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Production of artificial ionospheric layers by frequency sweeping near the 2nd gyroharmonic

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Abstract. Artificial ionospheric plasmas descending from the background F-region have been observed on multiple occasions at the High Frequency Active Auroral Research Program (HAARP) facility since it reached full 3.6 MW power. Proximity of the transmitter frequency to the 2nd harmonic of the electron gyrofrequency ($2f_{\mathrm{ce}}$) has been noted as a requirement for their occurrence, and their disappearance after only a few minutes has been attributed to the increasing frequency mismatch at lower altitudes. We report new experiments employing frequency sweeps to match $2f_{\mathrm{ce}}$ in the artificial plasmas as they descend. In addition to revealing the dependence on the $2f_{\mathrm{ce}}$ resonance, this technique reliably produces descending plasmas in multiple transmitter beam positions and appears to increase their stability and lifetime. High-speed ionosonde measurements are used to monitor the altitude and density of the artificial plasmas during both the formation and decay stages.

Keywords. Ionosphere (Active experiments; Ionization mechanisms; Instruments and techniques)

1 Introduction

Significant artificial enhancements in plasma density during high-power HF heating experiments at the High Frequency Active Auroral Research Program (HAARP) facility (62.4° N, 145.15° W, 62° Magnetic) were first observed in 2008 after expansion of the facility to a total power of 3.6 MW (Pedersen et al., 2009). Subsequent experiments revealed the formation of rapidly descending layers of enhanced ionization sufficiently dense to locally absorb power from the HF beam to produce a glowing spot of artificial ionization near 150 km altitude (Pedersen et al., 2010). Additional cases have recently been identified by Kendall et al. (2010). In all previous cases, the HAARP transmitter was operated at 2.85 MHz, which matches the 2nd harmonic of the local electron cyclotron frequency ($2f_{\mathrm{ce}}$) at approximately 230 km altitude. Lower F-region matching altitudes, corresponding to higher transmitter frequencies, were not possible due to a gap in the HAARP frequency allocation above 2.85 MHz. Proximity to $2f_{\mathrm{ce}}$ is known to greatly enhance optical emissions and fluxes of suprathermal electrons (Kosch et al., 2005, 2007; Djuth et al., 2005). Increasing offset from this resonance was suggested by Pedersen et al. (2010) as a possible reason for the generally unstable nature of the artificial plasmas, which disappeared rapidly upon reaching 150 km altitude, where $2f_{\mathrm{ce}}$ is ∼2.95 MHz, or 100 kHz above the 2.85 MHz transmitter frequency. In this article we summarize the results of a large number of frequency sweep experiments designed to maintain the transmitter frequency near $2f_{\mathrm{ce}}$ within the artificial plasmas as they descend in altitude. These experiments required a temporary frequency authorization to operate outside the standard HAARP allocation.

2 Experiment

The frequency sweep experiments were carried out between 11 and 21 November 2009. A typical experiment consisted of full-power (3.6 MW total power, ∼440 MW effective radiated power) fixed-frequency O-mode heating for one minute at 2.85 MHz to precondition the F-region followed by a frequency sweep from 2.85 MHz ($2f_{\mathrm{ce}}$ at 230 km) to 2.95 MHz (150 km) in 10 or more fixed steps over periods of 6–15 min. This 100 kHz span represents the largest frequency interval which could be swept without the HAARP transmitter being turned off for retuning. Most experiments were run in late twilight when optical observations were possible and the

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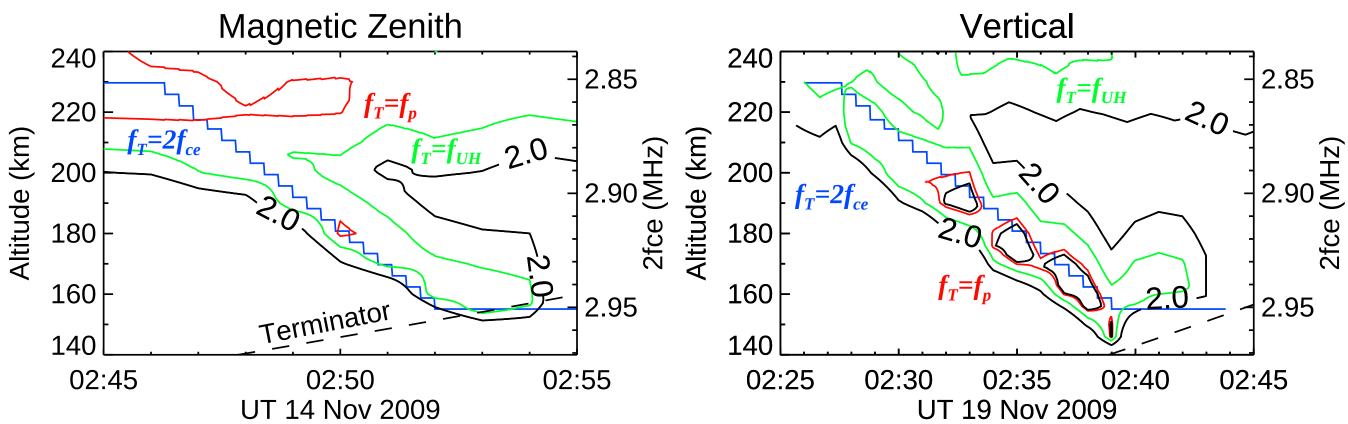

