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Artificial ionospheric layers driven by high-frequency radiowaves: An assessment

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Abstract High-power ordinary mode radio waves produce artificial ionization in the F region ionosphere at the European Incoherent Scatter (Tromsø, Norway) and High Frequency Active Auroral Research Program (Gakona, Alaska, USA) facilities. We have summarized the features of the excited plasma turbulence and descending layers of freshly ionized (“artificial”) plasma. The concept of an ionizing wavefront created by accelerated suprathermal electrons appears to be in accordance with the data. The strong Langmuir turbulence (SLT) regime is revealed by the specific spectral features of incoherent radar backscatter and stimulated electromagnetic emissions. Theory predicts that the SLT acceleration is facilitated in the presence of photoelectrons. This agrees with the intensified artificial plasma production and the greater speeds of descent but weaker incoherent radar backscatter in the sunlit ionosphere. Numerical investigation of propagation of O-mode waves and the development of SLT and descending layers have been performed. The greater extent of the SLT region at the magnetic zenith than that at vertical appears to make magnetic zenith injections more efficient for electron acceleration and descending layers. At high powers, anomalous absorption is suppressed, leading to the Langmuir and upper hybrid processes during the whole heater on period. The data suggest that parametric upper hybrid interactions mitigate anomalous absorption at heating frequencies far from electron gyroharmonics and also generate SLT in the upper hybrid layer. The persistence of artificial plasma at the terminal altitude depends on how close the heating frequency is to the local gyroharmonic.

1. Introduction

Coupling of high-power high-frequency (HF) pump electromagnetic waves with the ionosphere is mediated by HF-excited plasma turbulence. Its usual manifestations for HF pump waves of ordinary (O) polarization are enhanced plasma and ion lines in the incoherent scatter radar (ISR) spectra [e.g., Stubbe et al., 1992; Cheung et al., 2001], elevated electron temperature  \( T_e \) [e.g., Rietveld et al., 2003; Blagoveshchenskaya et al., 2005], enhanced radioaurora, i.e., HF radar coherent backscatter off enhanced field-aligned irregularities (FAI) \( \delta n_i \) [e.g., Robinson, 1989; Senior et al., 2004], secondary or stimulated electromagnetic emissions (SEE) [e.g., Thidé et al., 1982; Stubbe et al., 1984; Leyser, 2001] due to coupling of electrostatic HF waves with low-frequency (LF) counterparts and FAI, and enhanced optical emissions (artificial aurora) [e.g., Bernhardt et al., 1989; Kosch et al., 2000, 2004; Pedersen et al., 2003]. Optical emissions with the excitation energies 2–18 eV [e.g., Gustavsson et al., 2002, 2006; Mutiso et al., 2008] indicate accelerated suprathermal electrons [Carlson et al., 1982]. It is also worth noting HF-induced ion upflows and density ducts in the topside ionosphere [e.g., Rietveld et al., 2003; Milikh et al., 2010; Kosch et al., 2010].

Matching the pump frequency \( f_p \) to the plasma frequency \( f_{pe} \approx 9 \sqrt{n_e} \) kHz and the upper hybrid (UH) resonance, \( f_{n_0} = \sqrt{f_{pe}^2 + f_{ce}^2} \), defines the plasma resonance (O-mode reflection) point at altitude \( h_0 \) and UH resonance at \( h_{ce} \approx h_0 - \frac{\omega_p^2}{\omega_{ce}} \), respectively [e.g., Gurevich, 2007]. Here \( n_e \) is the plasma density in cubic centimeters, \( f_{ce} = 2.8 \cdot 10^6 \) MHz is the electron cyclotron (gyro) frequency, \( B_0 \) is the geomagnetic field in G, and \( l_s = [\ln n_e / dh]^{-1} \) is the density scale height. The dispersion relation of HF electrostatic waves in weakly magnetized \( \omega_p \) plasma

\[
\omega_k \approx \omega_p \left[ 1 + (3/2) k^2 l_s^2 \right]^{1/2} \sin \theta
\]

(1)
gives Langmuir (L) waves at \( \sin^2 \theta = k_L^2 / k^2 \to 0 \) and UH waves at \( \theta \to \pi / 2 \). Here \( r_D \) is the Debye radius (~1 cm in the F region), \( \sin^2 \theta = k_L^2 / k^2 \), and \( k \) is the wave number. Henceforth, “Lo” denotes oblique (or magnetized Langmuir) waves with \( 0 < \theta < \pi / 2 \). Another HF branch \( \approx L \) \( B \_0 \) is the electron Bernstein (EB) mode, \( \omega_{pe}(k) \) with \( \partial \omega_{pe} / \partial k_L < 0 \).

Langmuir waves are parametrically coupled with the O-mode pump via low-frequency (\( \Omega \ll \omega_p \)) density fluctuations (such as ion sound (S) waves, \( \Omega = \Omega_s \approx k c_s \)) or forced, \( \Omega^2 < 0 \), modulations (ion quasimodes). The former (three-wave) process, \( O \to L + S \), is parametric decay (PD\( ^O \)), while the latter is called modulational instability (MI), also known as oscillating two-stream instability (OTSI) [e.g., Galeev et al., 1977; Fejer, 1979; Shapiro and Shevchenko, 1984; DuBois et al., 1993; Robinson, 1997]. Here \( c_s = \sqrt{\eta T_e / m} \) is the ion sound speed, \( m_i \) is the ion mass, and \( \eta = 1 + \sigma T_e / T_i \) at \( \sigma \omega_i \ll \omega_{pe} \). Note that at \( T_e \leq \sigma T_i \), ion sound waves are heavily damped (Im\( \Omega \sim \Omega_e \)), so PD\( ^O \) develops in the so-called induced scattering regime. The PD\( ^O \)-excited red-shifted \( (\omega_o < \omega_p) \) waves are usually described in terms of weak turbulence (WT), while those in the MI regime constitute strong (cavitating) Langmuir turbulence (SLT). Each regime has distinct spectral characteristics, notably the WT “decay lines” and the SLT “caviton continuum” and “free mode” [e.g., DuBois et al., 1993]. Their growth times \( \tau_o \) are in the order of a few milliseconds. Most important for the artificial plasma production is the SLT acceleration of suprathermal (tail) electrons at energies \( \epsilon \geq \epsilon_{max} \to \tau_o \) (see equation (9)).

UH/EB waves can be excited via decay PD\( ^O \)\( \approx \)O \to \)UH/EB + LH, and OTSI\( ^O \approx O \to \)O + \( \delta n \) [e.g., Istimon and Leyser, 1995; Kuo, 2015, and references therein]. Here “LH” designates low-frequency waves near the lower hybrid resonance \( \omega_{hy} \approx \mu^{1/2} \omega_c \), where \( \mu = m_e / m_i \), is the mass ratio \( \approx 3 \cdot 10^{-3} \) in the F region. Another independent source is conversion of the pump wave on FAL, O + \( \delta n \to \)UH. Trapping UH waves inside striations, i.e., FAL with depleted plasma density \( \delta n \to 0 \), leads to enhanced ohmic heating in the tenuous regions. As a result, the pressure disbalance forces plasma out. This positive feedback loop leads to the thermal parametric instability (TPI) [e.g., Vaskov and Gurevich, 1977; Grach et al., 1981], with the growth time \( \tau_{p} \) of the order of seconds.

Scattering of an O-mode pump off striations into UH waves and slow extraordinary waves, known as the Z-mode, leads to (anomalous) absorption of the pump energy \( en\_route \to h_o \) [e.g., Stubbe et al., 1994; Gurevich et al., 1996; Eliasson and Papadopoulos, 2015], which inhibits PD\( ^{O} \) and MI in a few seconds. It has become a rule of thumb that Langmuir turbulence plays no role in persistent (\( \gg \tau_o \)) HF-induced phenomena, unless \( f_o \) is in the forbidden band, \( |f_o - fc| \leq f_{br} \), where OTSI\( ^{O} \)\( \approx PD\( ^{O} \)\#EB, and TPI are inhibited [e.g., Mjølhus, 1993; Stubbe, 1996].

HF beams pointed vertically propagate along the ionosonde density gradient \( \nabla n_o(h) \). This is favorable for the PD\( ^{O} \)/MI development, as the frequency mismatch

\[
\tilde{\omega}_o(h) = \omega_o / \omega_{pe}(h) - 1 \approx (h_o - h) / 2l_n
\]

vanishes at \( h_o \). The same is also true for incidence angles \( \theta_o \) within the Spitze cone \( \theta_o < \theta_s = \arcsin (\sqrt{\frac{f_o}{f_{br}} \sin(\chi)}) \) [e.g., Mjølhus, 1990]. Here \( \chi \approx 14.5^\circ \) at HAARP and 12° at EISCAT [e.g., Macmillan et al., 2003] is the conjugate of the magnetic dip angle, and in the Northern Hemisphere (downward \( B_n \)) the angles \( \theta_o \) are positive to the south of vertical. Near \( \theta_o = \theta_s \) and \( -\theta_s \), O-mode waves are converted to Z-mode waves moving upward and downward, respectively [e.g., Mjølhus, 1990]. Thus, the regions near to the Spitze angle \( \theta_o \) and its counterpart \( -\theta_o \), are called the upward and downward radio windows, respectively.

