Electron Gyroharmonic Effects in Ionization and Electron Acceleration during High-Frequency Pumping in the Ionosphere

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Optical emissions and incoherent scatter radar data obtained during high-frequency electromagnetic pumping of the ionospheric plasma from the ground give data on electron energization in an energy range from 2 to 100 eV. Optical emissions at 4278 Å from $N_2{}^+$ that require electrons with energies above the 18 eV ionization energy give the first images ever of pump-induced ionization of the thermosphere. The intensity at 4278 Å is asymmetric around the ionospheric electron gyroharmonic, being stronger above the gyroresonance. This contrasts with emissions at 6300 Å from $O(^1D)$ and of electron temperature enhancements, which have minima at the gyroharmonic but have no apparent asymmetry. This direct evidence of pump-induced ionization contradicts previous indirect evidence, which indicated that ionization is most efficiently produced when the pump frequency was below the gyroharmonic.

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When a powerful high-frequency (HF, 3–30 MHz) electromagnetic pump wave, with a frequency less than the peak ionospheric plasma frequency, is transmitted into a quiet ionosphere, plasma turbulence is excited. Depending on factors such as the pump frequency f_0, pump duration, and pump duty cycle, either Langmuir turbulence (LT) or upper hybrid (UH) turbulence can be excited (e.g., [1]). At high latitudes, LT dominates during the first few 100 ms (e.g., [2]) of HF pumping, after which UH turbulence starts to dominate. At lower latitudes, LT is dominating even though *in situ* observations of density striations [3] indicate that UH related processes also exist. Here the focus is on UH turbulence excited on long time scales (>1 s). Several of the ionospheric responses to the pump-excited turbulence are sensitive to f_0 near harmonics s of the electron gyrofrequency f_e: stimulated electromagnetic emissions [4,5], anomalous absorption of radio waves propagating through the pump-ionosphere interaction region [6], enhancements of the electron temperature T_e [7], excitation of filamentary density irregularities [8], and pump-induced emissions at 6300 Å from $O(^1D)$, I_{6300} [9,10]. Particularly in the bottomside ionosphere with a monotonically increasing plasma density and a decreasing f_e with increasing altitude, there is only one height where the local UH frequency $f_{UH} = sf_e$ for a given s [$f_{UH} = (f_e^2 + f_p^2)^{1/2}$, where f_p is the plasma frequency]. When f_0 equals this double resonance frequency, UH and electron Bernstein phenomena are suppressed, due to the linear dispersion properties of the wave modes. This results in a minimum in the anomalous absorption, density irregularities, T_e, I_{6300}, and excitation level of certain features of the stimulated electromagnetic emissions.

A long-standing problem is to understand the dissipation of the pumped turbulence by electron energization. Related to the question of electron energization and acceleration during HF pumping is the possibility to ionize neutral constituents in the ambient thermosphere. This, as well as enhancements in 4278 Å, has been theoretically predicted [11]. Experimental results on multifrequency Doppler sounding of the pumped ionosphere, in which weak HF electromagnetic waves are transmitted into and reflected from the pump-ionosphere interaction region, have previously been interpreted in terms of pump-induced ionization [12,13]. Specifically, positive Doppler shifts were attributed to ionization due to electron acceleration and negative Doppler shifts to plasma expulsion by heating. Experiments at the Sura facility in Russia for different f_0 around sf_e ($s = 4, 6$) resulted in positive Doppler shifts for $f_0 < sf_e$ and negative Doppler shifts for $f_0 > sf_e$, provided the pump reflection height was above about 220 km [13]. The multifrequency sounding capability used showed that the Doppler shifts occurred in an altitude region near the UH resonance height.

Inelastic collisions between electrons with energies above 1.96 eV and ionospheric atoms and molecules result in excited states that emit light at visible wavelengths. Thus, measurements of the enhanced emissions (also known as artificial airglow) is a direct observation of electrons with energy above the corresponding excitation threshold. Specifically, enhancements at 4278 Å, I_{4278}, from the $N_2^+(B\,^2\Sigma_u^+)$ state (18.75 eV threshold) is a direct observation of ionization.