Fig. 1. Frequency sweeps from 2.85 to 2.95 MHz on 14 November 2009 (left) and 19 November 2009 (right). The 14 November sweep took 6 min and the transmitter was pointed at magnetic zenith, while the 19 November sweep took 12 min and the beam was vertical. Contours of plasma frequency are shown in black for 2.0 and 3.0 MHz where they exist (3.0 MHz contours appear only inside the red contours on the right panel and are too crowded to be labeled). Matching altitudes for $f_T = 2 f_{ce}$, $f_T = f_{uh}$, and $f_T = f_p$ are shown in blue, green, and red, respectively. The terminator is shown as a dashed black line.

background ionospheric profiles were conducive to probing the double resonance between the upper hybrid frequency (f_{uh}) and $2 f_{ce}$. The primary diagnostic was a DPS-4D ionosonde (Reinisch et al., 2009) operated at the HAARP site in a fast sweep mode covering 1–5 MHz every 10 s. As the HAARP transmitter interferes with ionosonde reception within $\sim\pm500$ kHz of the transmitter frequency f_T, preventing crucial determination of whether the plasma frequency f_p is above or below f_T ("overdense" or "underdense," respectively), we blanked the HAARP transmitter for up to 5 s each minute to reduce interference or allow short high-resolution ionograms to be made. The artificial plasmas typically persisted through blanked intervals of up to 5 s, but were generally observed to lose resonance and decay if the transmitter was off for more than 10 s.

Figure 1 shows two examples of frequency sweeps and the artificial descending layers produced by them on 14 and 19 November 2009. Both modes started with 1 min of fixed 2.85 MHz, then stepped in frequency by 5 kHz to reach 2.95 MHz after 6 min (14 November) or 12 min (19 November), dwelling on each frequency for 18 s or 36 s, respectively. At the conclusion of the sweep the transmitter remained at 2.95 MHz until being manually turned off. Contours of plasma density in the background ionosphere and artificial layers were derived by inversion of hand-scaled ionogram traces. Note that topside density profiles are not observable with the ionosonde technique; contours on the topsides of both artificial and natural ionospheric layers are a product of the model used by the inversion software.

For the experiment beginning at 02:45 UT on 14 November (left panel), the transmitter beam was directed at the magnetic zenith (202° az 14° zen). At the start of the experiment, the matching altitudes for f_p (red) and f_{uh} (green) were below $2 f_{ce}$ (blue) by about 15 and 25 km in altitude, respectively. The contours descended slightly during the first few minutes of heating, but no clear artificial layer formed until 02:48 UT when the frequency sweep brought $2 f_{ce}$ close to f_{uh}. After this, the plasma density contours descended at an average rate of $\sim$170 m s^{-1} and closely paralleled $2 f_{ce}$, with f_{uh} maintaining a $\sim$5 kHz separation. Near 02:50 UT, the background ionosphere became underdense but f_p within the artificial layer reached f_T and remained just below it for the next 4 min. The f_{uh} contour crossed $2 f_{ce}$ at 02:51 UT as the density contours began to lag the transmitter frequency ramp. The layer persisted near $\sim$150 km altitude for 2 min after f_T reached 2.95 MHz, with $f_{uh} \approx 2 f_{ce}$ in the artificial layer. In this particular case, the decay of the layer corresponded closely with the terminator crossing, although artificial descending plasmas were formed during both prior and later experiments on this same night.

