Spatiotemporal dynamics of HF-induced ionospheric turbulence revealed by diagnostic stimulated electromagnetic emission and test radio waves at HAARP

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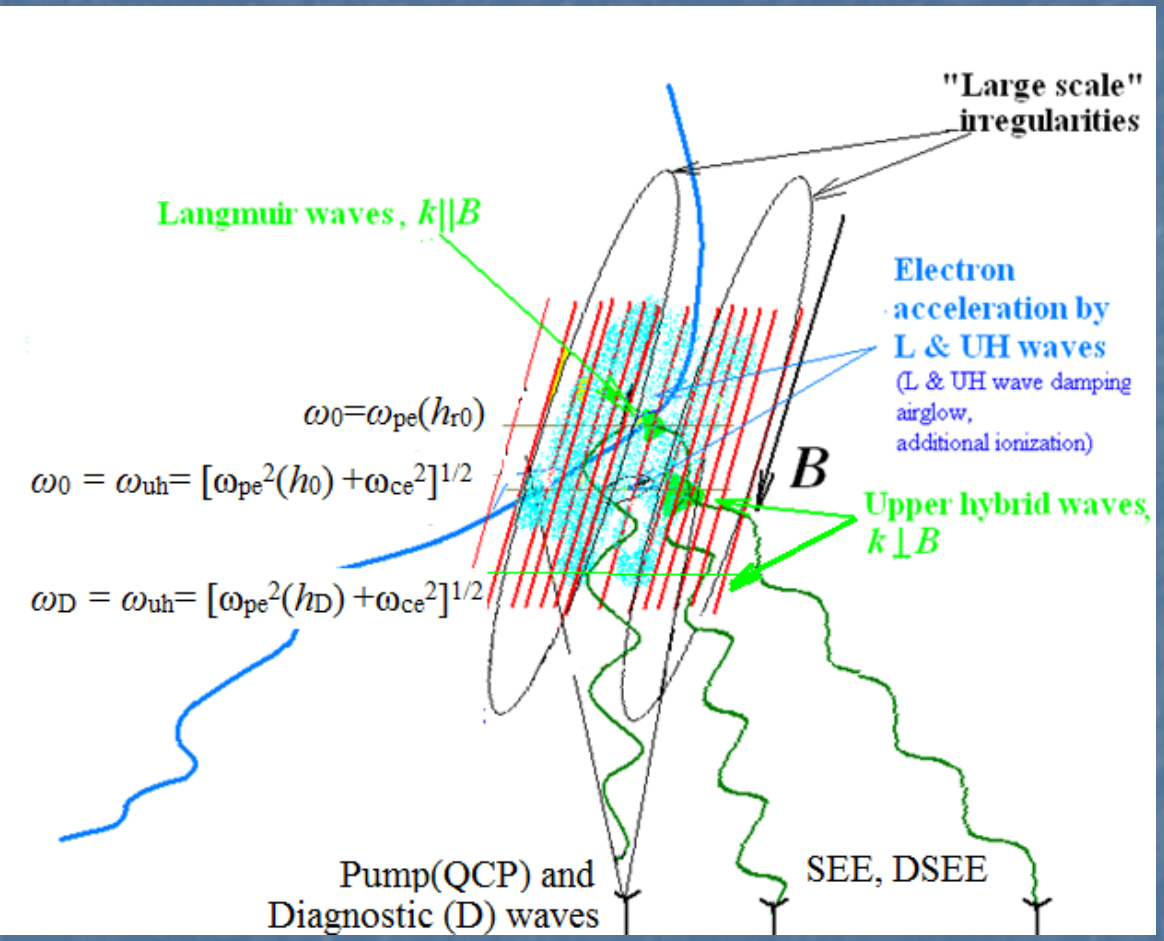
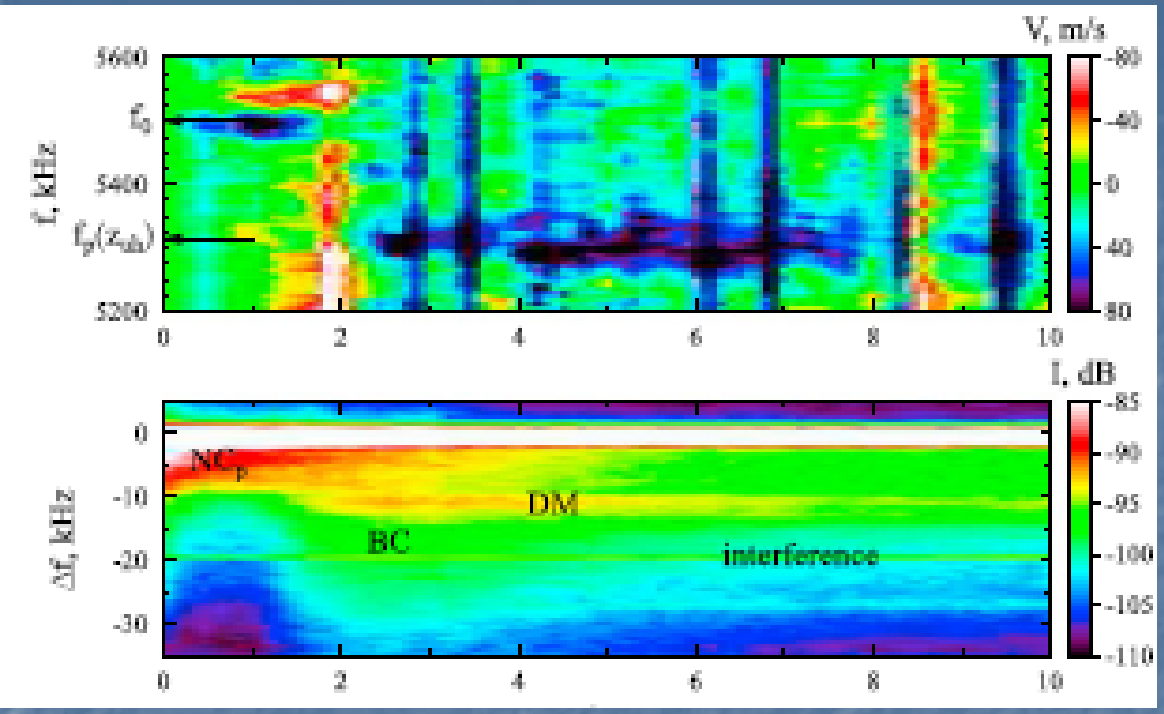
УНИВЕРСИТЕТ ЛОБАЧЕВСКОГО

