Artificial Small-scale Field-aligned Irregularities in the High Latitude Ionospheric F-region

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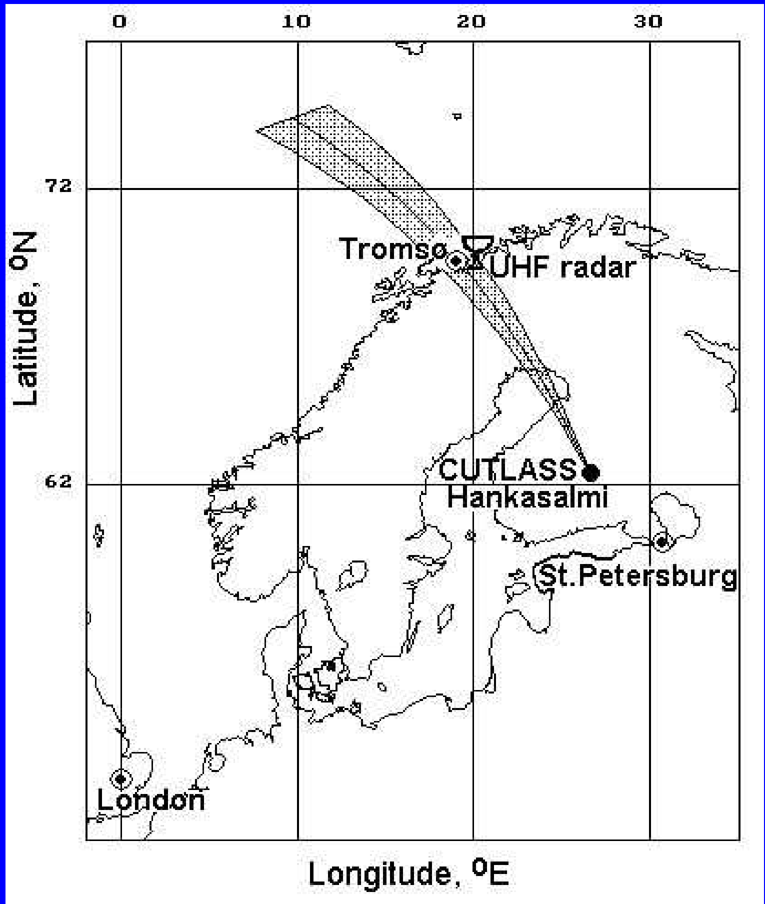
The ionospheric modification experiments are providing the means for understanding mechanisms and physical processes leading to the generation and evolution of ionospheric irregularities. We present experimental results concentrating on the features and evolution, generation conditions and mechanisms of small-scale field-aligned irregularities (FAIs), with spatial scale across the geomagnetic field of 7.5 – 15 m, in the high latitude ionosphere F region induced by the controlled injection of the powerful HF radio waves from the ground into the ionosphere. The behavior and properties of FAIs excited by the ordinary polarized (O-mode) HF pump waves are well known (see, for example, Robinson, 1989; Gurevich, 2007 and references therein). The main attention is paid to the recently discovered FAIs induced by the extraodinary polarized (X-mode) HF pump wave (Blagoveshchenskaya et al., 2011; 2014; 2015) and their comparison with the O-mode FAIs.

