oF2$ и $f_H > f_oF2$).

Figure 1 shows the altitude-temporal distribution of the electron density and temperature (N_e и T_e), the ISR backscatter power, labeled as the raw electron density, and intensities of HF-induced plasma lines (HFPL) on 16 February 2012 from 14:18 to 15:32 UT. Note that the strong ISR backscatter power is a direct indication of the excitation of the HF-enhanced ion

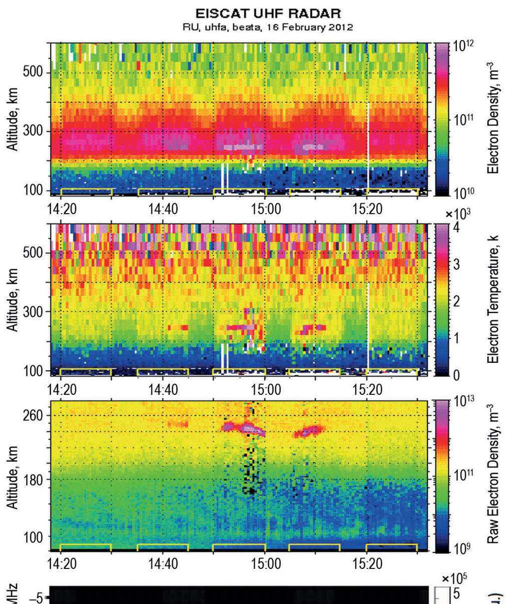

Fig.1. Altitude-temporal distribution of the electron density and temperature (N_e, T_e), the ISR backscatter power, labeled as the raw electron density, and intensities of HF-induced plasma lines (HFPL) on 16 February 2012 from 14:18 to 15:32 UT from the EISCAT ISR observations. The X-mode HF pump wave radiated towards the magnetic zenith at frequency of 6.2 MHz. The effective radiated power was ERP = 460 MW. Heater-on cycles are shown on the time axis

Рис. 1. Высотно-временное распределение N_e, T_e, мощности рассеянного сигнала (raw electron density) интенсивностей, вызванных нагревом плазменных линий (HF-induced plasma lines, HFPL) 16 февраля 2012 г. с 14:18 до 15:32 UT по данным EISCAT радара НР. Мощная КВ-радиоволна X-поляризации излучалась в направлении магнитного зенита на частоте 6,2 МГц при $P_{эфф}$ = 460 МВт. Циклы нагрева показаны на оси времени line (HFIL) in the radar spectra. In the course of the experiment,the HF pump wave radiated at a frequency of 6.2 MHz, which was above the critical frequency by 0.3–1.2 MHz ($f_H > f_oF2$). The effective radiated power was ERP = 460 MW.

As seen from Fig. 1, the large electron density enhancements N_e were observed in a wide altitude range up to about 550 km in all heater-on cycles and accompanied by not too strong increases in the electron temperature T_e due to the Ohmic electron heating. It is important that N_e enhancements occurred irrespective of the excitation of HFIL and HFPL (compare, for example, the pump cycles on 14:20 – 14:30 UT and 14:50 – 15:00 UT in Fig. 1).

Analogous N_e enhancements were observed on 25 February 2013 from 9:28 to 11:43 UT, when the X-mode HF pumping was produced at frequencies f_H= 6.77, 6.2 and 7.1 MHz, which were both above and below f_oF2 (see Fig. 2).

It was interesting to compare the N_e and T_e features observed in the course of alternating O-/X-mode HF pumping. Such a comparison was carried out for the experiment on 25 February 2013 from 14:45 to 178:15 UT (see Fig. 3). During the experiment, the HF pump wave with O- or X-polarization radiated towards the magnetic zenith at a frequency f_H = 5.423 MHz under ERP = 360 MW. The critical frequencies of the $F2$ layer slowly dropped from 5.9 to 5.5 MHz ($f_H \leq f_oF2$), which makes possible the excitation of non-linear phenomena induced by the O-mode as well as X-mode HF pumping.