We report on the dynamics of the HF-pumped ionosphere explored using measurements of stimulated electromagnetic emissions (SEE) and anomalous absorption (AA) of test radiowaves during the March 2011 HAARP heating experiments. In addition to the SEE excited by quasi-continuous pump waves (QCP), short-pulse test or diagnostic waves at frequencies shifted from the pump frequency excited diagnostic SEE (DSEE). Such an experimental setup allowed studying the dynamic spectra and damping rates of the plasma waves related to both test and QCP waves, as well as the QCP-related small-scale magnetic field-aligned irregularities (striations) inside the heated volume.

Very simple scheme of the processes occurring in the HF pumped volume of the *F*-region

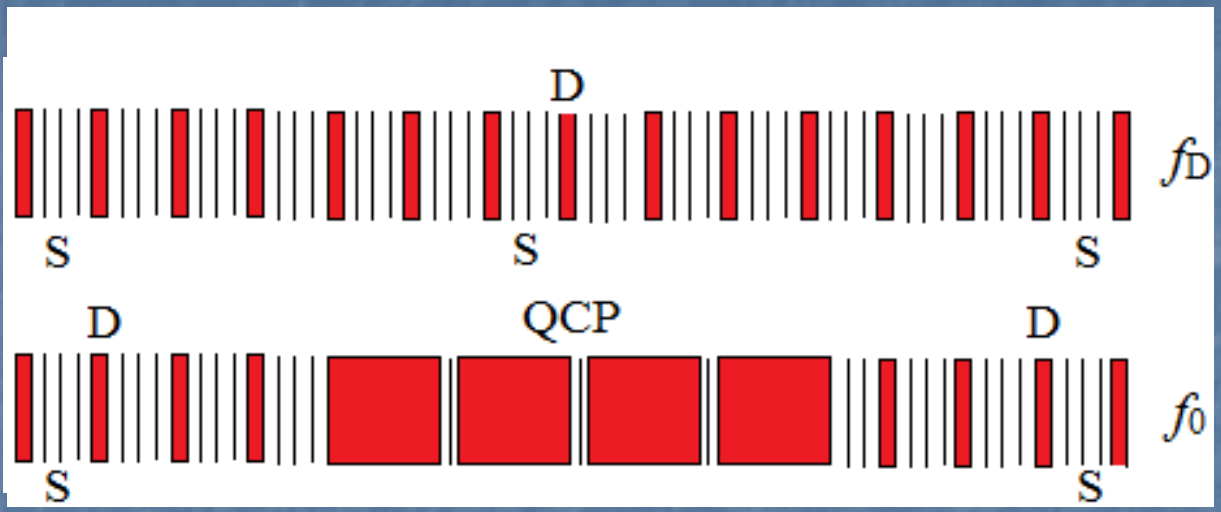


A typical dimension of the excited striations along ***B***, $l_{||}$~ 5-30 km, is close to the altitudinal extent of the heated region and the F-region thickness at the Sura, HAARP, and EISCAT facilities with χ = 18.5°, 14.5°, and 12°.The altitudes of the upper-hybrid resonances (h_D) for the diagnostic waves at frequencies f_D and the pump wave (h_0) at the frequency f_0 ($f_D \neq f_0$) significantly differ from each other. Measuring the diagnostic SEE (DSEE) generated by a short-pulse diagnostic wave (DW) will specify the DW-related Z/UH modes as well as the QCP related striations near h_D. Applying different frequencies f_D will provide the relevant information at different altitudes in the perturbed region. Additional information on the striation intensity can be revealed from measurements of anomalous absorption (AA) of the sounding (S) waves.