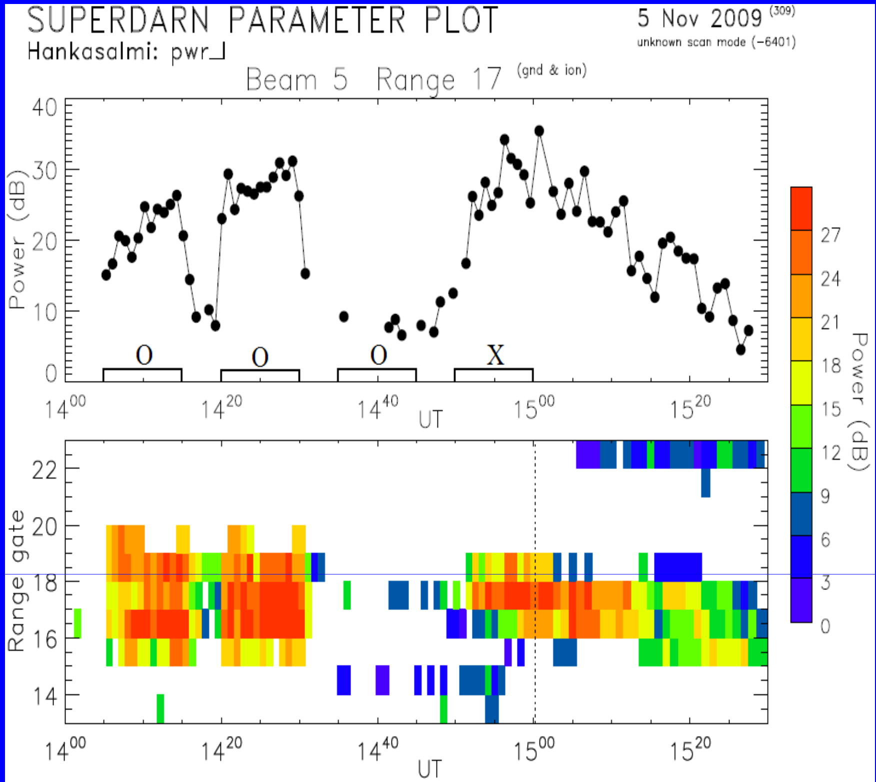
Instrumentation



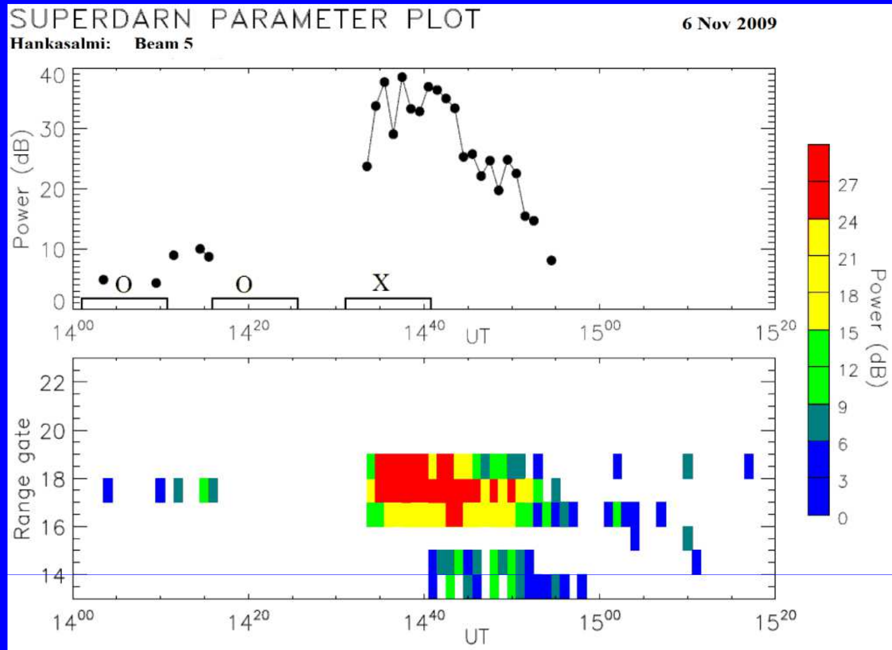
A map showing the experiment geometry. The EISCAT/Heating facility at Tromsø was used for HF ionospheric modification of F-region. HF heating facility was operating at heater frequencies of 4.0 – 8.0 MHz with an effective radiated power of 100 – 750 MW. HF pump wave with ordinary (O-mode) or extraordinary (X-mode) polarization was injected along the magnetic field line.

Instrument diagnostics included the CUTLASS (Co-operative UK Twin Located Auroral Sounding System) radar, the European Incoherent Scatter (EISCAT) UHF radar at 931 MHz near Tromsø and the EISCAT ionosonde (dynasonde).

Artificial small-scale field-aligned irregularities (f_H >foF2)