For injections outside the Spitze cone, the O-mode refraction height \( h_o(\theta_o) \) decreases with \( \theta_o \), so the frequency mismatch \( \tilde{\omega}_o(h_o) \) increases, seemingly hampering the PD\( ^{O} \)/MI development. However, low duty cycle (heater on period \( < \tau_o \)) experiments reveal plasma and ion line ISR backscatter with the SLT signatures developing at the magnetic zenith (MZ) in \( \approx 10 \) ms and with greater intensities than those from vertical [Isham et al., 1999; Oyama and Watkins, 2007]. Further experiments with extended (\( \gg \tau_o \)) injections also show the dominance of MZ [Kosch et al., 2000; Pedersen et al., 2003; Rietveld et al., 2003]. This is called the magnetic zenith effect, although due to the finite width of the HF beam, it is uncertain that the true maximum is along \( B_n \).

At high effective radiated powers, ERPs \( (P_o = \) transmitter output \( \times \) antenna gain), the regions of enhanced ion line (IL) backscatter from the EISCAT UHF radar, artificial aurora, and SEE descend by 15–20 km from the initial interaction altitude [Kosch et al., 2004; Dhillon and Robinson, 2005; Ashraf et al., 2007; Borisova et al., 2014]. In addition to the HAARP modular UHF incoherent scatter radar (MUIR) and optical imagers, Pedersen et al. [2009, 2010, 2011] used the HAARP ionosonde to reveal that descending layers (hereafter, DL) are patches
of newly ionized plasma. Sergeev et al. [2013] explored DL using concurrent measurements of SEE, reflected probing signals, and MUIR plasma line (PL) backscatter during frequency-stepping experiments around $4f_{ce}$. The DL-associated optical emissions at $\approx 732$ nm and $427.8$ nm (the blue line) indicate electron acceleration above the ionization energies $e_{i\text{ion}}$ [Pedersen et al., 2010; Hysell et al., 2014]. These results concern pencil-like radio beams. Conical (or twisted) beam transmissions at MZ with $f_0$ near $sf_{ce}(h_s)$ ($s = 2 – 6$) potentially sustain artificial ionization layers for multiple hours (P. Bernhardt et al., Large ionospheric disturbances produced by the HAARP HF Facility, submitted to Radio Science, 2016). Henceforth, we focus on the DL during transmissions of usual (pencil) radio beams.

The MZ effect and DL formation have not yet been fully understood. Gurevich et al. [2002] argued that self-focusing of the pump beam on striations and associated anomalous absorption define the MZ effect. However, the predicted dependence on $f_0$ disagrees with the observations. By the same token, in the daytime/twilight experiments [Pedersen et al., 2011; Sergeev et al., 2013] DL started well before striations could develop. In the Pedersen et al. [2010, 2011] experiments, DL emerge at $P_0 \geq P_{dx} \approx 400$ MW for $f_0 < 2f_{ce} \text{ and } 2f_{ce} - f_{bhr} < 5 – 20$ kHz, when TPI is inhibited [Mishin et al., 2005a,b]. Thus, the DL formation has been explained in terms of an ionizing wavefront created by the SLT-accelerated electrons [Mishin and Pedersen, 2011; Eliasson et al., 2012, 2015]. However, the DL in Sergeev et al.’s [2013] experiments were observed only for $f_0 > 4f_{ce}$, consistent with Gustavsson et al.’s [2006] observations of stronger 427.8 nm emissions at $f_0 > 4f_{ce}$. These observations suggest that some unknown interplay between Langmuir and UH processes is critical for the creation of artificial ionospheric plasmas.

This paper seeks to extend understanding of this top priority problem through an assessment of the EISCAT and HAARP HF-heating experiments (section 2) and numerical modeling (section 3), as well as expanding on the theory of HF-excited Langmuir turbulence and related effects (Appendix A). Discussion of the observations in terms of the theoretical/modeling results is given in section 4. Overall, we infer the salient DL features: (i1) appearance only for HF beam pointings at MZ in some experiments but (i1*) for all pointings at and between vertical and MZ in the others, (i2) broad IL/PL layers and (i2*) an asymmetry between upshifted and downshifted ion lines, (i3) the SLT persistence along with DL, (i4) appearance for various HF frequencies not limited to the gyroresonance frequencies, (i5) greater speeds at greater HF beam powers, (i6) decreasing speeds after passing the gyroresonance, i.e., at $f_0 < sf_{ce}(h_s)$, (i7) coexistence of UH and Langmuir processes and mitigation of anomalous absorption, (i8) greater descent speeds correspond to weaker PL/IL signals from MUIR, and (i9) more efficient production in the sunlit ionosphere. The listed items will be connected with the pertinent observations in section 2 and discussed in section 4.

2. Observations of Descending Layers

Descending radar echoes and the green line (557.7 nm, the excitation threshold $e_{g\text{al}} \approx 4.2$ eV) optical emissions from heating experiments at EISCAT have been observed earlier [Djuth et al., 1994; Kosch et al., 2004; Dhillon and Robinson, 2005; Ashrafi et al., 2007], but the first identification of descending layers with artificially produced plasma was in the Pedersen et al. [2010] experiments at HAARP.

2.1. Descending Layers of Ion Line Backscatter for $f_0 \sim 5f_{ce}$

Dhillon and Robinson [2005] studied IL backscatter excited by $7.1$ MHz ($\geq 5.2f_{ce}(h_s)$) O-mode waves at $P_0 = 600$ and $900$ MW, with a half-power (~3 dB) beam width $\Delta \theta_R \approx 7^\circ$ and $6^\circ$, respectively. The pump beam with the duty cycle $2$ min on/$2$ min off was pointed solely field aligned (into MZ) on 25 September 2002, whereas on 26 September it alternated between vertical (V) and MZ. The EISCAT UHF incoherent scatter radar at $f_s \approx 930$ MHz ($\Delta \theta_s \approx 0.5^\circ$) was observing (Bragg) backscatter at the resonant wavelength $\lambda_s = 2\pi/k_s = c/2f_s \approx 16$ cm from five pointing directions in the magnetic meridian plane with a $5$ s time resolution and $1.5$ km range gates. These directions are MZ, MZ+6 (≈Spitze), MZ+12 (≈V), MZ-6 (≈ south to MZ), and MZ-12 (12° south to MZ). Also, the CUTLASS SuperDARN radar ($f_0 = 16 – 19.5$ MHz) located $\approx 1000$ km south of the heater was observing 14–18 m FAl with a 1 s resolution and $15$ km range gates.

Figure 1 is representative of the UHF IL backscatter from V, MZ, and MZ-6 for vertical and MZ injections during $12:34 – 13:06$ UT on 26 September 2002. Overall, there are no effects in MZ-12 and only a few weak returns in MZ+6. For vertical injections, the enhancements in V and MZ are seen only in the first 5 s data dump and thus called overshoots. Henceforth, the term “overshoot” designates the transient response of the excited waves over a few seconds and less. For MZ injections, ≈20 dB overshoots at MZ turn into descending layers of IL backscatter ≈10 dB less (list items i1 and i4). Hereafter, for brevity, the notation “list items” will be omitted.
Figure 1. Ion line backscatter amplitudes from the EISCAT UHF radar on 26 September 2002 for (left) vertical and (right) MZ heater pointings. Three rows correspond to three UHF pointing directions: V, MZ, and MZ-6. The altitude versus the time is shown, and the colors give the backscatter amplitudes in log scale. Adapted from Dhillon and Robinson [2005].

The IL backscatter layers start descending from $\approx 220$–$225$ km at a speed $\frac{dh_{re}}{dt} = v_{re} \approx 250$ m/s and stop in $\approx 1$ min at $h_{re}^* \approx 206$ km. Hereafter, the subscript “re” designates IL or PL radar echoes, while $h_{re}^*$ means the terminal altitude of a descending feature $xx$. The large altitudinal spread $\Delta h_{re} \sim 10$ km, indicates the presence of small-scale irregularities. The IL layers last at the terminus $h_{re}^*$ until the heater is turned off (i3). There appear also persistent layers ($\Delta h \sim 5$–$7$ km) in MZ-6 that do not descend for both vertical and MZ injections. The intensity of the CUTLASS radar coherent backscatter was highest for the area excited by the central part of the heater beam ($<2$ range gates). Backscatter powers of $10$–$20$ dB at MZ were considerably lower than typically observed $30$–$50$ dB (i7).