For the case on 19 November (right panel), the transmitter beam was directed vertically, and the background ionosphere was at higher altitude, with f_{uh} already close to $2 f_{ce}$. Although the background ionosphere remained underdense throughout this experiment, with the peak frequency f_{0F2} declining from 2.70 to 2.55 MHz between 02:25 and 02:45 UT, the density contours began descending almost immediately, and the artificial layer became overdense much of the time after 02:32 UT, exceeding 3 MHz in many cases. The average rate of descent was 120 m s^{-1}. Unlike the 14 November case, f_{uh} remained well below $2 f_{ce}$ in altitude throughout, maintaining a steady 15–20 kHz separation. We note that in this and some other cases, the descending layers appeared in the ionosonde data as pairs of traces 10–20 km apart in range. We have not attempted to resolve multiple artificial layers with the contours in the figure, and have scaled only the lowest observed artificial layer. As horizontally separated echoes at the same altitude would need to be 20°–28° apart to

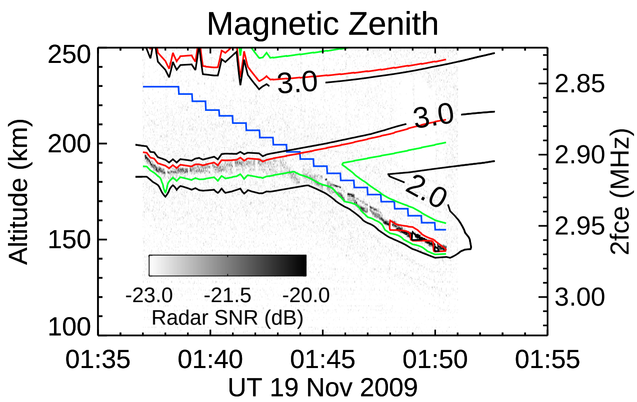

Fig. 2. MUIR radar short-pulse ion line echoes for a frequency sweep in the magnetic zenith from 01:37 to 01:50:30 UT on 19 November 2009. Contours of plasma frequency at 2.0 and 3.0 MHz are superimposed (black), as are contours where $f_T = f_p$ (red), f_{uh} (green) and $2f_{ce}$ (blue).

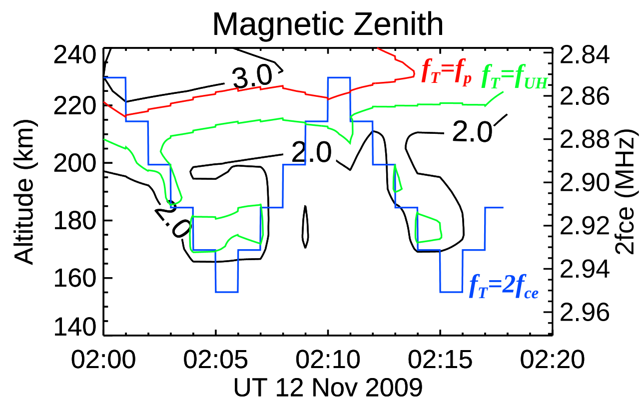

Fig. 3. Multiple triangular frequency sweeps from 02:00 to 02:18 UT on 12 November 2009.

produce the 10–20 km range difference observed, we believe the rise in altitude after 02:40 UT is the result of a higher altitude layer becoming apparent in the contours as a lower layer disappears.

An earlier frequency sweep on 19 November 2009, beginning at 01:37 UT when the background ionosphere was overdense and lower in altitude, further illustrates the dependence of layer formation on proximity to $2f_{ce}$. This experiment was identical to the 02:26 UT sweep in Fig. 1 except the transmitter beam was directed at the magnetic zenith. During this period, the MUIR radar (Oyama et al., 2006) was pointed at the magnetic zenith and operating in narrow-pulse ion line mode, which detects enhanced echoes from decay of Langmuir waves excited by the HAARP transmitter. The reflection height at 2.85 MHz at the start of the run was below 200 km altitude, compared to 230 km for $2f_{ce}$. After the first minute of heating, a slight lowering of the bottomside became apparent, corresponding to a sharp decrease in the altitude of radar echoes, but after this initial effect there were no significant changes in the ionosphere for the next 6 min. As $2f_{ce}$ approached f_p and f_{uh} near 01:45 UT, however, a layer became apparent on the bottomside and descended at $\sim$110 m s^{-1} to almost 140 km over the next 5 min, f_{uh} and $2f_{ce}$ closely paralleling each other with a separation of 10–20 kHz. As with many other cases, the descending layer became overdense toward the end of the sweep, with MUIR radar echoes strengthening. At 01:50:30 the transmitter went off, and the layer decayed in place.