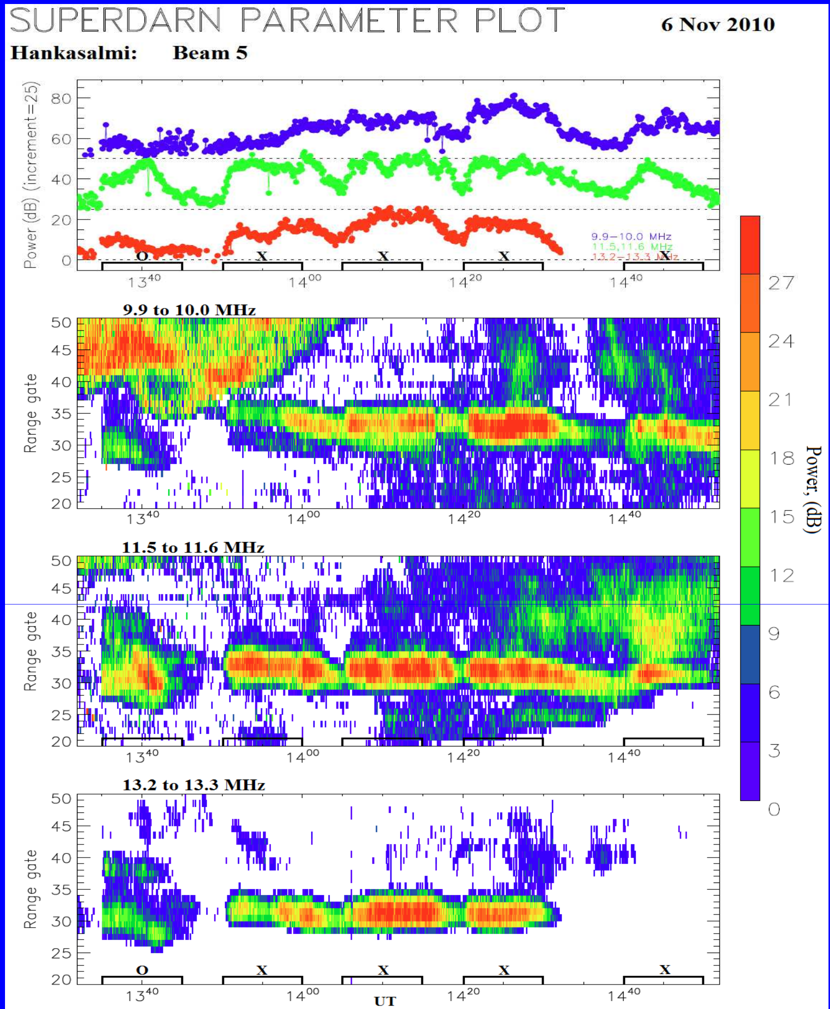


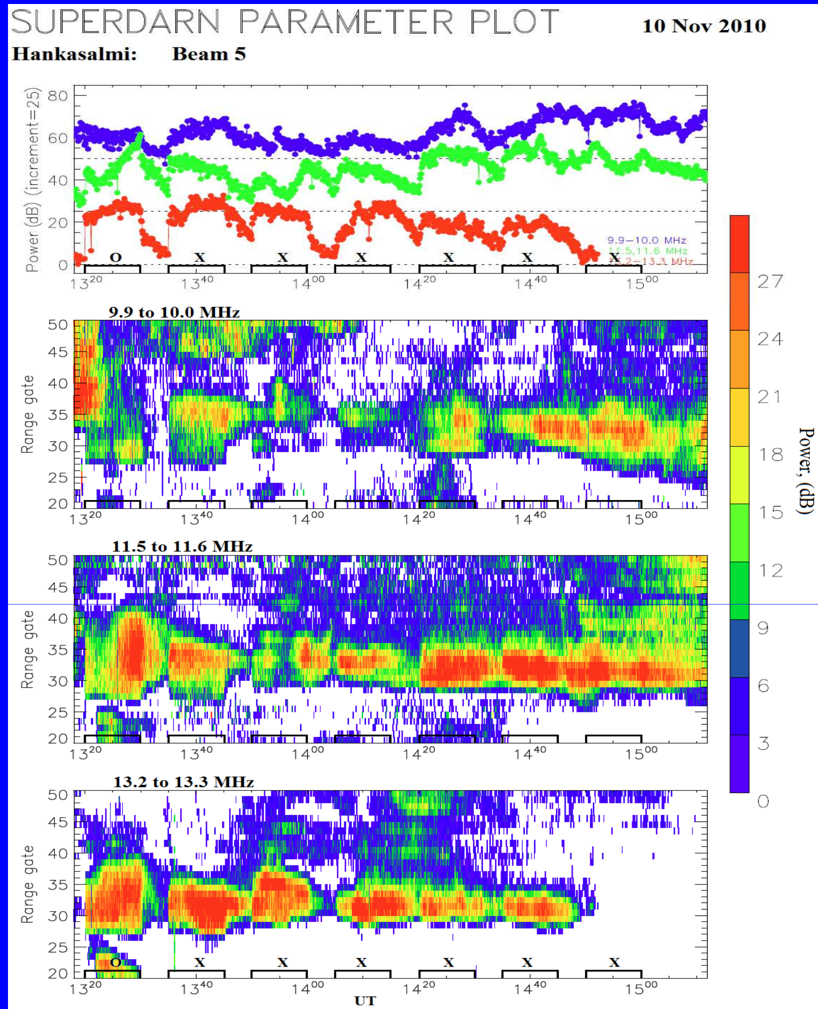
Backscattered power from the Hankasalmi (Finland) CUTLASS radar (beam 5) at f ≈ 10 MHz for alternating O/X-mode heating at f_H = 4.040 MHz (ERP= 123 MW) on 5 November, 2009.