Langmuir modes are excited near the PW reflection point, $f_{pe}(h_r) = f_0$, in a few milliseconds after the arrival of a high-power HF radiowave. Langmuir waves cause the so-called ponderomotive narrow continuum feature (**NCp**) of stimulated (or secondary) electromagnetic emissions (SEE) red-shifted by up to 40 kHz from f_0, i.e., $|\Delta f_{NC}| = f_0 - f_{NC} < 40$ kHz. The long-term, >0.5 s, HF pumping leads to excitation of the Z-mode and/or upper-hybrid (UH) quasi-electrostatic waves, as well as short-scale, 0.5-50 m across the magnetic field, field-aligned irregularities (striations). The strongest interaction between the pump, UH waves, and striations occurs near the UH height $h_0 < h_r$, where the UH frequency $f_{UH} = (f_{pe}^2 + f_{ce}^2)^{1/2}$ matches f_0 (f_{ce} is the electron cyclotron frequency). Transfer of the UH wave energy over frequencies and their scattering on striations leads to generation of the UH-related SEE features, such as the Downshifted Maximum (**DM**), $f_{DM} \approx f_0 - 10$ kHz, Broad Continuum (**BC**), -60 kHz $< \Delta f_{BC} = f_{BC} - f_0 < 0$

Pump schedule used during the experiment at HAARP, March 28, 2011



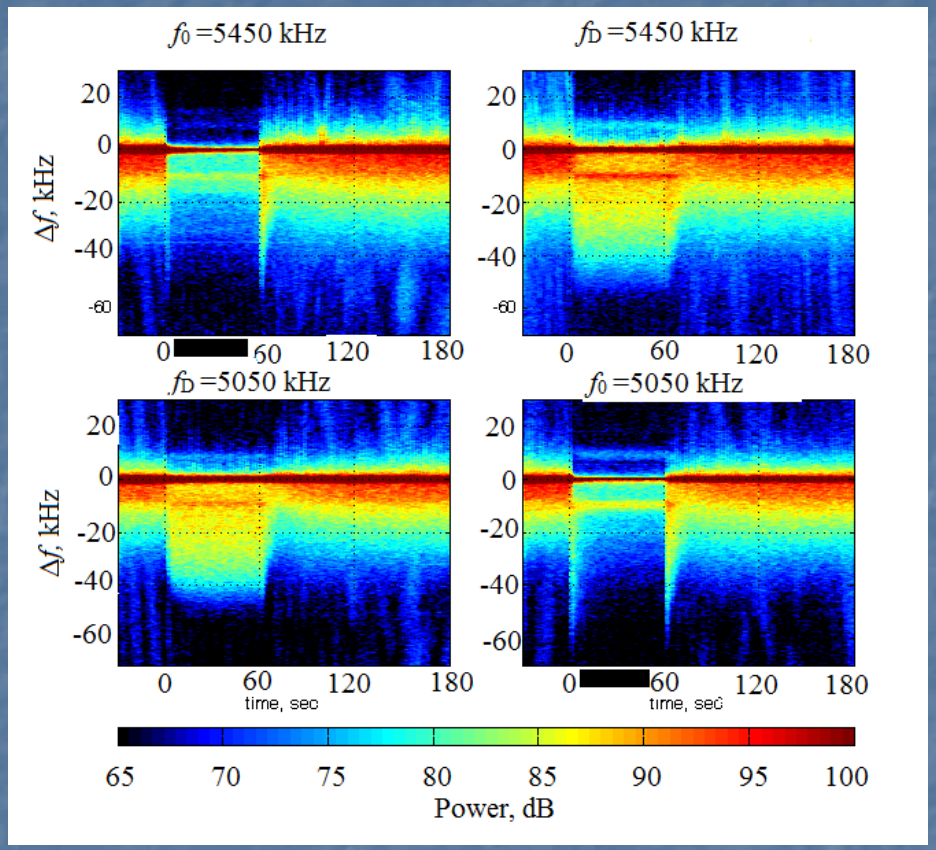
$\delta f = f_0 - f_D = = \pm 200$, ± 400, ± 600, ± 800 and ± 1000 kHz