As is evident from Fig.3, strong electron temperature enhancements of up to ~ 3000 K were observed under the O-mode HF pumping, which is a typical signature for

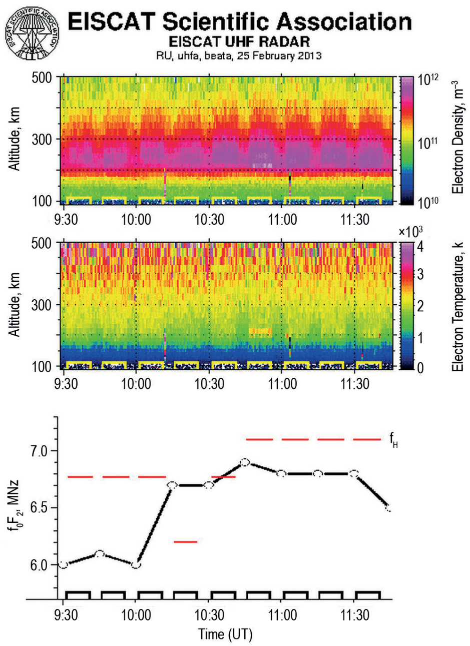

Fig. 2. Behavior in time of N_e, T_e, f_oF2, and f_H in the course of experiment on 25 February 2013 from 9:28 to 11:43 UT. The X-mode HF pump wave radiated at frequencies 6.77, 6.2, 6.77, and 7.1 MHz. Heater-on cycles are shown on the time axis

Рис. 2. Поведение N_e, T_e, а также критических частот слоя $F2$ и частот нагрева в период эксперимента 25 февраля 2013 г. с 9:28 до 11:43 UT. Мощная КВ-радиоволна Х-поляризации излучалась последовательно на частотах 6,77; 6,2; 6,77 и 7,1 МГц. Циклы нагрева показаны на оси времени

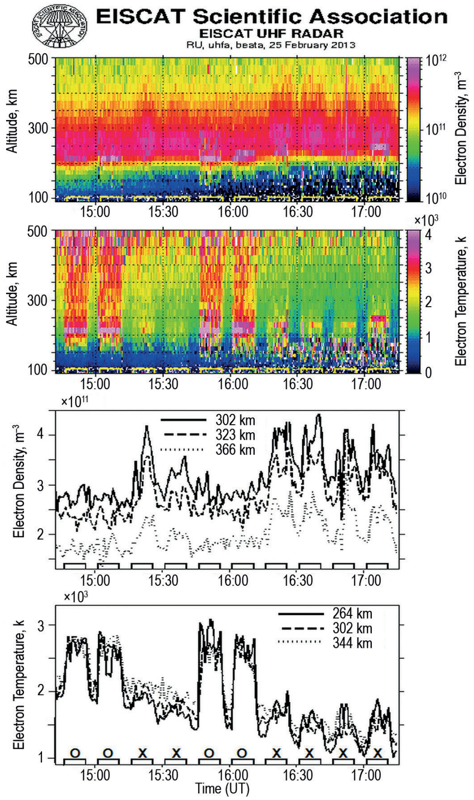

Fig. 3. Altitude-temporal distribution of N_e, T_e and behavior of N_e, T_e at fixed altitudes on 25 February 2013 from 14: 45 до 17:15 UT. Alternating O-/X-mode pumping was produced towards the magnetic zenith at frequency f_H = 5.423 MHz under ERP = 360 MW. Heater-on cycles and polarization of HF pump wave are shown on the time axis

Рис. 3. Высотно-временное распределение N_e, T_e а также вариации N_e, T_e на фиксированных высотах 25 февраля 2013 г. с 14: 45 до 17:15 UT. Альтернативный O-/X-нагрев производился на частоте 5,423 МГц в направлении магнитного зенита при $P_{эфф}$ = 360 МВт. Циклы нагрева и поляризация мощной КВ-радиоволны показаны на нижней панели оси времени