Backscattered power from the Hankasalmi (Finland) CUTLASS radar (beam 5) at f ≈ 10 MHz for alternating O/X-mode heating on 6 November , 2009. Power stepping mode of the Tromsø HF heating facility, utilizing an orderly sequence of 20%, 50%, 70%, 85%, 100%, 100%, 85%, 70%, 50%, 20% (from 30 to 157 MW and back) was used. The duration of each step is 1 min. The HF pump wave was radiated at f_H = 4.040 MHz towards magnetic zenith.

Artificial small-scale field-aligned irregularities (f_H >foF2)

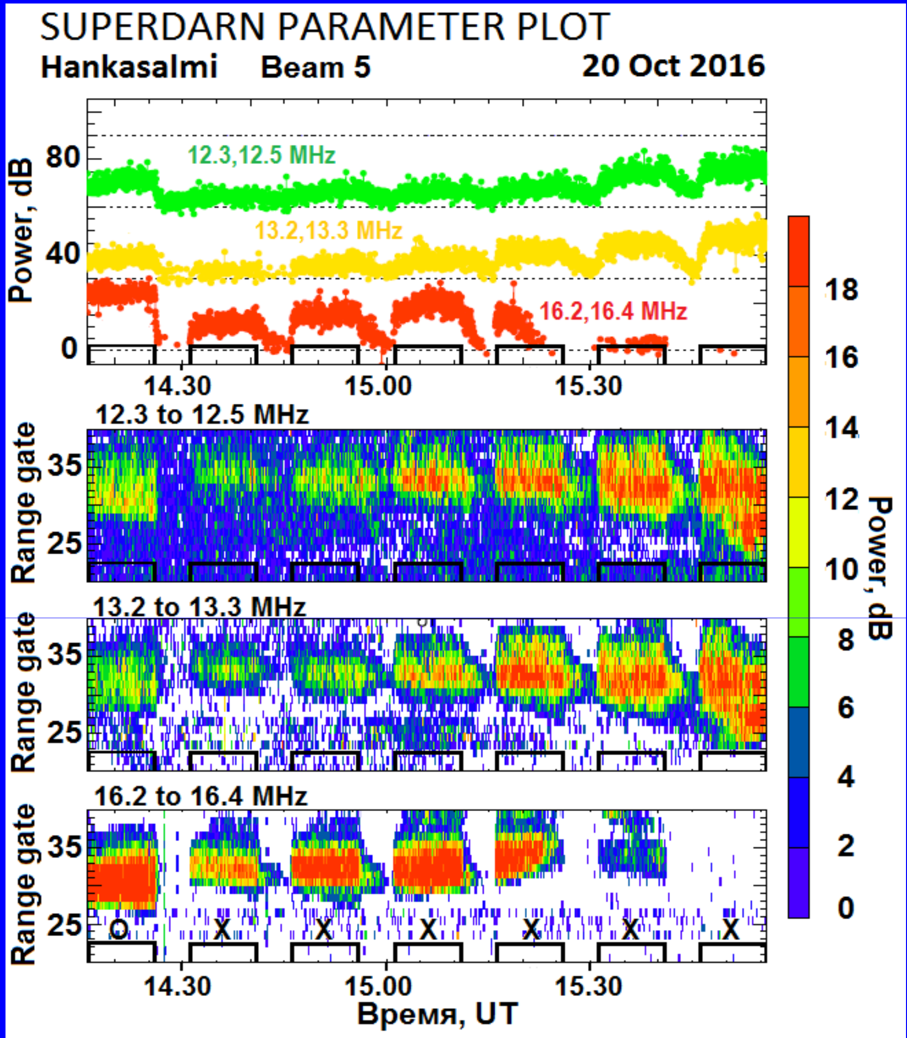




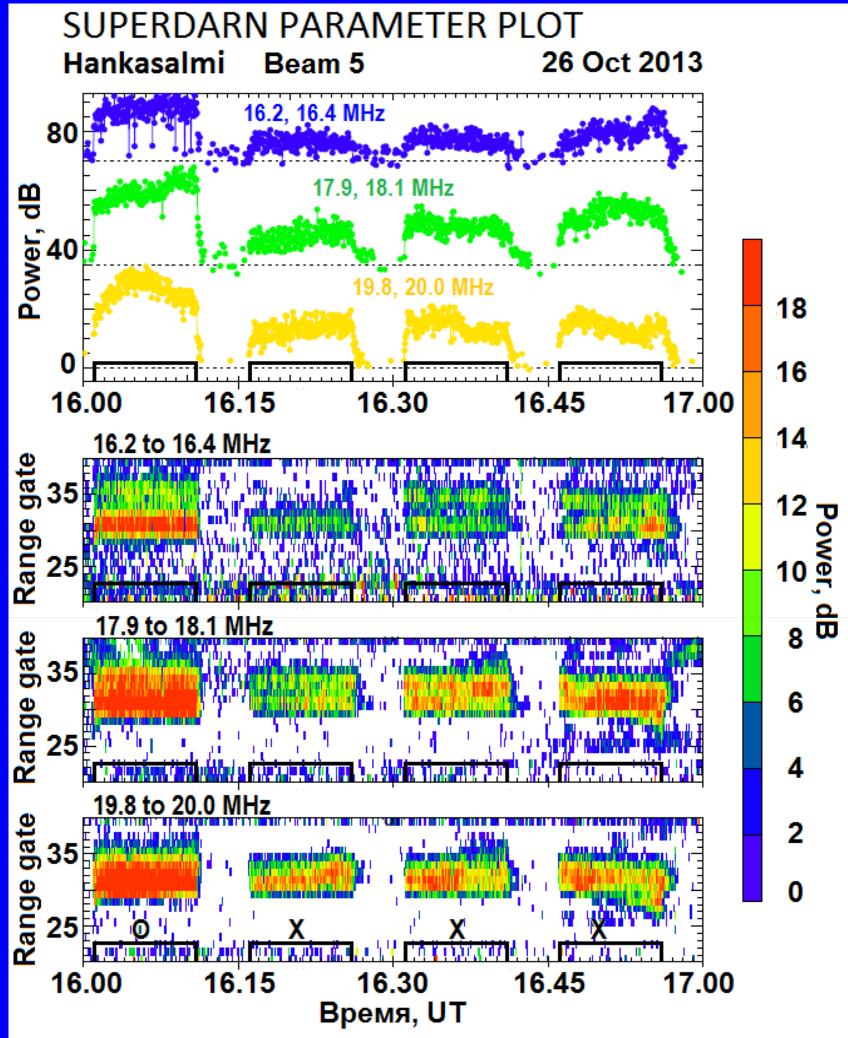
Backscattered power from the Hankasalmi (Finland) CUTLASS radar (beam 5) at f ≈ 10, 11.5, and 13 MHz for contrasting O/X-mode heating at f_H = 4.544 MHz (ERP=95 MW) on 6 November, 2010.

Backscattered power from the Hankasalmi (Finland) CUTLASS radar (beam 5) at f ≈ 10, 11.5, and 13 MHz for contrasting O/X-mode heating at f_H = 4.544 MHz (ERP=113 MW) on 10 November, 2010.

Artificial small-scale field-aligned irregularities ($f_H \leq foF2$)