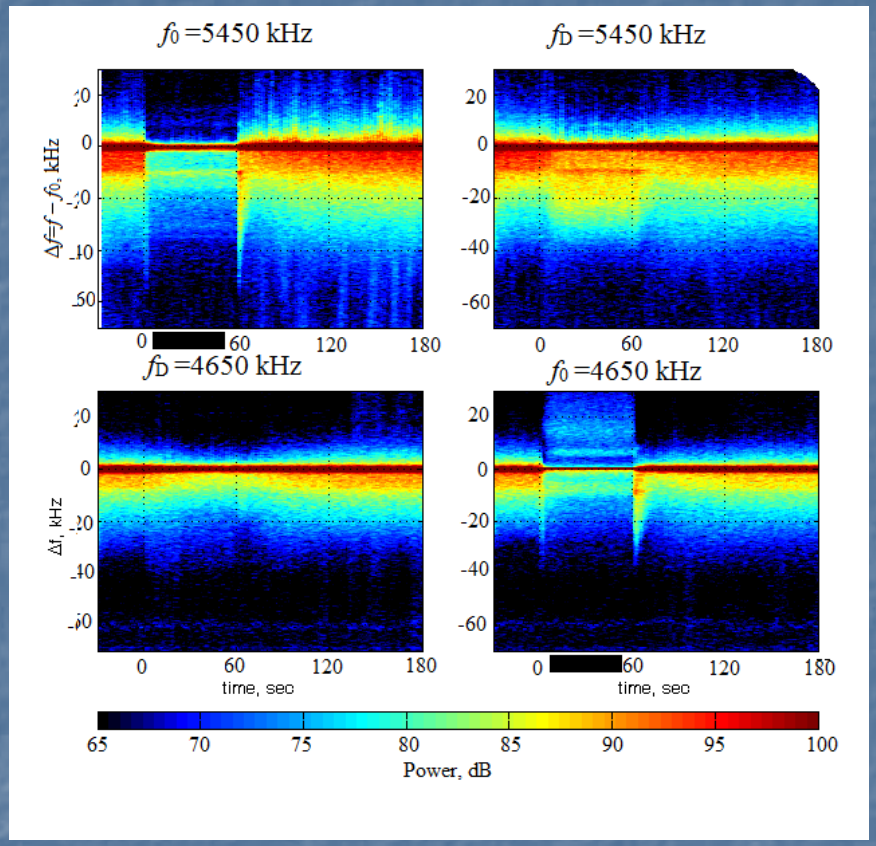
Corresponding reflection altitude differences were 5-6 km, 8-9 km, 13-17 km, 18-21 km, and 24-25 km, respectively.

30 s: the primary pump with P_{ef} =400 MW is transmitted vertically at f_0 = 5450 kHz in the low-duty diagnostic (D) regime ($f_0^D = f_0$), with τ_D=20 ms, T_D=1 s. **60 s:** quasi-continuous pumpimg (QCP), with τ_Q=160 ms and T_Q=200 ms. **210 s:** the D-regime. **Simultaneously:** the secondary pump at $f_D = f_0 + \delta f$ in the D regime, δf = –200 kHz, P_{ef} =400 MW. **In addition,** sounding (S) pulses (τ_S=100 μs, T_S=200 ms) at the same ERP and carrier frequencies, $f_S = f_0$ and $f_S^D = f_D$.