Figure 2 exemplifies UHF IL spectra in the directions MZ and MZ-6 for vertical and MZ injections (courtesy of R. Dhillon). The evolving spectra during the heater on period (solid lines) are averaged over two successive 5 s data dumps. After 30 s the spectra remained unchanged until the heater was off. The central spectral peak, one of the SLT features, is readily seen for the entire heater on period for MZ injections (i3) and corresponds to the descending IL feature in Figure 1. The asymmetry between downshifted and upshifted “shoulders” (i2*) indicates different amplitudes of upward and downward propagating ion acoustic waves.

The UHF radar was also monitoring the plasma parameters using long pulses with a 22.5 km range resolution. The background electron temperature near 220 km was typically $T_e = 0.15$ eV. During MZ injections, $T_e$ enhancements at altitudes 180–250 km in MZ were $\Delta T_{eMZ} \geq 0.17$ eV up to 0.3 eV. Those for MZ-6 were $0.13$–$0.17$ eV and present for the entire heater on interval. The typical values of $\Delta T_e$ in MZ-12, MZ-6, and V were $\approx 0.04$–$0.08$ eV and consistent with pure ohmic heating.
For vertical heating, $\Delta T_e$ in MZ-12 and MZ+6 were in general lower and not as clear as those for MZ heating, while in MZ-6 the temperature rose to ~0.45 eV.

Note that the actual values of $T_e$ in non-Maxwellian turbulent plasmas can differ from the quoted ones due to the distorted IL spectral shape, particularly at MZ-6. At any rate, non-Maxwellian tails of accelerated electrons (see equation (9)) make virtually no contribution to the mean energy (the temperature). The latter is still defined by the (heated) bulk electron distribution at $\epsilon < \epsilon_{\text{max}}$, which remains close to a Maxwellian [e.g., Mishin et al., 2000]. In turn, the location of the spectral peaks is still defined by the ion sound frequency $f_i = \pm k_c c_i / 2 \pi$ [e.g., Rosenbluth and Rostoker, 1962]. Their shift outward from the unperturbed values $f_i_0 = \pm k_c c_i / 2 \pi$ (Figure 2) clearly indicates plasma heating. As the peak amplitudes are affected by the ion sound turbulence [e.g., Volokitin and Mishin, 1995], using the peaks-to-valley ratio to determine the ratio $T_e / T_i$ is precluded. With $T_i_0 = \frac{1}{2} T_i$, calculating $f_i - f_i_0$ yields $\Delta T_{nz} \approx 0.2$ eV and $\Delta T_{nz-6} \approx 0.2 - 0.4$ eV, consistent with the quoted values.

Contrary to the overshoot behavior at vertical in Figure 1, the Djuth et al. [1994] daytime experiments at EISCAT, with $I_p = 40 - 45$ km for $P_0 \approx 1.1$ GW ($\Delta \theta_0 \approx 4^\circ$) and $\theta_0 = 0^\circ - 5^\circ$S, show persistent descending IL/PL layers (i1*). In particular, a $\approx 20$ dB, $\approx 2$ s PL overshoot at 6.77 MHz (1 s integration time) was centered near 210 km, with an altitudinal spread of $\approx 750$ m. It was sandwiched between layers ($\delta h \approx 500$ m) of echoes of $\sim 10$ dB amplitudes. The overshoot turned into a $\sim 1$ km thick layer of $\sim 10$ dB echoes (i2). Djuth et al. [1994] noted that cloud-like structures in the range-time-intensity plot indicate random small-scale irregularities. After the layer descended by $\sim 3.5$ km in 25 s, it has weakened and become more structured while retreating upward by $\sim 1$ km in $\sim 30$ s. This behavior was routinely observed whenever $\geq 2$ min off periods preceded HF turn on at $P_0 > 500$ MW. The PL/IL spectra, especially the IL central peak, indicate a steady descent of the SLT region (i3). Note that 6.77 MHz was within a few kilohertz of 5 MHz-6.7 MHz was within a few kilohertz of 5 MHz-6 kHz, which indicates the SLT development (i3) near the plasma resonance [2007].

2.2. Descending Features for $f_i$ Around 4$f_e$

Figure 3 is representative of the Ashrafi et al. [2007] results on 12 November 2001 at EISCAT when the heater transmitted O-mode waves at 5.423 MHz and $P_0 = 550$ MW. The $F_2$ peak plasma frequency ($f_p F_2$) was $\approx 8$ MHz before 17:10 UT, gradually declining to $\approx 6$ MHz at 17:40 UT. The pump beam ($\Delta \theta_0 \approx 7^\circ$) was centered at $9^\circ$ south (S) of vertical and had a 2 min on/off cycle until 16:55 UT. Then, it was scanned in $3^\circ$ steps between $3^\circ$ north (N, “-”) and $15^\circ$S of vertical with a 3 min cycle (2/1 min on/off). Data come from concurrent measurements of the red (630 nm, $\epsilon_{\text{red}} \approx 2$ eV) and green line emissions at two separate sites, UHF radar ion line backscatter with a 5.4 km range resolution and 5 s integration time and SEE with a 14 s integration time and 300 Hz frequency resolution. The UHF radar ($\Delta \theta_0 \approx 0.5^\circ$) was sweeping in $3^\circ$ steps from $3^\circ$ to $15^\circ$S of vertical in a north-south meridian scan during 15:08–16:55 UT and MZ pointed later on. Black dashes in Figure 3 (bottom) indicate the pump-on periods, and the upper (lower) labels mark the radar (pump) zenith angles.

Shown in Figure 3 (top) are the consecutive SEE spectra with added 10 dB offsets for the heating cycle starting at 16:17 UT. They contain downshifted, $\Delta f = f - f_i_0 < 0$, and upshifted, $\Delta f > 0$, features. Ashrafi et al. [2007] discussed the downshifted maximum (DM) and broad upshifted maximum (BUM) that indicate UH processes [e.g., Leyser, 2001]. In particular, the DM and BUM (at $f_i > f_{BU}$) are understood in terms of three- and four-wave interactions of UH and LH waves, respectively. We note also the persistent narrow continuum (NC) at $\Delta f > -(5–7)$ kHz, which indicates the SLT development (i3) near the plasma resonance [e.g., Thidé et al., 2005].

As it follows from Figure 3, the BUM peak frequency decreases with time at the rate $r_t \approx 0.2$ kHz/s. Grach et al.'s [2008] empirical relation for the BUM peak frequency

$$f_{\text{BUM}} = 2 f_0 - s f_{ce} + \delta f, \quad (\delta f \approx 10 - 15 \text{ kHz})$$

suggests that $f_{ce}(h_{\text{BUM}})$ increases with time, i.e., the BUM generation altitude $h_{\text{BUM}}$ descends. This spectral feature is hereafter called the BUM$_0$ (“descending”). Using the IGRF model, the descent speed is calculated as $v_{\text{BUM}} \approx r_t (4 f_{ce} / dh)^{-1} \approx 90$ m/s.

Figure 3 (bottom) shows altitude-time plots of raw IL backscatter power for several consecutive HF pump cycles. Ashrafi et al. [2007] calculated the matching altitudes $h_{gr}(s f_{ce}(h_{gr}) = f_i)$, $h_{\text{shv}}$, $h_{su}$, and $h_{\text{hBum}}$ using the
Figure 3. EISCAT experiments on 12 November 2001 at 5.423 MHz. (top) Consecutive SEE spectra from 16:17 to 16:18:21 UT with added 10 dB offsets. The red line indicates the peak BUMD frequency. (bottom) Raw ion line backscatter power in log scale from the UHF radar during the first (left) and second (right) halves of the experiment with the green line optical height triangulation results (black asterisks) and $h_{\text{bum}}$ (blue asterisks) superimposed. The pump-on periods are indicated by black dashes. The upper (lower) labels mark the UHF radar (HF pump) zenith angles. The blue solid (dashed) and dark solid lines indicate $h_{0}$ ($h_{\text{uh}}$) and the gyroresonance $h_{\text{gr}} \approx 215$ km, respectively. Color codes for the IL raw power in log scale are given at the right. Adapted from Ashrafi et al. [2007].

ionosonde data and IGRF model. The heights of the brightest part of the red/green line emissions were triangulated with the average uncertainty of 4–5 km. The green line heights $h_{\text{gl}}(t)$ were available only after 16:21 UT. The variation of the nominal heights $h_{0}$ and $h_{\text{uh}}$ in the background ionosphere is likely caused by a passing atmospheric wave.