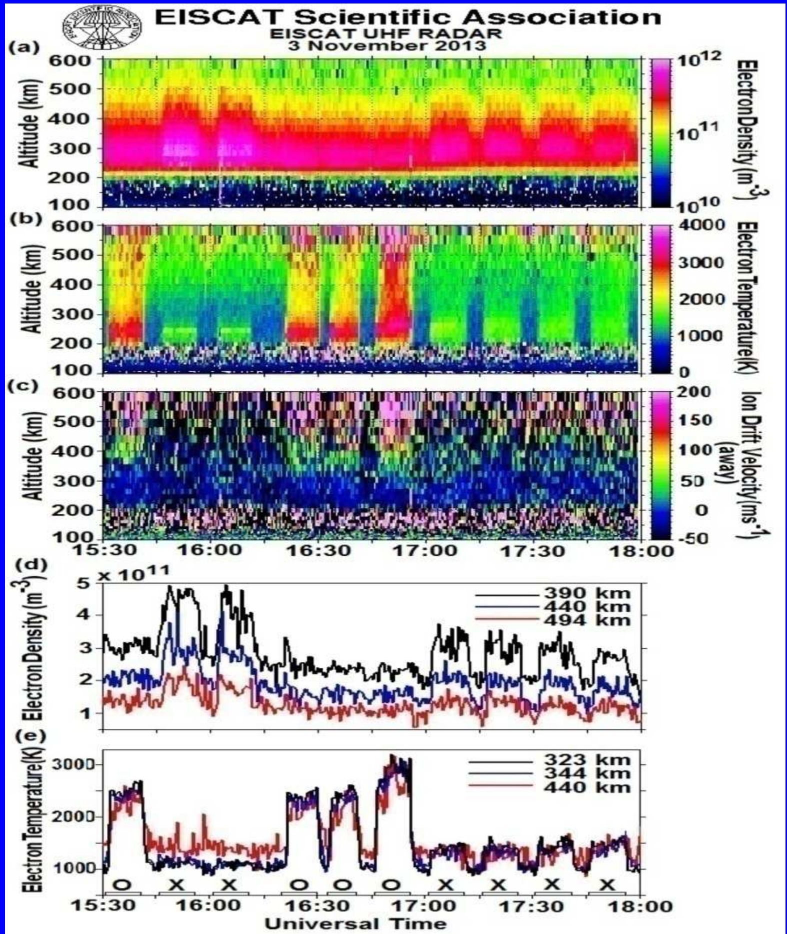


Backscattered power from the Hankasalmi (Finland) CUTLASS radar (beam 5) at f ≈ 12, 13, and 16 MHz for O/X-mode heating at f_H = 4.544 MHz (ERP=130 MW) on 20 October, 2016. Heater-on cycles and polarization is shown on the time axis.

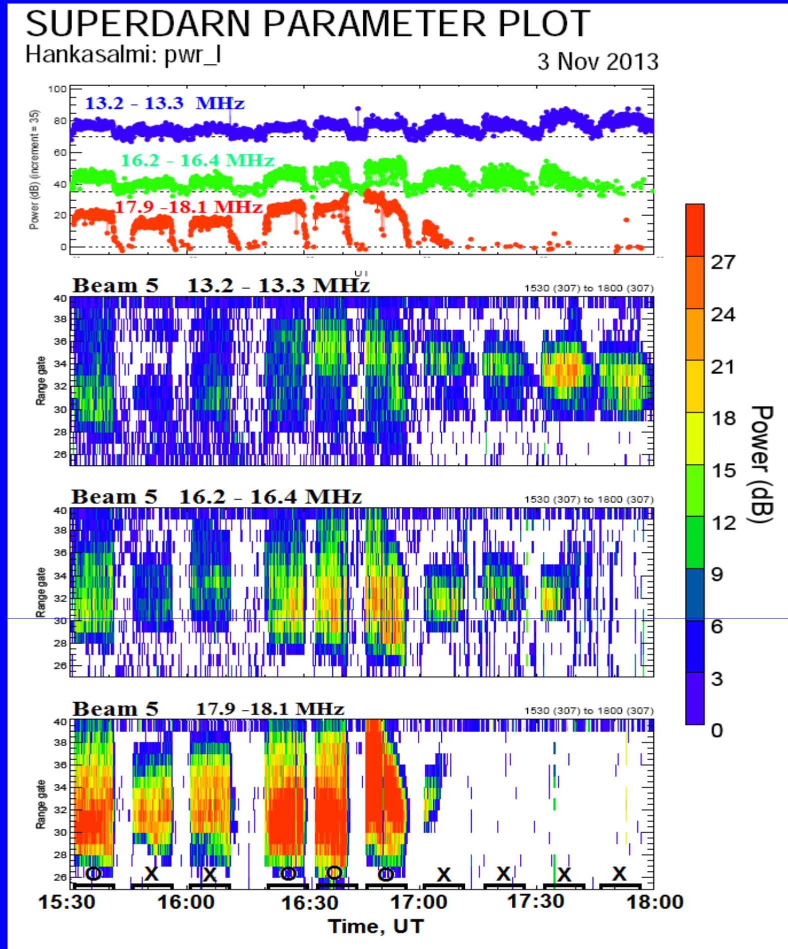


Backscattered power from the Hankasalmi (Finland) CUTLASS radar (beam 5) at frequencies of about 16, 18 and 20 MHz on 26 October 2013. HF pump wave was radiated towards MZ at fH = 6.96 MHz (ERP = 550 MW) .