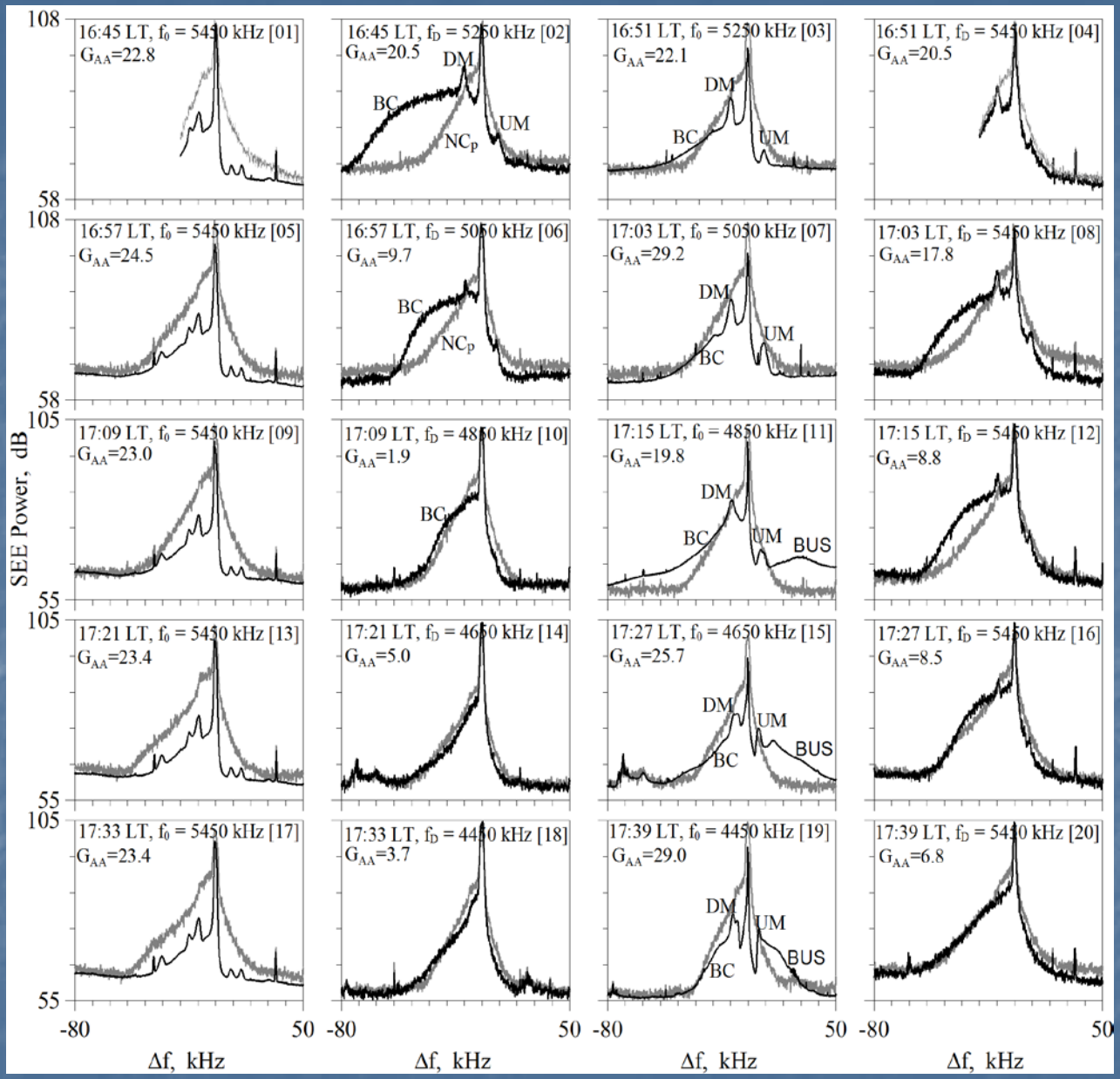
The next 5 min cycle starts after a 1 min intermission, with the **primary and secondary pump frequencies being interchanged**, i.e., f_D= 5450 kHz, $f_0 = f_D + \delta f$. Then, after the 1 min intermission, the whole 12 min sequence is repeated with $|\delta f|$ increased by 200 kHz.