Overall, with the pump beam centered at 9°S, enhanced IL echoes in MZ and 9°S radar positions persist during the on period, while only 10–15 s overshoots are seen for 6° and 15°S. The BUMD feature as in Figure 3 (top) remains throughout. Although Doppler spectra were unavailable, the persistent NC suggests that the enhanced IL echoes come from the descending SLT region (i3 and i7). With the HF beam scanning and the radar pointing in MZ after 16:57 UT, similar overshoots in MZ appear for HF beam zenith angles of $-3^\circ$ to $6^\circ$, as opposed to strong persistent signals for 9° and 12 °S. Clear and consistent BUMD was seen only near 17:20 UT at 3° and 6°S just above $h_{\text{gr}}$. Descending green line emissions are observed at all injection angles (i1*) except $-3^\circ$. On average, layers of persistent IL echoes spread over $\Delta h_{\text{re}} \sim 3$ km (i2) and descend at a speed $v_{\text{re}} \sim 120–150$ m/s until the heater is turned off. The terminal heights $h_{\text{re}}^*$ and $h_{\text{re}}^*$ are below $h_{\text{gr}}$ for injections in MZ, V, and 3°S (i4); the differences barely exceed the uncertainty range of 4–5 km though.

We next discuss the Sergeev et al. [2013] frequency-stepping experiment on 28 March 2011, 1500–1600 AST (AST = UT-9). The HF beam was pointed at vertical during the first 30 min and at MZ thereafter. Three observational sites were located approximately along the magnetic meridian to the south of the HAARP facility at distances $\approx$11 (A), 83 (B), and 113 (C) km. Sites A and B were practically under the heating region during injections at vertical and MZ, respectively. The SEE spectra and diagnostic HF radio reflections are very similar at each site, thus indicating broad stimulated radiation and scattering patterns.

O-mode waves were injected at full power ($P_{0} \approx 1.8$ GW, $\Delta \theta_{b} \approx 7^\circ$) and $f_{0}$ from 5.73 to 5.88 MHz, stepping by +30 kHz every 5 min; $f_{0}F_{2}$ was $\approx 6.5 \rightarrow 6.2$ MHz. Each 5 min interval comprises three pumping periods.
followed by 30 s off. Periods 1 and 3 consist of low duty pulses, 20/980 ms on/off, for a total of 30 and 180 s, respectively. A quasi-continuous period 2 comprises 160 ms pulses separated by 40 ms pauses, for a total of 1 min, with the mean \( f_0 \approx 1.44 \text{ GW} \). Diagnostic pulses of 0.1 ms were also transmitted in the middle of each pulse with the same power and frequency as the pump. During the last three 5 min steps at \( f_0 = 5.82, 5.85, \) and 5.88 MHz, MUIR (\( f_\text{p} = 446 \text{ MHz}, \lambda_\text{r} \approx 33 \text{ cm}, \) and \( \Delta \theta_b \approx 8.6^\circ \)) was measuring magnetic field-aligned PL echoes with 600 m and 10 ms range and time resolution, respectively.

Persistent descending signatures during period 2 appear only for MZ injections (i1) for all frequencies except 5.73 MHz (< \( 4f_\text{ce} \)). Figure 4 presents the results from site B for \( f_0 = 5.82–5.88 \text{ MHz} \) with the PL measurements from MUIR. SEE frequency-time spectrograms have a frequency (time) resolution of 200 Hz (0.2 s). Figure 4 (top row) displays the full range spectrograms featuring the BUM\(_{\text{c}}\) (“stationary”), BUM\(_{\text{bf}}\), and 2BUM\(_{\text{bf}}\) centered at \( f^\text{\_bum}_{\text{bf}} \) and \( f^\text{\_bum}_{\text{bf}}(t) \), and \( \approx 2f^\text{\_bum}_{\text{bf}}(t) \), respectively. The BUM\(_{\text{bf}}\) frequency drifts with time toward \( f_0 \) until the frequency offset with \( f_0 \) becomes 10–15 kHz (cf., equation (3)) at the terminal time \( t^\text{\_bum}_{\text{bf}} \). The frequency drift rate \( r_f \) is between 1.2 and 1.4 kHz/s for all \( f_0 \) and independent on the BUM\(_{\text{bf}}\) amplitude, while \( t^\text{\_bum}_{\text{bf}} \) increases with \( f_0 \) from \( \approx 5 \) at 5.76 MHz to 40 s at 5.85 MHz and at 5.88 MHz exceed 1 min. The speed of descent, \( v^\text{\_bum}_{\text{bf}} \approx r_f (4df^\text{\_ce} / dh)^{-1} \), is \( \approx 450–520 \text{ m/s} \). The increase of the overall descent with \( f_0 \) is \( \Delta h^\text{\_bum} = v^\text{\_bum}_{\text{bf}} \cdot t^\text{\_bum}_{\text{bf}} \approx 2 \to 20 \text{ km} \) at \( f_0 = 5.76 \to 5.85 \text{ MHz} \) and greater than 30 km at 5.88 MHz. Note that the 2BUM\(_{\text{bf}}\) drifts toward the BUM\(_{\text{bf}}\) until they “merge.”

Virtual (reflection) heights of diagnostic pulses (Figure 4, second row) have the quasi-stationary and descending signatures. The former is due to scattering from the bottomside \( F \) region (the “BF layer”). As for the low duty periods 1 and 3, the BF layer is initially centered at \( h^\text{\_cF} \approx 325, 340, \) and 360 km at 5.82, 5.85, and 5.88 MHz, respectively. The increase in \( h^\text{\_cF} \) is related to the rise of the \( F \) layer, consistent with PL overshoots during period 1 at altitudes \( h^\text{\_0F} \approx 203 \text{ km} \) at 5.82 MHz and 213 km at 5.88 MHz [Sergeev et al., 2013, Figure 4]. After about 30 s, the BF layer widens and shifts downward by 20–30 km. Descending virtual height layers are dubbed “D VH layers.” They are centered at \( h^\text{\_vhF}(t) \), appear just after the onset of period 2, and stop at \( t^\text{\_vhF} \approx t^\text{\_bum}_{\text{bf}} + (5–10) \text{ s} \), i.e., well below \( h^\text{\_bum}_{\text{bf}} \) (i4). Near the terminus \( h^\text{\_vhF} \), the DVH signals at 5.82 and 5.85 MHz intensify until the end of period 2. Their broad scattering pattern and cloud-like structure suggest scattering off randomly distributed small-scale irregularities. This is consistent with the disappearance of the DVH layer and the recovery of the BF to that of period 1 in just a few seconds after the end of period 2 [Sergeev et al., 2013, Figure 3].

Shown next are height-time plots of the PL intensity integrated for 0.5 s. The arrow points to a ~2 s overshoot at 5.85 MHz at the same altitude \( h^\text{\_cF} \approx 206 \text{ km} \) (\( h^\text{\_ce} = \text{range} \cdot \cos(14.5^\circ) \)) as for 20 ms pulses of period 1 [Sergeev et al., 2013, Figure 4]. The persistent PL signals descend at \( v^\text{\_re} \approx 500–600 \text{ m/s} \). The PL amplitude decreases with \( f_0 \), suggesting weaker amplitudes of the detectable 33 cm Langmuir waves, while the descent speed increases (i8). At 5.82 MHz, the enhanced PL signal remains until the end of period 2 at \( h^\text{\_re} \approx 175 \text{ km} \), well below \( h^\text{\_ce} \approx 182 \text{ km} \) and \( f_0 \) outside the forbidden band (i4).
Figure 5. SEE frequency-time spectrograms for vertical and MZ injections during period 2 in Figure 4, zoomed around $f_0 = 5.82, 5.85,$ and $5.88$ MHz. Color codes show the intensities in decibel. The NC and DM features are designated.

Figure 5 shows the bright band around $f_0$ in Figure 4 zoomed to distinguish the SLT signature (NC) from the UH signature (DM) [cf. Grach et al., 2015, Figure 6]. We note the apparent distinction in the NC and DM behavior at MZ and vertical. The NC spectral width $\delta f_{nc}$ at vertical contracts in ~15 s so that the NC power ($\propto \delta f_{nc}$) exhibits the overshoot behavior. The NC power at MZ is much stronger. The NC width $\delta f_{nc}$ gradually approaches to the ~1 kHz band at $\approx t_{dvh}$ for 5.82 and 5.85 MHz, while persisting for the entire period 2 for 5.88 MHz (i7). The DM features appear similar at vertical and MZ, thus suggesting the principal role of the NC (SLT) for the descending features in Figure 4 (i3).