Here we present observations of enhancements in T_e, I_{6300}, and I_{4278}, which are also the first images of pump-induced ionization of thermospheric N_2, during HF pumping with f_0 close to $4f_e$ and $3f_e$. The experiments were performed in March and November 2002 and November 2004 with the heating facility of EISCAT (European Incoherent Scatter Association) at Ramfjordmoen in Norway (69.6° N, 19.2° E). The optical emissions were imaged with one station of the Auroral Large Imaging System (ALIS) and the Digital All-Sky Imager (DASI), both at Skibotn (69.35° N, 20.36° N). The EISCAT-ultrahigh frequency incoherent scatter radar provided measurements of T_e and f_p. The geomagnetic field strength and derived f_e were obtained from the International Geomagnetic Reference Field [14]. On March 7 and November 8, 2002, the Heating facility was cycled 2 min on/1 min off, whereby the first minute of a new frequency involved the power slowly increasing as the beam is formed by phasing the individual transmitters. On March 7, the effective radiated power in the O mode was 490 MW, while on 8 November it was 586 MW. The beam, which had a −3 dB width of 7.2°, was tilted 9° south of zenith in both cases. Accounting for ionospheric absorption by no more than 3 dB, this gives a maximum electric field of about 1.2 V/m at the center of the beam, and, using the method of Ref. [15], we estimate the electric field at the first maximum of the standing wave pattern 9.5 V/m in the Spitze direction at 6° south. The higher value is comparable to what is estimated in Ref. [2].

The top panels in Figs. 1 and 2 show the frequency of the pump pulses (black) versus time. The dots (red online) show the resonance frequency where $4f_e = f_{UH}$ in the ionosphere. The second panels from the top show T_e. The third panels display the enhancement of optical emissions at 6300 Å by DASI (March 7, 2002) and ALIS (November 8, 2002), and the bottom panels show the enhanced emissions at 4278 Å (5577 Å from 1750 to 1820:30 UT on March 7, 2002) observed by the ALIS camera, all with 10 s time resolution. The optical emissions are presented as keograms made up from meridional cuts in the image through the maximum emission coincident with the pump pulse. After identifying I_{6300} enhancements, at 1800 UT on March 7, 2002 and at 1510 UT on November 8, 2002, f_0 was changed in steps of 20 kHz per pump pulse (10 kHz after 1839 UT on March 7, 2002). The HF pumping causes large increases of T_e which reach up to 3500 K (corresponding to a characteristic energy of 0.30 eV) on March 7, 2002 and above 3000 K on November 8, 2002. During the pulse at 1845 UT on March 7, 2002, some of the HF transmitters malfunctioned and full power was never reached, which explains the lower T_e during that pulse. Also, there were some technical problems during the