O-mode experiments at all the HF heating facilities at middle and high latitudes [1–3, 14]. In this case, the electron density N_e changes were insignificant. The opposite behavior of the N_e and T_e is exhibited by X-mode pumping. Strong electron density enhancements of up to 50–70 % above the background level in a wide altitude range were accompanied by small T_e increases of up to ~ 20–30 % under $f_H \le f_oF2$. Such field-aligned N_e enhancements form ducts, which are typical phenomena for X-mode HF pumping at frequencies below and above the critical frequency of the $F2$ layer ($f_H \le f_oF2$ and $f_H > f_oF2$).

Further we consider the features of the ducts with enhanced N_e in the high latitude upper (F-region) ionosphere in more detail. Fig. 4 depicts the evolution in time of the ducts with enhanced N_e after the onset of X-mode pumping on 12 October 2011. As is seen, the N_e enhancements started after the HF heater is turned on and reached the saturation within ~ 40 s. The decay time of the N_e enhancements was about 2–5 min after the HF heater was turned off.

Figure 5 demonstrates the altitude profiles of the electron density N_e (h), averaged over 2 min intervals, before the HF pump onset, during the heater-on cycle and after the HF heater is turned off on 10 and 12 October 2011. HF pump waves radiated towards the magnetic zenith

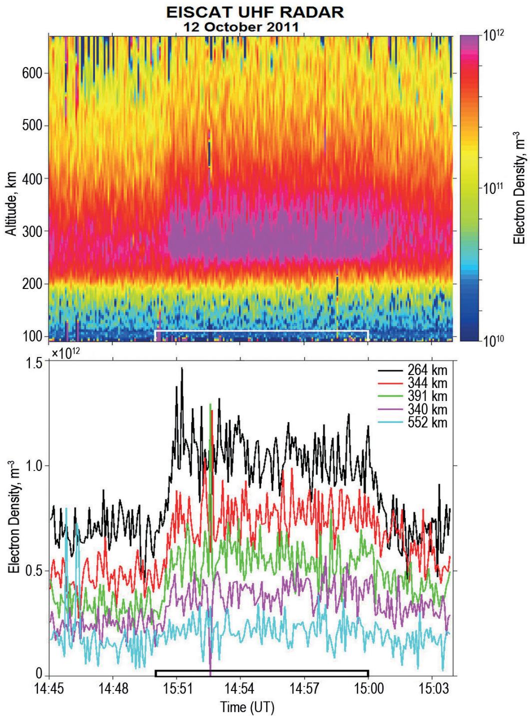

Fig. 4. Altitude-temporal distribution of N_e, and its behavior at fixed altitudes with 5 s temporal resolution on 12 October 2011 from 14: 45 to 15:04 UT. The X-mode HF pump wave radiated towards the magnetic zenith at f_H = 7.953 MHz ($f_H \approx f_oF2$) under ERP = 820 MW. Heater-on cycle is shown on the time axis

Рис. 4. Высотно-временное распределение N_e и вариации N_e на фиксированных высотах с 5 с разрешением по времени 12 октября 2011 г. с 14:45 до 15:04 UT. Мощная КВ-радиоволна Х-поляризации излучалась в направлении магнитного зенита на частоте f_H = 7,953 МГц ($f_H \approx f_oF2$) при $P_{эфф}$ = 820 МВт. Цикл нагрева отмечен на оси времени

at f_H = 7.1 MHz and f_H = 7.953 MHz on 10 and 12 October 2011 correspondingly, when the pump frequencies exceeded the critical frequency of the *F*2 layer by 0.3–0.4 MHz. As seen from Fig. 5, the N_e enhancements appeared from the altitude of 220–250 km and existed up to 550 km (the upper altitude limit of EISCAT ISR measurements during the experiments). The N_e values did not recover to the background N_e values after the HF heater was turned off, but were enhanced in a wide altitude range of up to 550 km during the next two minutes.