Figure 6 presents field-aligned upshifted PL echoes from MUIR during frequency stepping near $4f_{ce}$ on 10 March 2013 at HAARP. The critical frequency $f_{oF2}$ was $\approx 7.2$ MHz indicating steady daytime conditions. O waves at frequencies stepping by 20 kHz from 5.74 to 5.88 MHz were injected into MZ at $P_0 \approx 1.8$ GW ($\Delta \theta_b \approx 7^\circ$), with a 2 min cycle (1 min on/off). The PL overshoot heights (arrows) are well above $h_{gr}$ (horizontal lines) at all frequencies except 5.74 MHz. At 5.76–5.88 MHz, persistent signals with an altitudinal spread of ~2–3 km (i2) start after about 0.1–0.2 s at ~5–10 km below ~1 s overshoots and descend as heating time progresses. When $h_{gr}(t)$ passes through $h_{gr}$, the radar signals are significantly enhanced, while the descent speed slows down (i6 and i8). Note also that the PL amplitudes at $\geq 5.84$ MHz are quite weak, similar to Figure 4. Concurrent SEE observations (P. Bernhardt, personal communication, 2015) show the BUM spectrum similar to Figure 4 (i3 and i7).

2.3. Descending Layers of Ion Line Backscatter for $f_0$ Around $3f_{ce}$

Figure 7a shows ion line backscatter power from MUIR at $f_0$ stepping by 20 kHz from 5.74 to 5.88 MHz at HAARP, 10 March 2013. Solid horizontal and dashed oblique lines indicate the gyroresonance $h_{gr}$ and the descent rates, respectively. Arrows show initial overshoots. Colors give the backscatter intensity in decibel.

Figure 6. Plasma line backscatter power from MUIR at $f_0$ stepping by 20 kHz from 5.74 to 5.88 MHz at HAARP, 10 March 2013. Solid horizontal and dashed oblique lines indicate the gyroresonance $h_{gr}$ and the descent rates, respectively. Arrows show initial overshoots. Colors give the backscatter intensity in decibel.
Figure 8 exemplifies the DL development during Pedersen et al.\textsuperscript{f}

2.4. Descending Layers for persistent heating phase at full HF power for 1.1 GW. (b) HAARP, 1 May 2012: Doppler ion line spectra during the MUIR for MZ injections at 4.5 MHz, with ERPs ranging from 20% to 100% of (a) HAARP, 6 November 2010: Ion line backscatter power from Figure 7.

The matching heights and $h_{\text{GR}}(t)$ on 19 November 2009 are shown for MZ and vertical injections. The MUIR backscatter power from MZ (dark grey) is overlaid. In the overdense ionosphere (frame a), $h_0$ and $h_{\text{GR}}$ are initially below $h_{\text{GR}}(2f_{ce} - f_{\text{GR}}) \approx 60$ kHz. A ∼2 km thick layer of IL echoes (i2) remains just below $h_0 \approx 190$ km until $2f_{ce}(t)$ approaches $f_{\text{GR}}(t) + (10–15)$ kHz and the broad IL layer starts descending. During descent, the IL backscatter layer always remains above $h_{\text{GR}}(t)$ with $2f_{ce}(t) - f_{\text{GR}}(t) \approx (10–15)$ kHz. Near the terminus $h_0^* \approx 140$ km, the IL echoes intensify and last until the transmitter turns off. The same pattern is observed on
14 November, when the background ionosphere became underdense \((f_o F_2 < f_o)\) after \(\approx 5\) min in the heating. However, the plasma frequency within the DL \((f_{pe}^{DL})\) reaches \(f_o\). The layer near \(h^*_0 \approx 150\) km with \(f_{uhr}^* \approx 2f_{ce}\) persists for 2 min and decays after the solar terminator crossing, i.e., after the sunlit-to-dark transition and absence of photoionization of neutral gas near the terminus (i9).

For the initially underdense ionosphere (frame b), \(f_{uhr}\) is already close to \(2f_{ce}\) at the very beginning. Although \(f_o F_2\) declines from 2.70 to 2.55 MHz between 02:25 and 02:45 UT, the contours start descending almost immediately. The DL becomes overdense \((f_{pe}^{DL} > f_o)\) much of the time after 02:32 UT, with \(f_{uhr}(t) \approx 2f_{ce}(t) - 15\) kHz on average. Unlike HF pointing in MZ, MUIR does not detect any IL echoes within the first 5 min until 02:32 UT. The signals are very weak from all pointing directions (no vertical beam was used) and nonexistent in MZ. The strongest radar signal from 3\(^\circ\) S appears when \(f_{pe}^{DL}\) reaches \(f_o\). The layer retreats in altitude and disappears following the terminator crossing (i9).

On March 17, strong emissions during 05:13–05:17 UT appear as a diffuse glow and in \(\sim 1\) min gather into a slowly descending spot-within-ring bull’s-eye. The green and blue line emissions at the site develop in concert. This indicates enhanced ionization by \(\geq 18.75\) eV electrons during descent. Ionograms also show a secondary bottomside layer gradually descending at \(\sim 200\) m/s, with \(h^*_u\) approaching 200 km. As the central spot descends below \(h_{gr}\) to \(\approx 180\) km, it turns into a collection of bright field-aligned filaments (a few kilometers in diameter and 10–20 km along \(B_o\)) with intensity increased by a factor of 6. The average speed of descent also increases to \(v_{gl} \approx 300\) m/s. At \(\approx 160\) km the descent slows and ends at \(h^*_gl \approx 150\) km, with the DL plasma frequency above \(f_o\). Here field-aligned IL echoes, invisible during the fast descent, intensify between \(h^*_0\) and \(h^*_u\) (i8).
Near $h_{gl}^*$, the central bright emissions are quenched, whereas an empty ring near 200 km (the bottomside layer) remains in place. The same pattern is realized during a continuous on period beginning at 05:21 UT in the underdense ionosphere. The emissions at $h_{ce}^*$ are quenched themselves several times, initiating the process over again from higher altitudes until the UH resonance ceases. We note that the HAARP experiments with MZ injections at 4.1 and 4.2 MHz ($<3f_{ce}$) on 2 September 2011 (not shown) also show this pattern. Namely, after $\approx 20$–25 s of heating the descending PL echoes at $\approx 215$ km almost double its speed up to $\approx 350$ m/s and stop near $h_{ce}^* \sim 195$ km. Then, the layer is quenched a few times and initiated over again until the end of the transmission.

Overall, the $2f_{ce}$ experiments show that the IL backscatter is persistent for $f_0 < 2f_{ce}$ and intensifies at $2f_{ce} - f_{shr} \approx 5$–20 kHz, when the DL formation is also facilitated. Unfortunately, neither spectral IL data nor coherent radar backscatter data were available at that time to specify the LT regime and FAI at high powers. Some important clues can be deduced from low-power ($P_0 \approx 10$ MW, $\Delta f_0 \approx 32^\circ$) HAARP experiments exploring a frequency pass through $2f_{ce}$ in a decaying ionosphere [Djuth et al., 2005; Kosch et al., 2005, 2007a].

On 4 February 2005, the pump beam at 2.85 MHz was pointed in MZ with a 1 min on/off cycle during 03:00–04:45 UT [Kosch et al., 2007a, Figure 1]. Emissions at 630.0 and 557.7 nm increase near the gyroresonance $h_0 \approx h_{gr}$ [cf. Mishin et al., 2005a], but little change is seen after the double resonance crossing at $\approx 03:45$ UT. However, the Kodiak SuperDARN radar backscatter enhancements at $\lambda \approx 19$ m increased from 10–15 dB to 20–25 dB after the crossing. In fact, this transition starts when $h_{shr}$ exceeds $h_{gr}$ by $\approx 5$ km and $f_0 - 2f_{ce}(h_{gr}) \approx 6$ kHz, i.e., out of the forbidden band. The crossing particularly affected field-aligned PL backscatter measured by MUIR with range and time resolution of 1.5 km and 10 ms, respectively. Namely, persistent backscatter before the crossing changed to $\leq 2$ s overshoots thereafter. Broad SLT peaks with the purely growing mode at $f_0$ and the WT decay and first cascade lines in persistent PL spectra [Oyama et al., 2006, Figure 3] indicate the coexistence of the WT and SLT regimes (see Appendix A).

On 20 March 2004, the pump beam was pointed in MZ with 4 min (2/2 min on/off) and 10 min (8/2 min on/off) cycles during 06:00–07:00 UT when $f_0 = 2.75$ MHz was less than $2f_{ce}$ [Djuth et al., 2005, Figure 1]. Enhanced 630.0, 557.7, and 777.4 nm emissions indicate accelerated electrons at $\varepsilon \geq 10.7$ eV. Djuth et al. [2005] noted only the DM and 2DM SEE spectral peaks. However, the narrow continuum at $\Delta f > -(3–5)$ kHz, alike that in Figure 3, is also clearly seen in their Figure 4. Quite similar NC features have been revealed in the SEE data taken during the March 2011 experiment exploring DL near $2f_{ce}$ at HAARP (M. Kosch, personal communication, 2016).