Alternating O/X-mode HF pumping (f_H = 6.2 MHz)

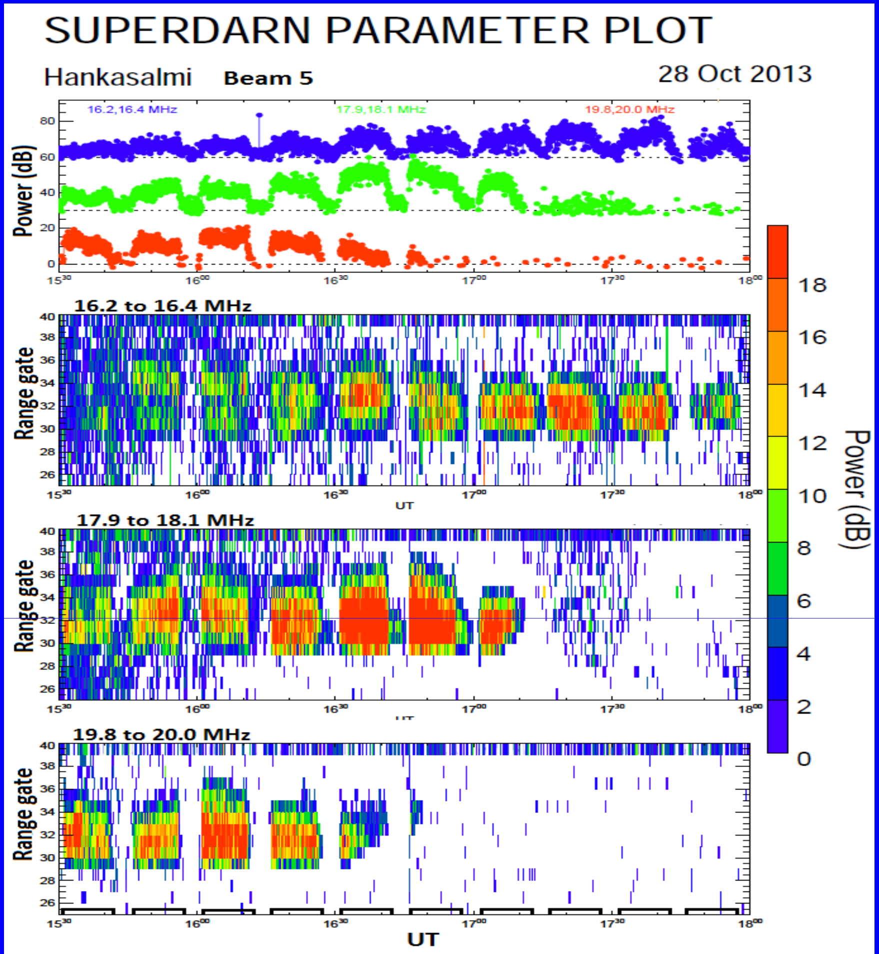


The behaviour of the Ne, Te , Vi from the EISCAT UHF radar observations at Tromso for O/X-mode heating on 3 November 2013. The O/X-mode HF pump wave at f_H =6.2 MHz (ERP = 450 MW) was radiated towards MZ by 10 min on, 5 min off cycles. The critical frequency foF2 dropped from 6.7 MHz at 15.30 UT to 5.2 MHz at 18 UT (f_H / foF2 = 0.92 – 1.2).