EISCAT ISR measurements in the elevation angle stepping make it possible to estimate the horizontal size of the ducts with N_e enhancements. Fig. 6 shows the behavior of the N_e enhancements depending on the elevation angle of EISCAT ISR in the course of 20 min heater-on cycle on 2 November 2013 from 12:31 to 12:51 UT.

As is evident from Fig. 6, the largest N_e enhancements were observed for the elevation angles between 77–79°. It is worth noting that the field-aligned pointing ISR corresponds to 78°. Therefore, the ducts occurred in the vicinity of the local magnetic field line and had a width of 3°, which corresponds to ~ 16 km at the altitude of 300 km.

The analysis of the features and formation conditions of the enhanced electron density ducts allows one to assume that the X-mode HF pumping into the high latitude ionosphere *F*-region towards the magnetic zenith produces electron acceleration. It is

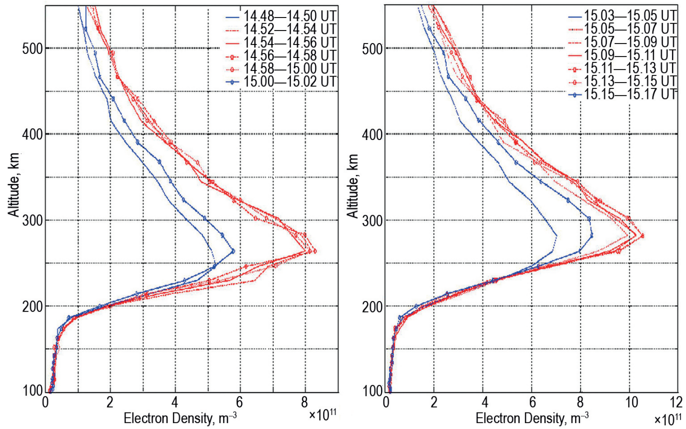

Fig.5. *Ne*(h)-profiles, averaged over 2-min intervals, before turning on the HF Heater, during heater-on cycle and after the turning off the HF Heater: (*a*) 10 October 2011, 14:48 — 15:02 UT, f_H = 7.1 MHz, ERP = 680 MW; (*b*) 12 October 2011, 15:03 — 15:17 UT, f_H = 7.953 MHz, ERP = 820 MW.

Рис. 5. N_e(h)-профили, усредненные на 2-минутных интервалах, до начала нагрева, в течение цикла X-нагрева и после выключения нагревного стенда: (*a*) 10 октября 2011 г., 14:48–15:02 UT, $P_{эфф}$ = 680 МВт, частота нагрева f_H = 7,1 МГц; (*b*) 12 октября 2011 г., 15:03–15:17 UT, $P_{эфф}$ = 820 МВт, f_H = 7,953 МГц