Recent high-power $2f_{ce}$ heating experiments at HAARP show that the DL formation is typically observed with a broad SEE peak downshifted from the pump by $0.3–0.5$ kHz [Bernhardt et al., 2013]. Samimi et al. [2013] have shown that for $f_0 < 2f_{ce}$ and $T_e \geq 3T_i$ the ion acoustic parametric decay (IAPD) instability, UH/EB $\rightarrow$ UH/‘EB’ + IA [Huang and Kuo, 1995], develops in the UH layer with a broad growth rate centered at $f_0 - (0.3–0.5)$ kHz and thus termed the peak the IAPD structure or simply IAPD. It has a number of similarities with the so-called downshifted peak revealed and thoroughly explored at EISCAT for $f_0/f_{ce} \geq 3$ [Leyser, 2001]. Mahmoudian et al. [2013] observed such peak during high-power $3f_{ce}$ heating at HAARP.

In summary, descending layers appear at various frequencies and injection angles but in some experiments only at MZ (i1,i1*, and i4). Greater HF powers correspond to greater DL speeds but weaker MUIR signals (i5 and i8). The descent slows down after passing the gyroresonance altitude $h_{gr}$, but MUIR signals increase (i6 and i8). The field-aligned IL/PL backscatter persists in, and out of, the forbidden band, $|f_0 - 4f_{ce}| \leq f_{shr}$, around the gyroresonance (i7). In addition to standard SLT/WT features, the IL/PL layers have a notable asymmetry between upshifted and downshifted ion lines and large spread in altitude (i2, i2*, and i3). The DL production is facilitated in the sunlit ionosphere (i9).

### 3. Modeling of HF-Driven Langmuir Turbulence

Mjølhus et al. [2003] presented a comprehensive review of early works on HF-driven Langmuir turbulence at $P_0 < P_{DL}$, including some results for oblique incidence. Eliasson et al. [2012, 2015] performed simulations of Langmuir turbulence and DL in the high-power regime. Before presenting typical nonlinear features at $P_0 > P_{DL}$, we describe (linear) propagation of $O$-mode waves at various incidence angles.
field amplitude normalized to $E$, the downward geomagnetic field is tilted south at an angle $\chi = 14.5^\circ$ at HAARP and 12$^\circ$ at EISCAT. We do not attempt to model each of the aforesaid experiments rather focusing on general $O$-mode characteristics near the turning point. The magnitude $B_0$ is assumed constant such that $f_{ce} = 1.425$ MHz. The plasma density profiles at HAARP are taken from the IRI model [Bilitza et al., 2011] on March 2009 at 01:00 AST for $f_0 = 5.7$ MHz (night-time). These, for example, give $h_0 \approx 229$ and 279 km and the density scale heights $l_p(h_0)$ $\approx 23$ and 42 km at $f_0 = 2.85$ and 5.7 MHz, respectively. To trace 6.5–7.1 MHz waves, we use Gaussian $F$ region altitude profiles with $l_p \approx 45$ km at EISCAT and 50 km at HAARP, giving $h_0(f_0) = 280 \rightarrow 289$ km. The electron-neutral collision rate is taken from Valthakuro et al. [2002] (the total electron collision frequency $v_e \approx 3 \cdot 10^7$ s$^{-1}$ at $\sim 200$ km).

Figure 9 synthesizes the simulation results. Figure 9 (top) shows the height difference $\Delta h_{nz} = h_{nz} - h_0$ and $\Delta h_{nh} = h_{nh} - h_0$ for $f_0$ stepping by 0.1 MHz from 6.5 to 7.1 MHz at EISCAT and HAARP. As anticipated, the height difference $h_{nz}$ decreases with $f_0$. In this particular case, the UH layer is above $h_{nz}$ at $f_0 > 6.8$ MHz ($\approx 4.8 f_{ce}$) at HAARP, while at EISCAT it is still below $h_{nz}$ by $\approx 0.4$ km at 6.8 MHz and 0.2 km at 7.1 MHz. Shown next is the normalized swelling factor $Y_0/Y_0$ at HAARP for $f_0 = 2.85$ (2$f_{ce}$), 4.275 (3$f_{ce}$), and 5.7 (4$f_{ce}$) MHz as a function of $\theta_0$. It drops at Spitze and approaches the unmagnetized limit $\sin^{2/3} \Theta_{nz} \approx 0.39$ [cf. Mjølhus et al., 2003, Figure 12]. As the free space field near the turning point is $E_{fr} \approx E_{fr} \cdot h_{in}/h$, the “standard” swelling factor $Y_0 = E_{fr}/E_{fr}$ is equal to $Y_{in} \cdot h_{fr}/h_{fr}$.

3.1. $O$-Mode Propagation

Assuming the absence of absorption along the path from the ground gives the free space field at an altitude $h$

$$E_{fr}[\text{V/m}] \approx 5.5 \sqrt{P_{fr}[\text{MW}]/h[\text{km}]} \quad (4)$$

Within the Spitze cone, the ratio between the first Airy maximum $E_A$ at $h_A \approx h_0 - l_p$ and $E_{fr}$ gives the swelling factor $Y_0 = E_A/E_{fr} \approx (2\pi/\sin \chi)^{2/3}(f_0/f_A)^{1/6}$. Here $l_0 \approx (c^2 \sin^2 \chi / \omega_p^2)^{1/3}$ is the scale length of the Airy function, $A_i(h - h_0)/l_0$, and $c$ is the speed of light [e.g., Mjølhus, 1990]. For incidence angles $\theta_0 > \theta_A$, as noted by Mjølhus et al. [2003], one should consider the caustic rather than the turning point $h_A$. Nonetheless, $A_i(h - h_1)/l_0$, with the scale length $l_0(\theta_0)$, is still a good representation for the swelling pattern.

To trace an $O$-mode wave up to its turning point, we use Lehtinen and Inan’s [2008] full wave algorithm for cold plasma. One-dimensional (1-D) simulations start with the fixed free space field $E_{in} = E_{fr}(h_{in})$ at $h_{in} = 80$ km and the horizontal component of the wave vector $k = -\omega \cos \theta_0 = \text{const}$ (an infinite beam). The $x$ axis is aligned with the magnetic meridian and pointed to the north. The downward geomagnetic field is tilted south at an angle $\chi = 14.5^\circ$ at HAARP and 12$^\circ$ at EISCAT. We do not attempt to model each of the aforesaid experiments rather focusing on general $O$-mode characteristics near the turning point. The magnitude $B_0$ is assumed constant such that $f_{ce} = 1.425$ MHz. The plasma density profiles at HAARP are taken from the IRI model [Bilitza et al., 2011] on March 2009 at 01:00 AST for $f_0 = 5.7$ MHz (night-time). These, for example, give $h_0 \approx 229$ and 279 km and the density scale heights $l_p(h_0)$ $\approx 23$ and 42 km at $f_0 = 2.85$ and 5.7 MHz, respectively. To trace 6.5–7.1 MHz waves, we use Gaussian $F$ region altitude profiles with $l_p \approx 45$ km at EISCAT and 50 km at HAARP, giving $h_0(f_0) = 280 \rightarrow 289$ km. The electron-neutral collision rate is taken from Valthakuro et al. [2002] (the total electron collision frequency $v_e \approx 3 \cdot 10^7$ s$^{-1}$ at $\sim 200$ km).
large as at vertical, \( l_o \). It is worth to note that \(|\Delta h_{mz}|\) increases nearly linearly with \( l_o (h_0) \) and is about 0.8, 1.3, and 2.7 km at 2.85, 4.275, and 5.7 MHz, respectively. Accordingly, the value of the frequency mismatch at MZ, \( \Delta f \approx -\Delta h_{mz}/2l_o \) (2), is about 0.017. The wave amplitudes in the downward radio window greatly increase just below \( h_0 \) due to accumulation of Z-mode waves [e.g., Mjølhus, 1990]. Waves propagating above \( h_0 \) within the upward window were not tracked during this run. However, as expected, quite the same accumulation pattern shifted farther south from the Spitzes is present in runs (not shown) that trace reflected Z waves.

Two-dimensional calculations for MZ injections have been performed in the Fourier \( (k_y) \) domain \( k_y \in [k_{mz} \pm \Delta k_y] \). Waves propagating above \( h_0 \) within the upward window were not tracked during this run. However, as expected, quite the same accumulation pattern shifted farther south from the Spitzes is present in runs (not shown) that trace reflected Z waves.

3.2. One-Dimensional Simulations of SLT and DL

We now present some results of a full wave 1-D modeling of Langmuir turbulence driven by an O-mode pump at \( f_o = 3.2 \) MHz and various incidence angles \( \theta_0 \) [Eliasson et al., 2015]. The simulation details are given in [Eliasson et al., 2012; Eliasson et al., 2013]. In brief, the code uses a 1-D geometry, with a computational box from \( h = 142 \) km to 342 km. A Gaussian F region altitude profile is assumed \( n_e(h) = n_0 e^{-h-h_m} \), with \( f_m(h_m) = 3.4 \) MHz, \( l_m = 31.6 \) km, and \( h_m = 242 \) km. The downward magnetic field \( B_0 = 0.5 \) G \( (f_c \approx 1.4 \) MHz) is directed at \( \chi = 14.5^\circ S \) (HAARP) to the vertical. The electron and ion temperatures are taken as \( T_{e0} = 2T_{i0} = 0.4 \) eV, about two times higher than in the quiet ionosphere. The damping rates of Langmuir and ion acoustic waves are set to \( 10^2 \) and \( 10^3 \) s\(^{-1} \), respectively. Near \( h_0 \approx 231 \) km, the gradient scale is \( l_n \approx 43 \) km and the Airy scale \( l_o \approx 75 \) m.

