Artificial Ionospheric Layers during Pump Frequency Stepping Near the 4th Gyroharmonic at HAARP

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(Received 14 September 2012; published 5 February 2013)

We report on artificial descending plasma layers created in the ionosphere $F$ region by high-power high-frequency (HF) radio waves from High-frequency Active Auroral Research Program at frequencies $f_0$ near the fourth electron gyroharmonic $4f_{ce}$. The data come from concurrent measurements of the secondary escaping radiation from the HF-pumped ionosphere, also known as stimulated electromagnetic emission, reflected probing signals at $f_0$, and plasma line radar echoes. The artificial layers appeared only for injections along the magnetic field and $f_0 > 4f_{ce}$ at the nominal HF interaction altitude in the background ionosphere. Their average downward speed $\sim 0.5 \text{ km/s}$ holds until the terminal altitude where the local fourth gyroharmonic matches $f_0$. The total descent increases with the nominal offset $f_0 - 4f_{ce}$.

DOI: 10.1103/PhysRevLett.110.065002

High-power high-frequency (HF) radio beams (pump waves) of ordinary (O) polarization transmitted from the ground into the ionosphere excite plasma eigenmodes, e.g., Langmuir and upper hybrid (UH), due to parametric instabilities [1–5]. The pump-plasma interaction is strongest between the reflection height $h_r$, where the plasma frequency $f_{pe}$ matches the pump frequency $f_0$, and heights slightly below the upper hybrid resonance height $h_{ub}$ where $f_0 = f_{ub} = [f_{pe}^2 + f_{ce}^2]^{1/2}$ (the UH resonance frequency). The excited plasma waves generate secondary or stimulated electromagnetic emissions (SEE) [6] via conversion of the plasma modes into electromagnetic waves (see e.g., Ref. [7]) and accelerate electrons up to a few tens of eV (e.g., Ref. [8]). The accelerated electrons cause optical emissions (artificial airglow) and can ionize neutral gas if their energy exceeds 12–18 eV [8–11].

The upgraded High-frequency Active Auroral Research Program (HAARP) heating facility situated near Gakona, Alaska ($62.4^\circ \text{N}, 145.15^\circ \text{W}$, magnetic dip angle $\theta = 14.2^\circ$) provides enough power to produce artificial ionospheric ionization [12,13]. The original experiments [12] employed $f_0 = 2f_{ce}$, and artificial ionospheric plasma layers were observed descending by tens of kilometers below the nominal interaction altitude in the background $F2$-region ionosphere. Their creation was explained [14,15] in terms of an ionizing wave front created due to electron acceleration by strong Langmuir turbulence generated by the $O$-mode pump wave in the critical layer near $h_r$. It is also found [13] that production of artificial plasma layers is optimized for $f_0$ slightly below the double resonance frequency $f_d$, at which $2f_{ce}$ matches $f_{ab}$. This suggests the importance of O-UH wave coupling. Determining the effects of both Langmuir and upper hybrid interactions is critical for understanding the mechanism of electron acceleration creating artificial ionospheric plasmas.

This Letter reports artificial ionospheric layers created at HAARP for $f_0$ near the fourth electron gyroharmonic. The data include measurements of SEE and diagnostic HF radio reflections at three separate sites and enhanced magnetic field-aligned plasma line (PL) radar echoes by the modular UHF incoherent scatter radar (MUIR) located at HAARP.

The experiment was run on 28 March, 2011 between 1500 and 1600 AST. The HF beam was pointed vertically ($V$) during the first 30 min and toward the magnetic zenith (MZ), i.e., along the geomagnetic field, thereafter. Injections of $O$-mode pump waves were made at full pump power $P_0 \approx 1.8 \text{ GW ERP}$ (effective radiated power), and pump frequencies $f_0$ ranging from 5730 to 5880 kHz, stepping by 30 kHz every 5 min. Each 5-min interval was comprised of three pumping periods followed by 30 s off.

The first and third periods consisted of low-duty pulses of duration $\tau_p = 20 \text{ ms}$ and an interpulse period $T_p = 1 \text{ s}$ (mode $p$), for a total of 30 and 180 s, respectively. The second period consisted of $\tau_q = 160 \text{ ms}$ pulses separated by 40-ms pauses (mode $q$ of $T_q = 0.2 \text{ s}$), for a total of 1 min. In order to monitor the pump wave absorption and reflection altitude, short diagnostic pulses of length...
\( \tau_d = 100 \, \mu s, \) of the same power and frequency as the pump wave, were also transmitted 20 ms prior each mode \( p \) pulse and in the middle of each mode \( q \) pause. Note the difference in average radiated power \( P_{r,p,q} = P_0 \tau_{p,q}/T_{p,q} \) between mode \( p \) \((=0.036 \, \text{GW ERP})\) and mode \( q \) \((=1.44 \, \text{GW ERP})\).