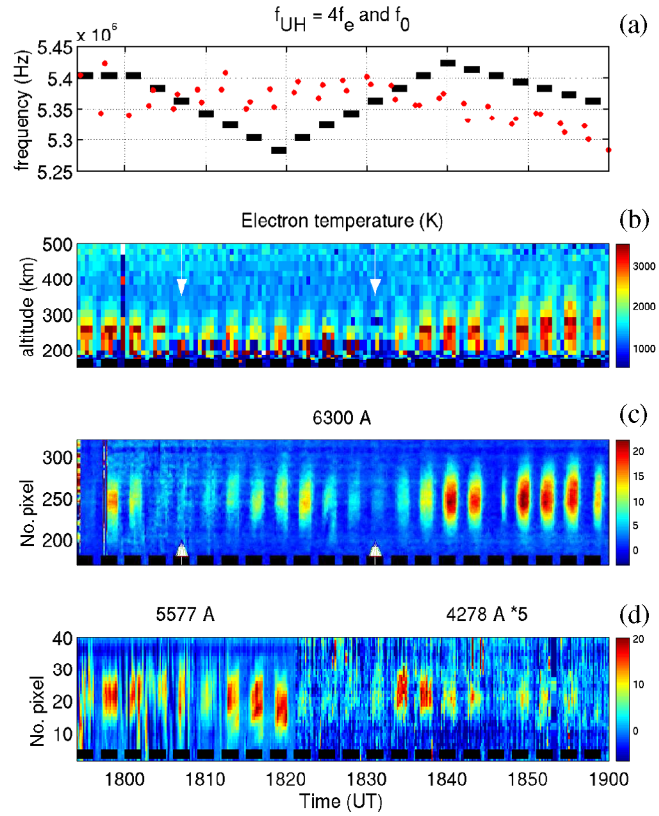

FIG. 1 (color online). Experimental results for March 7, 2002. (a) The HF-pump frequency f_0 for each pulse (black) and the double resonance frequency (dots, red online) versus time. The subsequent panels show (b) the temporal evolution of T_e, (c) emission at 6300 Å, while the bottom panel (d) displays emissions at 5577 Å until 1820:30 UT and at 4278 Å thereafter.

pulses starting at 1518 and 1521 UT on November 8, 2002 when the transmitters did not reach full power.

From the second and third panels in Figs. 1 and 2 we can see that the pump enhancements in T_e and I_{6300} have simultaneous minima for the pulse starting at 1806 ($f_0 = 5.363$ MHz) and then again for the 1830 UT pulse ($f_0 = 5.363$ MHz) on March 7, 2002 and 1548 UT ($f_0 = 5.303$ MHz) and 1551 UT ($f_0 = 5.323$ MHz) on November 8, 2002. For the earlier part of November 8, 2002, there is no clear minimum in T_e enhancements but for I_{6300} the enhancement during the pulse starting at 1533 UT ($f_0 = 5.323$ MHz) is at minimum. These instances correspond to $f_0 \approx 4f_e = f_{UH}$.

The measurements on March 7, 2002 of I_{4278} during the pump pulses from 1821 to 1830 UT show insignificant or very weak enhancements, as can be seen in the bottom panel in Fig. 1. For the pulses from 1833 UT and later, the enhancements are clearly distinguishable. For November 8, 2002, pump-induced emissions at 4278 Å are difficult to separate from the background level before the pump pulse at 1512 UT for which there might be some enhancement as seen in Fig. 2(c). For the pulses starting at

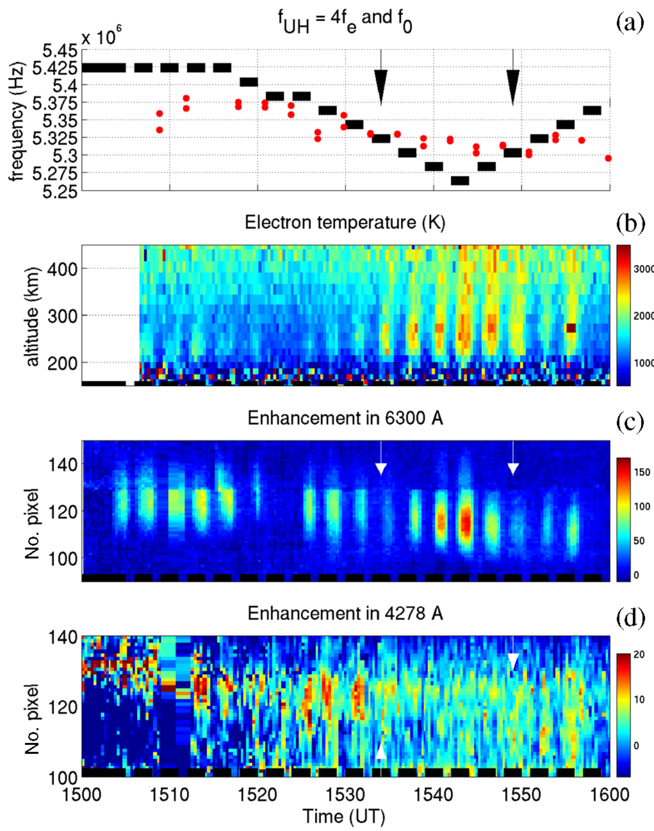

FIG. 2 (color online). Experimental results for November 8, 2002. (a)– (c) display the same quantities as in Fig. 1, and (d) shows emissions at 4278 Å.