Figure 11 exemplifies the evolution of the vertical electric field \( E_v \) and ion density fluctuations \( \delta n_i \) near \( h_t \) at vertical, 10.5°S, and MZ, with the input amplitude \( E_{in}=3 \) and 2 V/m at \( h_{in}=200 \) km. Clearly, Airy-like structures of the electric field are set up first. For \( E_{in}=1 \) V/m, the first Airy maximum is \( E_A \approx 22 \) V/m at vertical and \( \approx 13 \) V/m at MZ [Eliasson et al., 2015, Figure 1]. The nonlinearity parameter

\[
w_0 = E_A^2/8\pi n_0 T_e
\]
is \( \approx 0.26 \) at vertical and 0.09 at MZ and \( \tilde{h}_{nz} \approx 0.016 \) \( (\Delta h_{nz} \approx -1.4 \text{ km}) \). In about 1–1.5 ms this structure within the first few maxima starts breaking into small-scale turbulence. In saturation, solitary wave packets in the SLT region are trapped in density cavities (Figure 11, right column) of widths \( l_d \sim (10 – 20) r_D \) spaced apart by \( \sim 50 r_D \). It is seen that the SLT region is sandwiched between the WT regions with turbulent electric fields but without density cavities. Another notable common feature revealed in full wave modeling is the emergence of \( Z \)-mode waves around \( h_0 \), concurrent with the cavitating turbulence \([cf. Eliasson, 2008]\).

The SLT development at vertical (within Spitzes \( \theta_s \approx 7.7^\circ \)) follows a certain pattern. That is, saturation is followed by a gradual downward shift of the turbulent layer. The r.m.s. (root-mean-squared) amplitude \( \delta E_{sat} \) of the saturated turbulent electric fields is smaller than that for the initial stage (the SLT overshoot). The initial stage at 10.5° S and MZ appears the same as at vertical, except for the difference consistent with the frequency mismatch \( \tilde{h}_{nz}(h) \) (2). However, at later times the SLT layer at 10.5° S expands in both directions. Ultimately, its upper boundary reaches \( h_o \), while the lower boundary overlaps with the second peak, so the SLT altitudinal extent is \( l_{LT} \sim 3 l_o \). At MZ, the SLT layer remains near the first peak for \( E_{in} = 1 \text{ V/m} \) while for 2 V/m \( l_{LT} \) increases with time up to \( \sim (3 – 5) l_o \).

The fast time downward shift and the appearance of \( Z \)-mode waves can be understood in terms of Brillouin scatter \( (O + \delta n_k \rightarrow O') \) and \( O + \delta n_k \rightarrow Z \) conversion due to scattering off short-scale cavities and ion oscillations \([e.g., equation (A10)]\). When SLT develops in lower Airy maxima, the pump energy is scattered en route to \( h_o \).
Figure 12. Modeling of the accelerated population and descending layers at HAARP: (top) Turbulent electric fields $E_z$ and the TDF $F_t(\varepsilon) = F_t(u) du/d\varepsilon$, calculated for MZ injections with $E_m = 1$ and 2 V/m and $T_e = 0.4$ eV. (bottom) Time versus altitude plots of the plasma density in cubic centimeters at V and 10.5°S calculated for various $E_m$ and $T_e$ indicated in frames. Adapted from Eliasson et al. [2012, 2015].

1d SLT simulations for HAARP: $T_e = 0.4$ eV, $E_m = 1$, 2 V/m @ MZ

$\frac{d}{dt} F_t = \frac{\alpha^2 \varepsilon}{m_e n_0} \frac{\partial}{\partial u} \left( \frac{W_{mn}/u}{u} \right) - \frac{\partial}{\partial u} D(u) \frac{\partial F_t}{\partial u}$

\[ \int W_s dk = \int_{z_0}^{z_{LT}} dz \left| E_z^2 \right| / 4 \pi L^\perp \]

Here $d/dt = \partial/\partial t + u \partial/\partial z$, $W_k$ is the spectral energy normalized by the integral (8), and $k$ is the wave number.

The TDF (9) agrees with the prior results [Galeev et al., 1983; Wang et al., 1997], yet $b$ depends on $E_m$ and $T_e$ [Eliasson et al., 2012, Table 1]. This is understood as follows. The particle flux into the tail is defined by $D(u_{\min}) = \frac{W_{mn}}{m_e n_0}$ in the right-hand side of equation (7). In turn, the tail density $n_t \approx C_t \cdot \varepsilon^{1+b} / (b-1)$ is mainly defined by the matching condition, $F_t(u_{\min}) = F_t(u_{\max})$ (the ambient Maxwelian distribution). The maximum energy $\varepsilon_{\max}$ depends also on the transit time $t_{\max} \sim l_{LT} / \varepsilon_{\max}$. Overall, at each incidence angle the simulated spectral width $\Delta k$, $\delta E_{\text{sat}}$ and $l_{LT}$ increase with $E_m$. These factors and the input value of $T_e$ lead to considerable differences in the TDF and DL. In particular, the TDF at 3.5° and 10.5°S is more enhanced than that at vertical due to greater SLT extents $l_{LT}$. The TDF at MZ for $E_m = 2$ V/m is close to that at vertical for $E_m = 1.5$ V/m [Eliasson et al., 2012, Figure 8, 2015, Figure 10].

thereby inhibiting SLT at $h_0$. Overall, it appears that scattering off cavitons is less harmful for the SLT development at 10.5°S and MZ, where the SLT region gradually expands with time. At 10.5°S, Brillouin scatter seems capable of making O-mode waves close to the Spitze cone to produce SLT near $h_0$.

While crossing an individual caviton of the size $l_a \sim k_0^{-1}$, electrons can gain or lose energy, depending on the phase of the trapped oscillations. Fast electrons, whose passage time is shorter than $\omega^{-1}$, i.e., $v_1 = u > \omega/k_0$, experience a localized quasi-stationary field and acquire or lose energy $\sim e |E| l_a$.

Here $u = \sqrt{2e/m_e}$ is the parallel ($||B|$) velocity. For an isotropic electron distribution, the first-order energy gains are averaged out, thus leaving the net gain $\Delta \varepsilon \propto E_{\text{sat}}/E_a$. Due to a random distribution of cavities in space, electrons will experience a random walk (diffusion) in velocity space and form a non-Maxwellian high-energy tail. This process can be modeled [Eliasson et al., 2012, 2015] by a Fokker-Planck equation for the averaged 1-D (tail) distribution (TDF) $F_t(u)$.

$$ F_t(\varepsilon) = C_t \cdot \varepsilon^{-b} $$
The DL development is defined by the input values $E_{in}$, $T_e$, and $\theta_0$ [Eliasson et al., 2012, 2015]. Shown in Figure 12 are the DL calculated at vertical and 10.5°S with the TDF for $E_{in} = 1 - 1.5$ V/m and $T_e = 0.4 - 0.6$ eV. As discussed in Appendix A, the critical parameter for DL is the density of the ionizing ($e_i > e_{ion}$) electrons $n_i^{ion}$. It follows from the simulations that $a_{ion}^{DL} \equiv n_i^{ion}/n$ should exceed $a_{ion}^{DL} \approx (2 - 6) \cdot 10^{-3}$ for DL to descend from $\approx 220$ km to $h_o^{DL} \approx 180 - 150$ km [Eliasson et al., 2012, Figure 12]. In particular, $a_{ion}^{DL} \approx 6 \cdot 10^{-4}$ is obtained for $T_e = 0.4$ eV and $E_{in} = 1.5$ V/m at vertical [Eliasson et al., 2012, Table 1]. For a Gaussian (2-D) HF beam, a $\sim 2$ dB additional swelling factor at MZ (Figure 10) should reduce $n_{ion}^{DL}$ to $E_{in}^{DL} \approx 1$ V/m.

A few remarks are in order (see Appendix A). Although $w_0 \ll \alpha_{ion}^{2}/\alpha_{pe}^{2}$, the modulational instability is excited in a narrow cone around $B_{0}^{\circ}[\theta] \ll 1$, pancake-shaped cavities (equation (A7)) are not described by the 1-D approximation. In general, either the pumping for the 1-D turbulence or/t and $T_{e}$ should be greater than that for $\geq 2$-D in order to achieve the same TDF. Another deficiency is that the TDF is kept unchanged throughout the descent, presuming the same conditions for acceleration. And finally, the presence of photoelectrons significantly enhances the SLT acceleration (see Appendix A), thereby relaxing the dependence on $T_{e}$. Therefore, one should exercise caution comparing the 1-D SLT simulations against data.