Experimental results





SEE and DSEE spectrograms during the QCP and D regimes with $|\delta f|$ = 400 kHz and $|\delta f|$ = 800 kHz

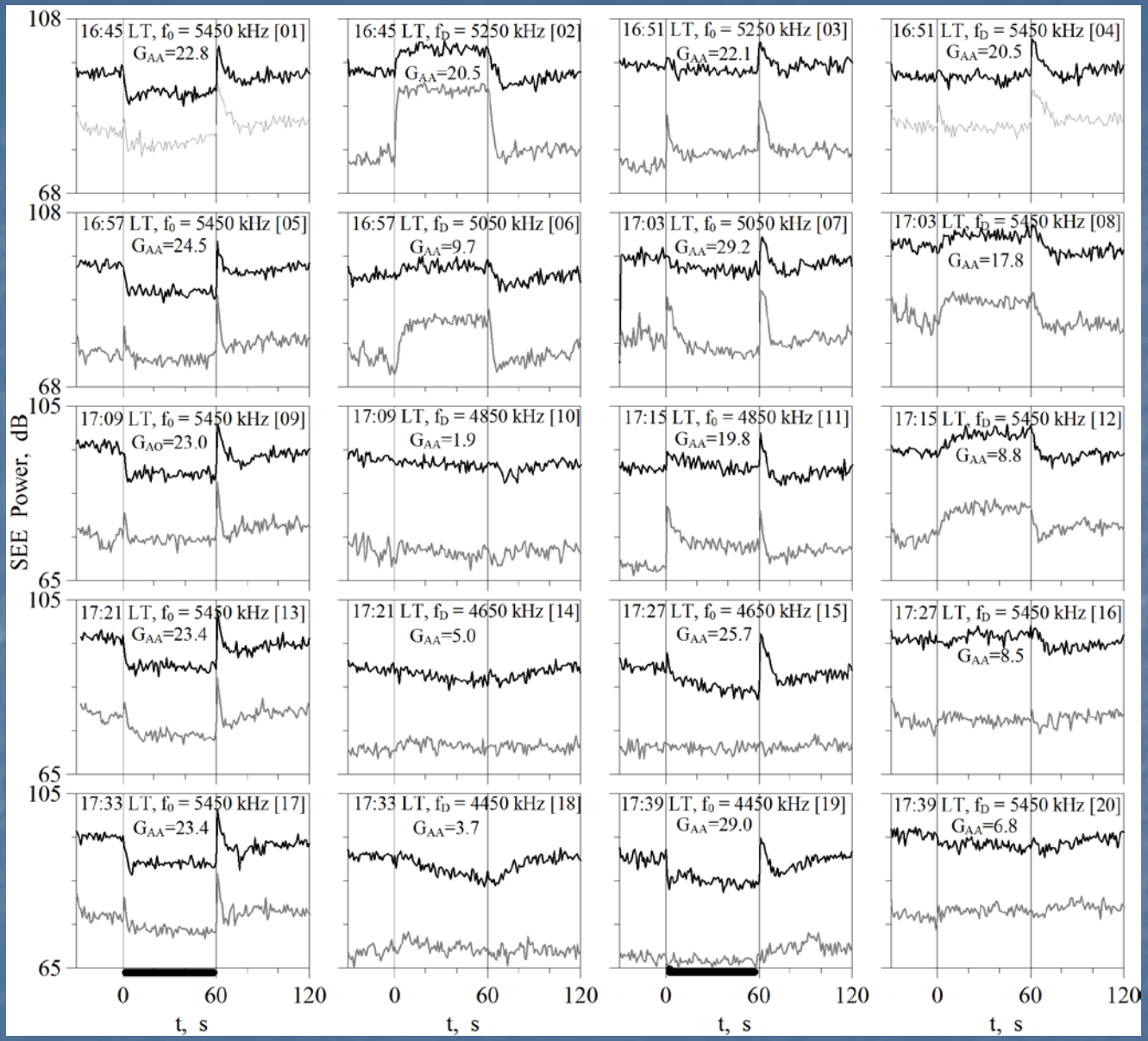


(left column) SEE spectra for f_0=5450 kHz during QCP (30-60 s, black), (2nd column) DSEE for different D-wave frequencies f_D during QCP (40-60 s, black) at f_0=5450 kHz, (3rd) SEE for different f_0 (black), (right) DSEE related to f_D= 5450 kHz during QCP (black) at different f_0. The gray lines: DSEE during the D-regime before QCP, i.e., from – 30 to 0 s. The time and number of each cycle, with the pump frequencies f_0 and f_D and the magnitude of the S-wave anomalous absorption at $f_S = f_{0,D}$ in dB (G_{AA}), are shown.