1524, 1527, and 1530 UT, there are clear pump-induced emissions. It is also impossible to rule out enhancements during the 1533 UT pulse. For the pulses from 1536 to 1551 UT, there are no significant pump-induced emissions at 4278 Å, despite the fact that the emissions at 6300 Å are the strongest in this time period. However, for the pulse starting at 1554 UT, emissions at 4278 Å are clearly seen.

In addition to the data presented here, one run was made on November 8, 2002 with f_0 close to but above $3f_e$, and on November 19, 2004 one run was performed with f_0 below $3f_e$ where enhancements in I_{4278} show the same pattern. Further, during an experiment on March 10, 2002, I_{4278} enhancements were seen for f_0 up to 200 kHz above $4f_e$ [16]. The pump-induced emissions at 5577 Å on March 7, 2002 are contaminated by a naturally varying background from 1801 to 1807 UT. However, it is apparent that the emission enhancement for the pulse starting at 1809 UT is significantly smaller than during the 1757 pulse and the pulses at 1812 and later, which is consistent with the minimum in the T_e and I_{6300} mentioned above.

The strongest emissions at 4278 Å occur very near $4f_e$ but with $f_0 > 4f_e$, i.e., after 1836 on March 7, 2002 and before 1533 UT and for the pulse starting at 1554 UT on November 8, 2002. There are no significant I_{4278} enhancements when $f_0 < 4f_e$, i.e., before 1833 on March 7, 2002 and between 1536 and 1551 UT on November 8, 2002. I_{6300} in Figs. 1 and 2(c) generally follow the pattern of the T_e enhancement. However, the strongest enhancements at 4278 Å occur for the pump pulses starting at 1833 and 1836 UT for f_0 just above $4f_e$ when the emissions at 6300 Å have not reached their maximum yet. The enhancement in 6300 Å are the strongest, first at slightly higher f_0 in the pulses starting at 1839 and thereafter when the emission enhancements at 4278 Å have weakened again.

From previous optical observations [16], it was concluded that the electron distribution was Maxwellian with characteristic energy of 2–4 eV from 2 to about 15 eV and almost flat from 15 to 60 eV. Since the excitation threshold for ${N_2}^+(B\,^2\Sigma_u^+)$ is 18.75 eV, we can conclude that this high energy tail is more sensitive to f_0 close to sf_e than the Maxwellian between 2 and 15 eV. An adequate model of HF-wave electron acceleration has to produce acceleration to energies above 18 eV. Further, the acceleration mechanism has to be strong for $f_0 > sf_e$ and weak for $f_0 < sf_e$.