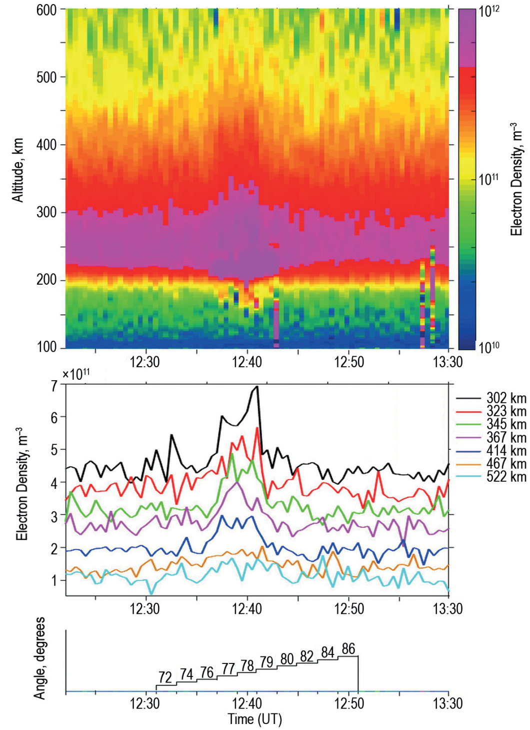

Fig. 6.Altitude-temporal distribution of N_e and behavior of N_e at fixed altitudes in the course of the X-mode HF pump cycle on 2 November 2013 from 12:31 to 12:51 UT. The HF pump wave radiated towards the magnetic zenith at frequency f_H = 6.96 МГц ($f_H \leq f_oF2$) under ERP = 550 MW. In the course of 20 min heater-on pulse the EISCAT ISR run in the elevation angle stepping mode, when the radar elevation angle was changed every 2 min in an orderly sequence of 72–74–76–77–78–79–80– 82– 84–86°, shown on the time axis.

Рис. 6. Высотно-временное поведение N_e, а также вариации N_e на фиксированных высотах в цикле X-нагрева 2 ноября 2013 г. с 12:31 до 12:51 UT. Мощная КВ-радиоволна излучалась в магнитный зенит на частоте f_H = 6,96 МГц ($f_H \leq f_oF2$) при $P_{эфф}$ = 550 МВт. Радар НР измерял при ступенчатом изменении углов возвышения в последовательности: 72–74–76–77–78–79–80–82–84–86°.

due to the fact that the electric field of a circular X-polarized HF pump wave rotates in the same direction as the electron gyro-motion. It leads to the acceleration of electrons. Also, we cannot rule out that other unknown acceleration mechanisms come into play. The acceleration of electrons is amply confirmed by the high ratio (0.35–0.5) of the green to red line of the radio-induced optical emission induced by X-mode HF pumping [6, 15]. In such a case, according to the results obtained in [16, 17], the flux of accelerated electrons can lead to an increased production of ionization.

CONCLUSIONS

Our EISCAT ISR observations have demonstrated that X-mode HF pumping into the high latitude ionosphere *F*-region towards the magnetic zenith leads to the formation ofducts with an enhanced electron density N_e. It has been found that they are created under quiet magnetic conditions, when the pump frequencies are both below and above the critical frequency of the *F*2 layer ($f_H \le f_oF2$ and $f_H > f_oF2$), irrespective of the excitation of HF-induced Langmuir and ion-acoustic plasma waves. The electron density inside the ducts is enhanced by 50–70 % from the background level in a wide altitude range of up to ~ 600 km. The ducts were formed in the vicinity of the local magnetic field line and had a width of about 3°, which corresponds to ~ 16 km at the altitude of 300 km. A plausible mechanism of duct formation could be the enhanced production of electron density by accelerated electrons, induced by an X-mode HF pump wave.

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REFERENCES

1. *Gurevich A.V.* Nonlinear effects in the ionosphere. Physics-Uspekhi. 2007, 50: 1091–1121.

2. *Robinson T.R.* The heating of the high latitude ionosphere by high power radio waves. Physics Reports. 1989, 179: 79–209.

3. *Stubbe P.* Review of ionospheric modification experiments at Tromso. Journal of Atmospheric and Solar-Terrestrial Physics.1996, 58: 349–368.

4. *Kuo S.* Ionospheric modifications in high frequency heating experiments. Physics Plasmas. 2015, 22. doi: 10.1063/1.4905519.

5. *Blagoveshchenskaya N.F., Borisova T.D., Yeoman T., Rietveld M.T., Ivanova I.M., Baddeley L.J.* Artificial field-aligned irregularities in the high-latitude F region of the ionosphere induced by an X-mode HF heater wave. Geophysical Research Letters. 2011, 38.