During the diagnostic regime before the QCP regime is turned on and approximately 20 s after the QCP is turned off, the DSEE spectra show only Langmuir-related NCp feature generated near the reflection points of the primary and secondary pump waves.

After the QCP turn-on, the NCp suffers strong suppression due to anomalous absorption. On the contrary, for $f_0 = f_D$ the DM and BC are intensified.

The DM, BC and UM features in the SEE spectra are generated for all QCP frequencies used (columns 1,3), while for DSEE with $f_D \neq f_0$ these features during QCP are well distinguished for δf=200, 400, 600, 800 kHz, i.e. $h_D - h_0 \leq$ 20 km, and for δf= –200 and –400 kHz, i.e. $h_0 - h_D \leq$ 9 km.

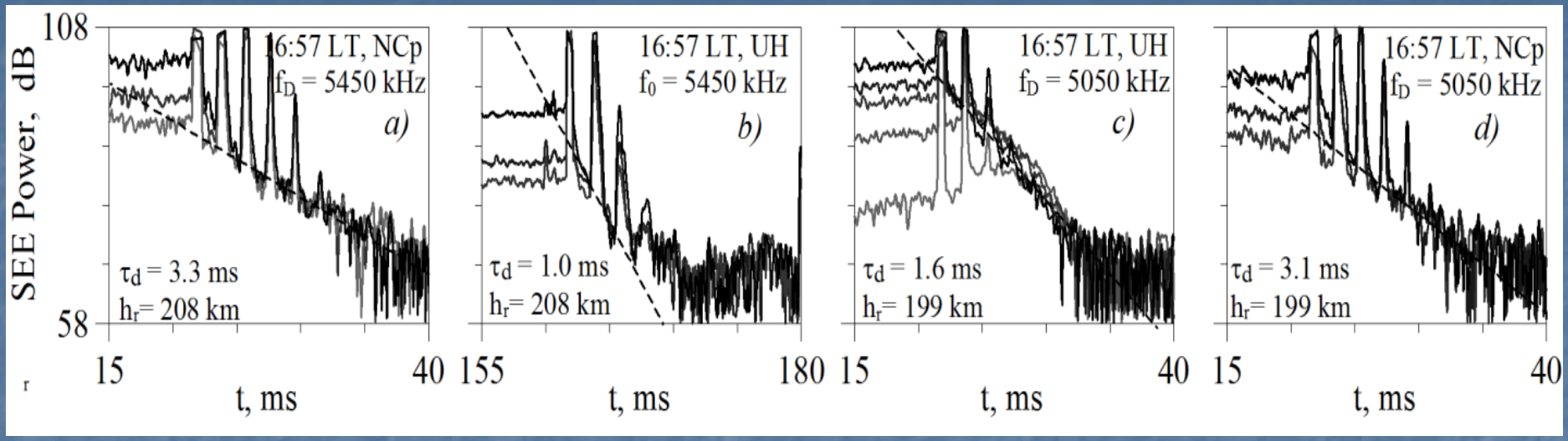


Dynamics of the SEE and DSEE at frequency shifts corresponding to the UH-related features DM (Δf_{DM} = –10 kHz, black) and BC (Δf_{BC}= –20 kHz for the panels [01] and [04], and Δf_{BC}= –40 kHz for other panels, gray).

For $f_0 = f_D$ the DM and BC are intensified and exhibit the overshoot effect, i.e., the intensity drops after achieving the maximum. Even stronger overshoots of the DM and BC appear when QCP is switched to the D-regime.

The maximum overshoot, i.e., the ratio of the SEE intensity at the maximum to that at the steady state of 10-15 dB occurs at the primary pump frequency f_0 in the center of the pumped volume near h_0.