An additional test of dependence on the 2nd gyroharmonic is provided by comparing descending (in matching altitude) sweeps with ascending sweeps. Figure 3 shows two repetitions of such an experiment carried out between 02:00 and 02:18 UT on 12 November 2009. The transmitter stepped from 2.85 Mhz to 2.95 MHz in 20 kHz steps over 5 min and then reversed in frequency after 1 min at 2.95 MHz, the cycle repeating after reaching 2.85 MHz. As the contours show, artificial plasmas were produced and followed $2f_{ce}$ downward both times, but died off when the matching altitude rose back up into the natural F-region. In this particular experiment f_{uh} remained very close to $2f_{ce}$ in the descending phase. Estimated descent rates were 210 m s^{-1} for the sweep starting at 02:00 UT, and 220 m s^{-1} for the second repetition at 02:10 UT. The relatively large frequency steps and high descent rates in this experiment perhaps prevented the descending plasma from building up to larger densities: the spotty appearance of the contours of f_{uh} suggest that the density barely reached f_{uh} to within the error in the ionogram scaling.

The high temporal resolution of the DPS-4D ionosonde deployed specifically for the November 2009 experiments allowed accurate measurements of the decay of the artificial plasmas to be made for the first time. Measurements of layer decay provide a critical constraint on any explanation of layer production, as the production mechanism must be capable of maintaining the plasma density against the losses causing the decay once production ceases. Here we examine the plasma densities after the frequency sweep shown in Fig. 2 ended at 01:50:30 UT, while an artificial layer was present at low altitude just below 150 km. The transmitter was off for 30 s before beginning a fixed-frequency mode at 01:51:00. This eventually created a new descending layer, but the original layer lost resonance during the 30 s off period and continued to decay even after the transmitter came back on. The left panel of Fig. 4 shows density profiles within the decaying layer; the portion of the profiles above the peak is shown as dashed, as the topside is not observable and results from a model used by the ionogram inversion software. Thirty seconds prior to shutdown, the peak frequency in the artificial layer (f_{0A}) was slightly over 3.0 MHz. Peak frequency dropped steadily over the course of the first minute, at which point f_{0A} had declined below 2.0 MHz. Ionogram echo traces were still visible for approximately another minute,

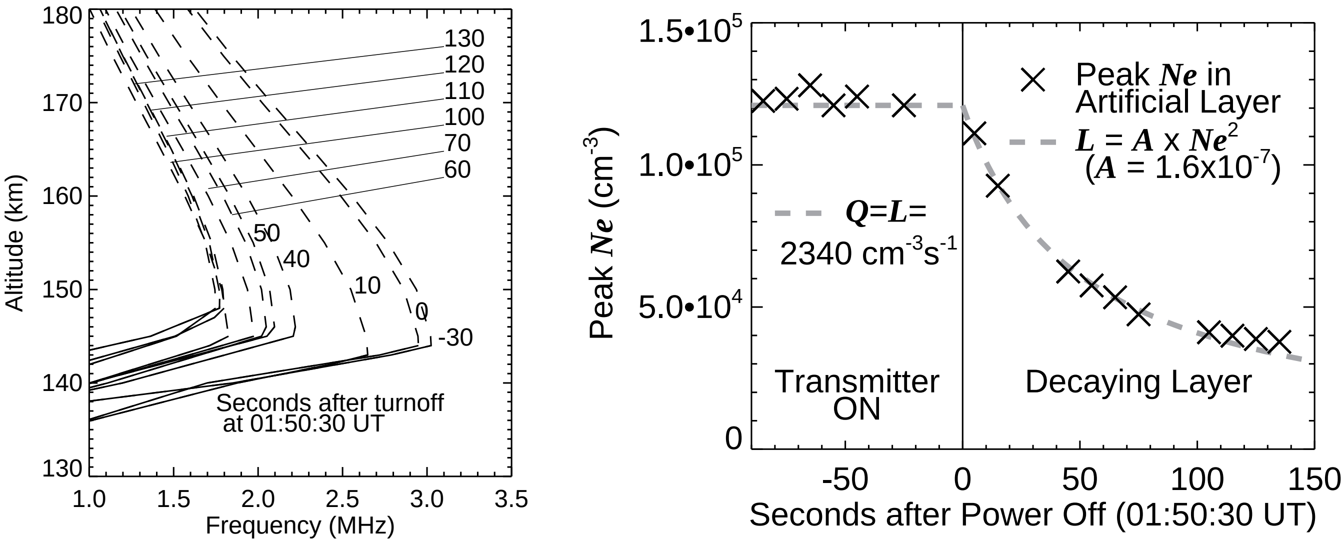

Fig. 4. Left: density profiles at 10 s resolution from high-speed ionograms near the end of the frequency sweep experiment in Fig. 2. Right: loss (L) and production (Q) rates estimated from peak densities as the layer decayed.