6. *Blagoveshchenskaya N. F., Borisova T. D., Kosch M., Sergienko T., Brändström U., Yeoman T.K., Häggström I.* Optical and Ionospheric Phenomena at EISCAT under Continuous X-mode HF Pumping. Journal of Geophysical Research: Space Physics. 2014, 119: 10483–10498.

7. *Blagoveshchenskaya N.F., Borisova T.D., Yeoman T.K., Häggström I., Kalishin A.S.* Modification of the high latitude ionosphere F region by X-mode powerful HF radio waves: Experimental results from multi-instrument diagnostics. Journal of Atmospheric and Solar-Terrestrial Physics. 2015, 135: 50–63.

8. *Blagoveshchenskaya N.F., Borisova T.D., Kalishin A.S., Yeoman T.K., Häggström I.* Distinctive features of Langmuir and Ion-acoustic Turbulences induced by O- and X-mode HF Pumping at EISCAT. Journal of Geophysical Research: Space Physics. 2020, 125 (7). https://doi.org/10.1029/2020JA028203.

9. *Blagoveshchenskaya N.F.* Perturbating the High-Latitude Upper Ionosphere (F Region) with Powerful HF Radio Waves: A 25-Year Collaboration with EISCAT. Radio Science Bulletin. 2020, 373: 40–55. doi:10.23919/URSIRSB.2020.9318436.

10. *Rietveld M.T., Senior A., Markkanen J., Westman A*. New capabilities of the upgraded EISCAT high-power HF facility. Radio Science. 2016, 51: 1533–1546.

11. *Rietveld M.T., Wright J.W., Zabotin N., Pitteway M.L.V.* The Tromsø dynasonde. Polar Science. 2008, 2 (3): 55–71.

12. *Rishbeth H., van Eyken T.* EISCAT: Early history and the first ten years of operation. Journal of Atmospheric and Solar-Terrestrial Physics. 1993, 55: 525–542.

13. *Lehtinen M.S., Huuskonen A*. General incoherent scatter analysis and GUISDAP. Journal of Atmospheric and Solar-Terrestrial Physics. 1996, 58: 435–452.

14. *Djuth F.T.* Response of the Arecibo ionosphere to large HF-induced electron temperature enhancements. Adv. Space Res. 1989, 9 (5): 123–131.

15. *Gustavsson B., Eliasson B*. HF radio wave acceleration of ionospheric electrons: Analysis of HF-induced optical enhancements. Journal of Geophysical Research. 2008, 113: A08319. doi: 10.1029/2007JA012913.

16. *Carlson H.C., Wickwar V.B., Mantas G.P.* Observations of fluxes of suprathermal electrons accelerated by HF excited instabilities. J. Atmos. Terr. Phys. 1982, 44: 1089–1100.

17. *Carlson H.C., Djuth F.T., Zhang L.D.* Creating space plasma from the ground. Journal of Geophysical Research: Space Physics. 2016, 122: 978–999. doi: 10.1002/2016JA023880.

Возмущения электронной концентрации в высокоширотной верхней (*F*-область) ионосфере, вызванные воздействием мощных КВ-радиоволн Х-моды поляризации по данным наблюдений EISCAT радара некогерентного рассеяния радиоволн

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Резюме

Представлены результаты экспериментальных исследований возмущений электронной концентрации N_e в высокоширотной *F*-области ионосферы, вызванные воздействием мощных КВ-радиоволн необыкновенной (Х-мода) поляризации. Эксперименты выполнялись на КВ нагревном стенде EISCAT/Heating в г. Тромсё, Норвегия при эффективной мощности излучения 360–820 МВт. В качестве средства диагностики возмущений N_e использовался EISCAT радар некогерентного рассеяния радиоволн (НР) на частоте 930 МГц, пространственно совмещенный с КВ нагревным стендом. Обнаружено возрастание N_e в широком диапазоне высот, которое формирует каналы повышенной электронной плотности, вытянутые

вдоль магнитного поля Земли. Исследованы характеристики и условия создания каналов. Обсуждается возможный механизм формирования каналов N_e при Х-нагреве высокоширотной F-области ионосферы.