Theoretical studies of UH oscillations localized in density depletions for f_0 near sf_e predict an asymmetry in the trapping mechanism, which allows deeper density depletions for $f_0 > sf_e$ than for $f_0 < sf_e$ [17–19]. This asymmetry, affecting phenomena such as anomalous heating, anomalous absorption [18], and electron acceleration [19], is most pronounced at the lowest gyroharmonic $s = 3$. The prediction of stronger electron acceleration for $f_0 > sf_e$ than for $f_0 < sf_e$ is consistent with the present experimental results for the emissions at 4278 Å. Since the theory concerns the intensity of density striations and the trapped UH oscillations in addition to the actual acceleration mechanism, the asymmetry should also exist for the enhancement of T_e and emissions at 6300 Å. This is not seen in the present experimental results. Later experiments with f_0 near $2f_e$, where the 6300 Å intensity increased when f_0 was just above $2f_e$ [20], is in line with these predictions. In our data for f_0 near $4f_e$, the T_e enhancement and emissions at 6300 Å are the strongest for $f_0 > 4f_e$ in Fig. 1 but for $f_0 < 4f_e$ in Fig. 2. This variation suggests that additional experiments are needed to find the detailed dependence of T_e and the emissions at 6300 Å on f_0 near sf_e. However, we conclude that the dependence of T_e and the emission at 6300 Å on f_0 are similar to each other but both are different from that at 4278 Å. It may be noted that an asymmetry consistent with the theory can be seen in the data for 6300 Å and radar scatter from pump-induced small scale density striations in Ref. [10], although this was not discussed by the authors. That experiment was performed with f_0 near $3f_e$ where the asymmetry is expected to be the strongest, whereas the data we present were obtained at $s = 4$. The optical emissions are the weakest for $f_0 \approx 4f_e = f_{UH}$. Together with the minimum in the anomalous electron heating, there is a minimum in the anomalous absorption for such f_0, as previously obtained in daytime experiments [7,21]. Since these UH phenomena occur in the UH resonance region where $f_{\rm UH} \approx f_0$, typically a few kilometers below the pump reflection height, their suppression for $f_0 \approx 4f_e = f_{\rm UH}$ allows the pump energy to propagate up to the pump reflection height where $f_p \approx f_0$. Therefore, the pump fields are the highest in the HF reflection region where now Langmuir turbulence is excited. However, our observations show that at high latitudes this Langmuir turbulence does not result in any significant optical emission at 6300 nor 4278 Å. This is different from the paradigm of optical emissions due to Langmuir turbulence which has been used to explain observations made at the midlatitude Arecibo facility [22] [and references therein]. An interesting question thus arises: Is Langmuir turbulence sufficient to cause the optical emissions at Arecibo, or are UH processes needed also at low latitudes? That UH turbulence is excited at Arecibo during pumping for long time scales (>1 s) is evident from the excitation of small scale density striations [23] and the down-shifted maximum feature in stimulated electromagnetic emissions [4,24].

The results presented in this Letter are a direct measurement of the ionization of N_2 and clearly show that the pump-induced ionization is stronger for $f_0 > 4f_e$ than for $f_0 < 4f_e$. This dependence of I_{4278} on f_0 contradicts previous indirect evidence of pump-induced ionization obtained by multifrequency Doppler sounding [13]. Therefore, our results, obtained by a direct and independent method, call for a revision of the interpretation of positive Doppler shifts in terms of pump-induced ionization.

In summary, we have presented measurements of HF-pump-induced T_e enhancements (up to 0.3 eV), optical emissions at 6300 Å (threshold of 1.96 eV), 5577 Å (threshold of 4.17 eV), and 4278 Å (threshold of 18.75 eV) for different f_0 near $4f_e = f_{\rm UH}$, obtained in experiments with the EISCAT-Heating facility. The optical emissions at 4278 Å are the first unambiguous evidence of pump-induced ionization of thermospheric N_2. The enhancements of optical emissions and T_e are minimum for $f_0 \approx 4f_e = f_{\rm UH}$, which is consistent with the suppression of UH and electron Bernstein phenomena at this frequency. The enhancement at 4278 Å is markedly larger when f_0 is just above $4f_e = f_{\rm UH}$, whereas no consistent asymmetry is observed at 6300 Å nor in the T_e enhancement. The different dependence of the optical emissions at 4278 and 6300 Å on f_0 suggests that the emissions are due to different mechanisms, albeit both driven by UH and/or electron Bernstein turbulence because of the sensitivity on f_0 near $4f_e$. Together with the excitation threshold of 18.75 eV of ${N_2}^+(B\,^2\Sigma_u^+)$, this indicates that the acceleration of electrons to energies of a few tens of eV is more efficient for f_0 slightly above $4f_e$. The fact that the asymmetry was observed only in the emissions at 4278 Å, but not in the emissions at 6300 Å nor in T_e, is inconsistent with present theories for electron heating and acceleration.

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