The background ionosphere was monitored by the HAARP DPS-4D ionosonde during the 30-s off periods. The critical frequency \( f_{\text{c}} \) was \( 6.2–6.5 \, \text{MHz} \), so the pump nominal reflection altitude \( h_d^* \) was \( 210–220 \, \text{km} \). The observational sites were located along the meridian to the south of the HAARP facility at (A) Riverview Lodge (about 11 km distant), (B) Tonsina River Lodge (83 km), and (C) Tiekel River Lodge (113 km). Site A (B) was nearly under the heated region during injections at vertical (MZ). A 30-m folded-dipole BWDS antenna was used in site A, an AS-2259/GR inverted-V antenna was used at site B, and a 10-m\(^2\) diamond magnetic loop was used at site C. The receiver at A (B and C) digitized a band of 250 \((300–400) \, \text{kHz} \) around the pump frequency. The dynamic range of the instruments after spectral processing is estimated to be better than 90 dB. Despite the differences in the receiving systems, the main features of the SEE and diagnostic reflections observed at each site are virtually the same. The results shown below from site B are representative of all three sites.

Overall, the low-duty pumping periods 1 and 3 (mode \( p \)) produced only downshifted emissions, i.e., \( f_c > f - f_0 < 0 \). The nearly continuous pumping during period 2 (mode \( q \)) produced well-known downshifted and upshifted features, i.e., the downshifted maximum (DM) and broad upshifted maximum (BUM)

\[
\Delta f_{\text{DM}} = f_{\text{DM}} - f_0 = f_0 - s \, f_{\text{ce}} + \delta f,
\]

where \( s \) is the harmonic number and \( \delta f \approx 15–20 \, \text{kHz} \) (see e.g., Refs. [16–23]). According to the purpose of this Letter, we will focus on the SEE dynamics only during period 2 (mode \( q \)).

Figure 1 presents SEE frequency-time spectrograms at site B for vertical and MZ injections. Each spectrogram is obtained using a 130-ms window centered at the 95th ms within each \( \tau_q \) pulse, with a frequency (time) resolution of 200 Hz (0.2 s). As the BUM exists only at \( f_0 > s \, f_{\text{ce}} \) \((s \approx 3)\) and \( f_{\text{BUM}} > f_a \) and the BUM feature is seen at \( f_a \approx 5760 \, \text{kHz} \), we conclude that \( 5730 < 4 \, f_{\text{ce}} < 5760 \, \text{kHz} \) in the interaction region. Furthermore, the absence of the DM for \( f_0 = 5760 \, \text{kHz} \) indicates that the DM frequency matches the double resonance, i.e., \( f_{\text{DM}} = 4 \, f_{\text{ce}} = f_{\text{uh}} \) \([18,21]\). For a given pump frequency, this occurs at a unique altitude \( h_d \). Using the IGRF-11/2010 geomagnetic field model for \( f_{\text{ce}}(h) \) and taking \( 4 \, f_{\text{ce}}(h_d) = f_{\text{uh}}(q_d) = f_{\text{DM}} = 5750 \, \text{kHz} \) gives \( h_d \approx 203 \, \text{km} \) at MZ.

As seen in Figure 1, the initial stage appears virtually the same for V and MZ injections. However, later in the heating, the development of the BUM differs significantly.

Not only are the spectra at MZ more intense and broader but the BUM spectrum is also divided into two distinct features, hereafter called BUM\(_S\) (S for stationary) and BUM\(_D\) (D for descending). The BUM\(_S\) does not drift in frequency, the same as the BUM for V injections. The new component, BUM\(_D\), drifts with time towards \( f_0 \) until its frequency offset \( \Delta f_D \) reaches the minimum \( = \delta f \) [see Eq. (1), which is close to the so-called BUM cutoff (see, e.g., Ref. [23]). The cutoff time \( t^* \) amounts to \( \approx 5, 10, 30, \) and 40 s for \( f_0 = 5760, 5790, 5820, \) and 5850 kHz, respectively, and exceeds 60 s (the duration of period 2) for \( f_0 = 5880 \, \text{kHz} \). However, the frequency drift rate \( r_f \) is \( \approx 1.2–1.4 \, \text{kHz/s} \) for all \( f_0 \).