but at these much lower densities the decay was greatly reduced, the profiles bunching up near $f_{0\mathrm{A}} = 1.5$ MHz. A plot of peak density (N_{mA}) vs. time (right panel) clearly shows the decay of the density, which when fit to a standard N^2 loss formula gives a loss coefficient of $1.6 \times 10^{-7}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$. This rate closely matches the theoretical rate (Rees, 1989) for a plasma with the 65% NO^+ and 35% O_2^+ composition specified by the IRI model at a reduced temperature of 800 K, which is in turn very close to the neutral temperature of 744 K predicted by the MSIS model. Although recombination rates decrease with the higher temperatures expected during heating, this measurement made soon after turn-off provides an upper limit of $\sim$2300 $\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$ for the production needed to maintain the observed density of $1.2 \times 10^5\,\mathrm{cm}^{-3}$ against recombination.

3 Discussion

The primary result of these frequency sweep experiments is a direct confirmation that the $2f_{ce}$ resonance is key to production, reproduction, and maintenance of the descending artificial plasmas. When the transmitter is swept upward in frequency (downward in altitude), artificial plasmas were observed to begin forming almost every time $2f_{ce}$ neared f_{uh}, and the plasma descended to maintain f_{uh} on the bottomside of the layer just below $2f_{ce}$ (in both altitude and frequency) whenever the sweep rate was slow enough for the process to keep pace. The artificial plasmas were also more stable and longer-lived, remaining detectable for up to 20 min compared to the $\sim$3 min life cycles seen at fixed frequencies. Reverse ramps sweeping upward in matching altitude sometimes produced small bumps in density contours when $2f_{ce}$ crossed f_{uh}, but resulted in loss of resonance and decay if a layer was already present. The strong dependence on $2f_{ce}$ explains the sporadic nature of prior observations: when frequencies were limited to 2.85 MHz or lower (altitudes above 230 km), layer initiation depended on the specific altitude of the background ionosphere, and resonance close to $2f_{ce}$ could not be maintained locally in the plasma as it descended in altitude. Frequency sweeps have an additional advantage of requiring only a rough estimate of the true density profile and resonance altitudes, which can be difficult to determine in real time.

While frequency sweeps represent a practical breakthrough, allowing artificial descending layers to be produced almost on demand and in multiple transmitter beam positions, there are also implications for the physical mechanisms operating to create the plasmas. The strong preference for descending (in matching altitude) frequency ramps over ascending ramps or fixed frequencies clearly illustrates the dominant role of local resonance within the descending plasma. This is confirmed by ion line echos from the MUIR radar, which also originate primarily from the bottomside of the artificial layers just below the reflection height. The observed decay of the layers after more than $\sim$10 s without power transmission also indicates that the layers are locally produced and maintained. Non-local effects dependent on transport of either plasma or accelerated electrons from higher altitudes could be expected to resume after even longer breaks, and should be able to also produce lower-density non-resonant artificial plasmas. These have not been observed thus far: all layers not already decaying have been dense enough for f_T to match at least f_{uh} to within the margin of error in the ionosonde measurements. Decay appears irreversible, regardless of transmitter power or frequency, once densities drop below f_{uh}, again with allowance for measurement uncertainty. The presence of MUIR radar ion line echoes even in apparently underdense regions suggests that the layers may actually be overdense to within the uncertainty in the ionosonde measurements, and that Langmuir waves may play a significant role in their formation, even though there are clear cases (such as the right side of Fig. 1) where artificial layers appear to be initiated in a completely underdense ionosphere.

4 Conclusions

Frequency sweeps through a previously unavailable band at the HAARP facility have allowed a large number of artificial descending layers to be produced in multiple beam positions. Production is optimized when when $2f_{ce}$ is near f_{uh} in the background ionosphere and the frequency is swept to maintain the double resonance locally in the artificial plasma as it descends. Typical rates of descent range from 100–250 $m\,s^{-1}$, with f_{uh} generally remaining 5–20 kHz below $2f_{ce}$. The artificial layers are able to persist up to $\sim$10 s without power from the transmitter, but lose resonance and decay irreversibly for longer periods. These facts limit the role of non-local production mechanisms and indicate that the dominant processes require resonance in the artificial plasma. High-speed ionosondes have allowed loss rates in decaying layers to be measured, providing a quantitative constraint on plasma production mechanisms.

We expect this technique for reliable reproduction of this recently discovered phenomenon to greatly aid experimentation and research into the physical mechanisms and potential uses of artificial ionospheric plasmas at the HAARP facility, other existing or planned heating facilities, or under a wider range of ionospheric and transmitter conditions.

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