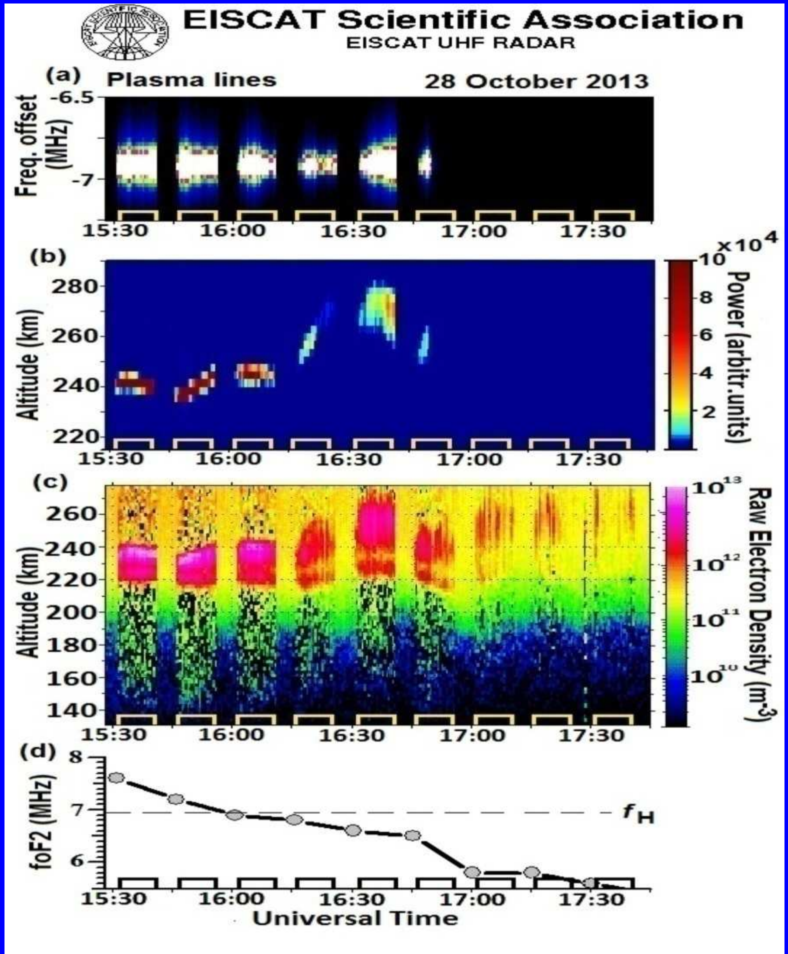


Backscattered power from the Hankasalmi (Finland) SuperDARN radar (beam 5) at operational frequencies of about 13, 16 and 18 MHz on 3 November 2013. HF pump wave was radiated towards MZ at fH = 6.2 MHz (ERP = 450 MW) .

X-mode FAIs and HF-induced plasma turbulences



Backscattered power from the Hankasalmi (Finland) SuperDARN radar (beam 5) at operational frequencies of about 16, 18 and 20 MHz on 28 October 2013. The X-mode HF pump wave was radiated towards MZ at fH = 6.96 MHz (ERP = 550 MW) . The foF2 values dropped from 7.6 to 5.3 MHz.



The behaviour of HF-induced plasma lines and raw electron densities obtained from the EISCAT UHF radar on 28 October, 2013. The X-mode HF pump wave was radiated towards MZ at fH = 6.96 MHz (ERP = 550 MW) . The foF2 values dropped from 7.6 to 5.3 MHz (f_H / foF2 = 0.91 - 1.35) .

Distinctive features of FAIs

	X-mode	O-mode
generation	$f_H \leq foF2$;	$f_H \leq foF2$
	$f_H > foF2$ (up to 2 MHz)	
spatial scale	$l_\perp \approx 7.5 – 15$ m	$l_\perp \approx 7.5 – 15$ m
growth time	12 – 120 s	3 – 9 s
decay time	40 – more than 300 s	12 – 30 s
threshold of excitation from the "cold start"		
low f_H = 4 MHz	75 MW	8 – 10 MW
high f_H = 8 MHz	160 MW	26 MW

- Generation mechanisms of the FAIs under O-mode HF pumping at $f_H \leq foF2$ is the thermal parametric (resonance) instability at the upper hybrid resonance altitude (Grach and Trachtengertz, 1975; Gurevich and Vas'kov 1978).
- Generation mechanisms of the FAIs under X-mode HF pumping excited at $f_H \leq foF2$ and $f_H > foF2$ both is not completely understood. It is suggested that X-mode FAIs are generated via two-step process (Borisov et al., 2018; Blagoveshchenskaya et al., 2011). 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) due to the self-focusing instability is occurred. Excitation and behavior of small-scale FAIs is driven by large-scale irregularities. Their possible generation mechanisms can be the temperature gradient-drift instability (Borisov et al., 2018) or the filamentation instability (Kuo, 2015).

Summary

- It was found that the features and physical driving mechanisms of FAIs 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.
- X-mode FAIs are excited in the regular high-latitude ionosphere F-region under quiet magnetic conditions when the heater frequency is below as well as much above the critical frequency of the F2 layer (up to 2 MHz), whereas the O-mode FAIs can not be fundamentally generated when the pump frequency f_H is above foF2.
- The X- and O-mode FAI behaviors exhibit the different grow and decay times, and thresholds of excitation that is indicative of different physical mechanisms of their generation.
- As is found from EISCAT UHF radar measurements FAIs greatly impact on the development of strong artificial turbulence such as Langmuir and ion-acoustic plasma waves.

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Acknowledgements

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