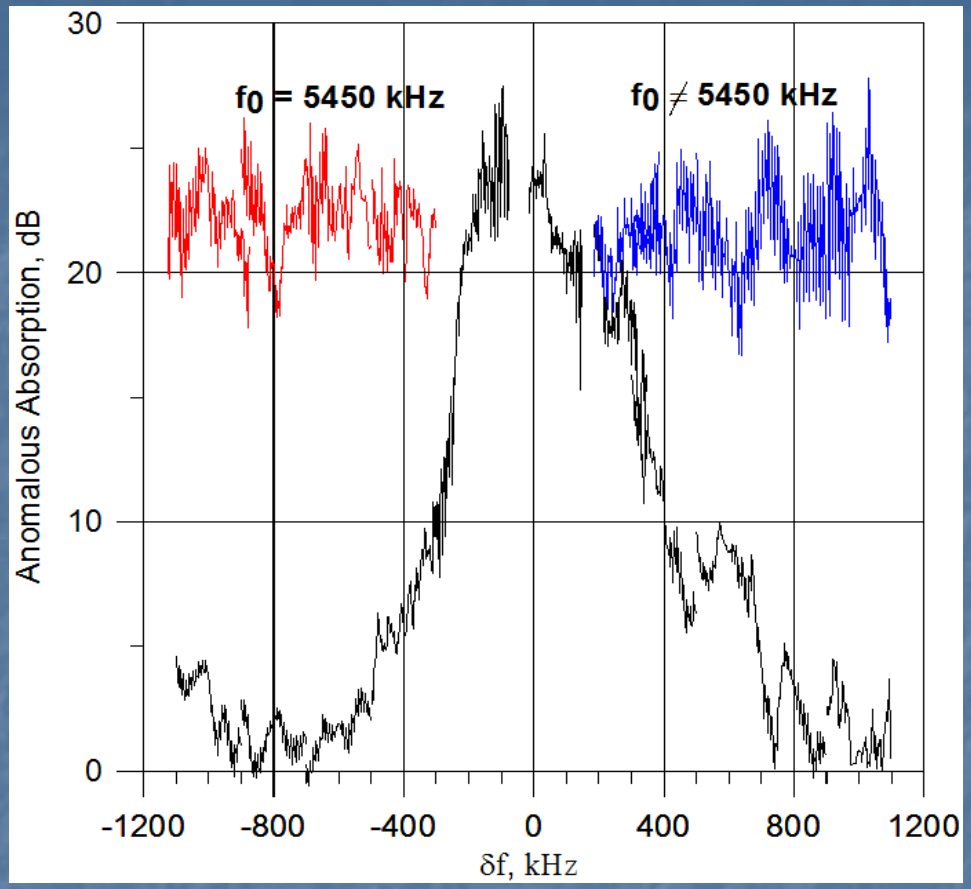
These overshoots after QCP is turned on (off) are readily explained in terms of the competition between the increase (decrease) of the AA and growth (fall) of the SEE source due to developing (relaxing) striations



Variation of the DSEE after 20-ms pulses and SEE during 30 ms pauses in QCP at different frequency shifts corresponding to frame [05] in Figs. 2 and 3. (*a*) and (*d*): the NCp feature without QCP; (*b*) the SEE and (*c)* DSEE features related to UH waves. . The primary pump wave (QCP) frequency f_0=5450 kHz. The SEE/DSEE decay time τ_d and reflection heights of the D and QCP waves h_r are shown in the frames. The step between the frequency offsets for different lines is 5 kHz for the NCp and 10 kHz for the UH-related SEE features starting from Δf = –11 kHz (the upper line).

It is established that

1) during QCP the decay time of the UH-related SEE features (in the center of heated volume, panel *b*) is shorter than that of the UH-related DSEE features in the heated volume periphery (panel *c*);
2) the decay time of the Langmuir related NCp (τ_d ~3.1-3.3 ms) is longer than that of the UH related SEE and DSEE features and close to the collisional plasma wave damping rate.



A synopsis of the anomalous absorption coefficient (G_{AA}) of the S-wave spectral components vs. the frequency offset $\delta f = f - f_0$ for frequencies f in the range $|f - f_S| < 100$ kHz. The red and blue lines show G_{AA} for 5 cycles at $f_S = f_0 = 5450$ kHz and $f_0 < 5450$ kHz, respectively. The black line shows G_{AA} for $f > f_0$ (on the right) at $f_0 < f_S = f_D = 5450$ kHz and for $f < f_0$ (on the left) at $f_D < f_0 = 5450$ kHz.

It is seen that the AA magnitude maximizes (G_{AA} ~25 dB) at the center of the heated volume for $f_S \sim f_0$ and decreases down to 2-3 dB with $|f - f_0|$, i.e., towards the periphery. Interestingly, G_{AA} decreases faster at negative offsets or $h_0 > h_D$.

The results obtained allow to study a dependence of the intensity and spatial spectrum of striations excited by the primary pump wave on altitude, i.e. on the distance from the center of the heated volume.

The similarity of these results with that obtained earlier at the “Sura” facility with much smaller ERP remain to be understood, as well as the asymmetry of the DSEE and AA behavior relative to the center of the heated volume.

Thank you for the attention!