Figure 2 presents successive SEE spectra 5 s apart for \( f_0 = 5850 \, \text{kHz} \). Dashed lines correspond to the BUM\(_S\) and BUM\(_D\) peaks. The stationary quality of the BUM\(_S\) after \( \approx 10 \, \text{s} \) and the drift of the BUM\(_D\) peak toward \( f_0 \) are evident. After the drift stops at \( t = t^* \), the offset \( \Delta f_D = \delta f \) remains, while the BUM\(_D\) magnitude decreases to the background at \( t^* = t^* + \delta t \), where \( \delta t = 7–12 \, \text{s} \).

We interpret these results by employing Eq. (1) and the fact that the BUM exists only for \( f_0 > 4 \, f_{\text{ce}} \). According to Eq. (1), the decrease of \( \Delta f_D \) with time suggests the increase of \( f_{\text{ce}}(h(t)) \) and hence the descent of the BUM\(_D\) generation region. Using the IGRF-11/2010 model for
The concurrent MUIR observations of descending layers of enhanced PL echoes (cf. Ref. [14]) agree with the DL/BUM\textsubscript{D} characteristics. Figure 4 shows the altitude dependence of the PL echo intensity, as seen by the MUIR with the altitude resolution of 600 m. The PL signal was integrated for 0.5 s. The radar was turned on about 20 s after the start of period 3, i.e., switching back to the low-duty cycle mode \( p \), the lower layer (the DL) disappeared in a few seconds, and the BF magnitude recovered to that of period 1. Thus, the nearly continuous pumping at MZ for \( f_0 > 4f_{ce} \) results in two distinct layers of reflection, i.e., BF and DL.

Similar to the SEE features, there is a stark difference between the V and MZ injections above \( 4f_{ce} \). Most notable is the development of the layers of scattered or reflected signals below \( h_{BF} \) at MZ. Their virtual altitude \( h_{DL} \) (DL for descending layers) descends with time well below \( h_{BF} \) for \( f_0 \gtrsim 5760 \) kHz. From Figure 3 it is seen that the decrease of \( h_{DL} \) stops near the BUM\textsubscript{D} cutoff time \( t_f \). After that, the magnitude of the DL signal increases by nearly 50 dB and at \( t = t_f \) attains the BF magnitude. The overall virtual descent \( \Delta h_{DL} \) increases with \( f_0 \), that is, \( \Delta h_{DL} \approx 50 \rightarrow 145 \) km for \( f_0 = 5760 \rightarrow 5880 \) kHz, respectively. After the start of period 3, i.e., switching back to the low-duty cycle mode \( p \), the lower layer (the DL) disappeared in a few seconds, and the BF magnitude recovered to that of period 1. Thus, the nearly continuous pumping at MZ for \( f_0 > 4f_{ce} \) results in two distinct layers of reflection, i.e., BF and DL.

The concurrent MUIR observations of descending layers of enhanced PL echoes (cf. Ref. [14]) agree with the DL/BUM\textsubscript{D} characteristics. Figure 4 shows the altitude dependence of the PL echo intensity, as seen by the MUIR with the altitude resolution of 600 m. The PL signal was integrated for 0.5 s. The radar was turned on about 20 s after the start of period 2 for 5820 kHz at MZ. The PL echoes are clearly seen near the nominal reflection altitude (BF), 210–220 km, during periods 1 and 3. However,
Finally, the speed of descent exceeds that for $2f_{ce}$ [12,13] by 2–3 times. This can be attributed to a more efficient electron acceleration due to (i) higher HF pump power $P_0 \sim f_0^2$ and (ii) existing photoelectrons that can be accelerated much more efficiently than thermal electrons (cf. Ref. [25]). The sensitivity to the sign of the offset $f_{uh} - 4f_{ce}$ indicates the important role of upper hybrid waves (e.g., Refs. [8,21]). However, the fact that the descent starts during the first few pulses of period 2, i.e., before UH-induced anomalous absorption can develop, and the presence of enhanced descending PL echoes also indicate the significance of Langmuir turbulence.

HAARP is a DoD program operated jointly by the U.S. Air Force and U.S. Navy. E.S., S.G., and A.S. were supported by EOARD/AFOSR and RFBR Grants No. 11-02-00125-a and No. 12-02-00513-a and the Ministry of Education and Science of the Russian Federation, Project No. 14.132.21.1434. E.M., P.B. and S.B., and B.I. were supported by AFOSR, ONR, and ARO Grant No. W911NF-11-1-0217, respectively.

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