Ключевые слова: высокоширотная ионосфера, канал, мощная КВ-радиоволна, поляризация, радар некогерентного рассеяния радиоволн, эксперимент, электронная концентрация, EISCAT, F-область.

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Возмущения электронной концентрации в высокоширотной верхней (F-область) ионосфере, вызванные воздействием мощных КВ-радиоволн Х-моды поляризации по данным наблюдений EISCAT радара некогерентного рассеяния радиоволн (расширенный реферат)

Представлены результаты экспериментальных исследований возмущений электронной концентрации в высокоширотной F-области ионосферы, вызванных воздействием мощных КВ-радиоволн необыкновенной (Х-мода) поляризации. Эксперименты выполнялись на КВ нагревном стенде EISCAT/Heating (69,6º с.ш., 19,2º в.д., L = 6,2, I = 78º), г. Тромсё, Норвегия. Мощные КВ-радиоволны Х-поляризации излучались в направлении магнитного зенита (диаграмма направленности антенны наклонена на 12° от вертикали к югу) на фиксированных частотах в диапазоне от 5,4 до 8 МГц при эффективной мощности излучения ERP = 360–820 МВт. В качестве основного диагностического средства эффектов воздействия использовался EISCAT радар некогерентного рассеяния радиоволн (НР) на частоте 930 МГц, пространственно совмещенный с нагревным стендом. Радар НР определял параметры ионосферной плазмы в диапазоне высот от 80 до 700 км с разрешением по времени 5 с и 3 км по высоте. По данным многочисленных экспериментов установлено, что типичным явлением при Х-нагреве является возрастание электронной концентрации N_e в F-области ионосферы в широком диапазоне высот, вплоть до верхней высотной границы измерений радара НР (~ 600–700 км), которые образуют каналы (дакты) повышенной плотности электронов. Выполнены исследования условий генерации и характеристик каналов (дактов) повышенной электронной плотности в высокоширотной верхней (F-область) ионосфере. Установлено, что каналы повышенной электронной плотности создаются при спокойных фоновых геофизических условиях при излучении мощной КВ-радиоволны необыкновенной (Х-мода) поляризации в направлении магнитного зенита на частотах нагрева как ниже, так и выше критической частоты слоя $F2$ ($f_Н \leq f_oF2$ и $f_Н > f_oF2$). Рассмотрены характеристики каналов для различных частот нагрева и отношений частоты нагрева к критической частоте слоя $F2$. Поведение N_e в каналах характеризуется сильными возрастаниями N_e до 50–70 % относительно фоновых значений в широком диапазоне высот, сопровождающимися сравнительно небольшими повышениями температуры электронов T_e (~ 20–30 % при нагреве на частотах $f_Н \leq f_oF2$ и до 40–50 % при нагреве на частотах $f_Н > f_oF2$) вследствие омического нагрева электронов. Возрастания N_e начинаются после включения нагревного стенда и достигают насыщения через ~ 30–50 с. После выключения стенда возвращение N_e к фоновым значениям в различных экспериментах происходило через 2–5 мин. Измерения радара НР в режиме сканирования искусственно возмущенной области ионосферы по углам возвышения дают возможность оценить горизонтальный размер каналов повышенной плотности электронов. Горизонтальный размер каналов повышенных значений N_e составлял ~ 3–4° и регистрировался только вблизи направления локального магнитного поля. Анализ условий создания и характеристик каналов повышенных значений N_e позволяет заключить, что воздействие мощной КВ-радиоволны Х поляризации на F-область высокоширотной ионосферы в направлении магнитного зенита вызывает ускорение электронов. Это обусловлено совпадением вращения электрического поля мощной волны с левосторонней круговой поляризацией (Х-мода) с гировращением электронов.