4. Discussion

The “pure” SLT scenario of the DL formation [Mishin and Pedersen, 2011; Eliasson et al., 2012, 2015] implies that the overall data set shows that strong Langmuir turbulence is the principal cause of the DL formation. Then, the SLT persistence, consequent to mitigation of anomalous absorption, Langmuir processes in the UH layer, and the DL evolution at the terminal altitude are discussed.

4.1. SLT and Descending Layers

For completeness, we outline the SLT features for $P_0 \geq P_{DL}$ or $P_0 = P_{DL} \geq 1$. For vertical injections at HAARP at $h_o = 220$ km, $f_0 = 3 \rightarrow 7$ MHz or $10^{-8}n_c \approx 1 \rightarrow 5.4$ cm$^{-3}$, and $l_o = 40$ km, we get the swelling factor $\Upsilon_0 \approx 28 \rightarrow 32$ and $p_0^{-1/2}E_0 \approx 0.5 h_o^{DL} / 14 \rightarrow 16$ V/m, thus giving $w_0 / p_0 \approx 0.1 \rightarrow 0.03$ for $T_e = 0.3$ eV (see equations (4) and (6)). Taking $P_0(f_0) = 1$ at 3 MHz and 3 at 7 MHz yields $w_0 \approx 0.1$. The swelling coefficient $\Upsilon_0$ at MZ for a 2-D beam is $\approx 0.8h_o^{DL}$. At any rate, $w_0$ exceeds the frequency mismatch (equation (2)), $\alpha_{ion}^{2} \approx l_0^{2}/2l_0 \approx 10^{-3}$ and $\alpha_{ion}^{2} \approx 0.017$ at vertical and MZ, respectively. Thus, the initial development of plasma turbulence in the first few Airy maxima at MZ and vertical should be nearly the same (cf., Figure 11). As $w_0 \geq w_{sat} \sim 10^{-3}$ (equation (A9)), the turbulence develops in the superstrong (SST) regime and, furthermore, like in isotropic plasmas at $w_0 > \alpha_{ion}^{2}/\alpha_{pe}^{2}$. The latter is easily satisfied for $f_o / f_{ce} \sim 4 - 5$. Therefore, the SLT acceleration is expected to be more efficient than in the 1-D approximation (Figure 12).

First, we argue that the DL formation is not tied to the BUM$_{p}$ mechanism, which operates at $h > h_{rum}^{DL} > h_{fr}$ (see equation (3)) and has the minimum excitation threshold $E_{rum} \approx 0.3$ V/m at $f_{rum} \approx f_0 + 3f_{pe}$ [Huang and Kuo, 1994; Hussein et al., 1998]. Note that the free space field $E_{in}$ (4) exceeds $E_{rum}$ at $h \approx 220$ km for $p_0 > 0.4$, i.e., well below the applied powers. The independence of the DL speed on the BUM$_{p}$ intensity (Figure 4) and the continuous descent after passing $h_{rum}^{DL}$ (Figures 3–6) show that the BUM$_{p}$ mechanism is minor for DL. At the same time, the SLT development in the descending region (3) is indicated by the persistent central IL peak (Figure 2) and NC (Figures 3 and 5). The descent follows the NC power, whereas the DM features appear similar at MZ (with DL) and at vertical (without DL). Furthermore, the descending features and DM follow the onset of heating too rapidly for significant striations to develop, thereby excluding the TPI-related heating. The same is true for the descending PL/IL echoes (Figures 6 and 7). Thus, it appears conclusive to relate the SLT to the DL development.

The observation that DL appear in the sunlit ionosphere at $\approx P_{DL}/2$ (see Figure 7a and Djuth et al. [1994]) and that the sunlit-to-dark transition quenches the persistent DL at the terminus (Figure 8) indicates more efficient ionization (acceleration) when photoelectrons are present (9). This is the consequence of the SLT acceleration, which is enhanced in the presence of the ambient suprathermal population (photoelectrons) [e.g., Mishin et al., 2004]. Another consequence is that the DL speed $v_0$ anticorrelates with the MUIR signal amplitude (Figures 4 and 6–8) during daytime (8). Note that the resonance electron energy for 33 cm waves detected by MUIR is $\epsilon_r \approx m_{e}\alpha_{pe}^2/2k_r^2 \approx 9$ eV at $f_0 = 6$ MHz and $\approx 6$ eV at $4.5$ MHz. Actually, as the wave absorption by the tail electrons increases, collapse can be arrested at greater scales than $1/k_r$, i.e., at $\epsilon_{min}^{(s)} > \epsilon_r$. In other words,
while the density of the ionizing \( (\varepsilon > \varepsilon_{\text{ion}}) \) electrons \( n_{\text{ion}} \) and hence \( v_{\text{ce}} \) (see equation (A13) and Eliasson et al., 2012, Figure 12) increases, the detectable wave energy reduces. At the same time, the persistent NC (Figure 5) reveals the waves with \( k < k_i \), undetectable by MUIR. This is consistent with the gap between the initial overshoots and the persistent PL/IL signals (Figures 4, 6, and 7a), which is of the order of the ionization length of accelerated electrons [see Mishin and Pedersen, 2011, Figure 2].

The energy flux in the short scales increases due to conversion of long-scale waves on short-scale density oscillations (equation (A10)). The presence of such oscillations is indicated by the large altitudinal spread of the IL/PL layers (i2) and the cloud-like structure of the DVH layers (Figure 4). In the heated plasma (\( T_e \sim 0.3 - 0.4 \) eV), short-scale oscillations can be produced by “burned out” cavities in the SLT region [e.g., Galeev et al., 1977] and the heat flux-driven instability (see Appendix A). The latter easily develops at altitudes \( \sim 200 \) km where the mean free path of heated electrons \( \lambda_f \) is \( \sim 2 - 3 \) km and \( f_f \left( = \left| v_{||} \ln T_e \right| \right) \lesssim 100 \) km [cf. Dhillon and Robinson, 2005, Figures 5 and 6]. As discussed in Appendix A, this instability leads to the asymmetry (i2*) between downshifted and upshifted shoulders in the IL spectrum (Figure 2).

4.2. Mitigation of Anomalous Absorption and Parametric UH Interactions
Eliasson et al.’s [2015] Figure 11 shows the SLT-driven DL for a broad range of incidence angles, in agreement with some of the data (i1*). Indeed, for \( f_0 \sim 2f_{ce} \) (Figure 8), DL appear both at MZ and at vertical. For \( f_0 \sim 5f_{ce} \) and \( f_0 \sim 4f_{ce} \), the descending (SLT) features have been observed within the Spitzer cone [Djuth et al., 1994] and from vertical to MZ (Figure 3), respectively. However, Figures 1 and 2 and Figures 4 and 5 show DL only at MZ (i1) and overshoots at vertical for nearly the same frequencies. We consider anomalous absorption (TPI) as the main factor demarcating the overshoot and persistent behavior.

In particular, anomalous absorption is inhibited in the Djuth et al. [1994] experiments, as \( f_0 = 6.77 \) MHz is within the forbidden band, i.e., \( f_0 \sim 5f_{ce} < f_{\text{ce}} \). Similarly, the TPI development is suppressed for \( f_0 \leq f_{ce} \) [Mishin et al., 2005a]. Indeed, UH waves exist only for \( f_0 > 2f_{ce} \). EB modes in the region \( f_{\text{dhr}} \leq f_{ce} \) and \( k_i \rightarrow 0 \) are not trapped by striations and hence do not contribute to TPI. For small \( k_i \ll r_{ce} ^{-1} \) (\( r_{ce} \) is the thermal electron gyroradius), trapping is limited to waves with relatively small \( q_i \ll 5q_i \) [e.g., Grach, 1979; Hysell and Nossa, 2009]. Such oblique waves are unable to attain short transverse wavelengths; thereby, deep striations necessary for strong absorption are not formed. This conjecture agrees with persistent PL signals at \( f_{\text{dhr}} \leq 2f_{ce} \) i.e., before the double resonance crossing, and overshoots and increased (by 10–15 dB) Kodiak radar echoes thereafter [Kosch et al., 2007a].

In turn, the DL at MZ and their absence at vertical in Figure 1 can be explained using Figure 9 (top). It gives \( h_{xz} - h_{\text{ce}} \approx 230 \) m (\( \approx 3f_{ce} h_{\text{ce}} \)) at MZ for 7.1 MHz, i.e., the SLT and UH layers overlap. Apparently, scattering of the pump and excited UH waves off short-scale cavitons and ion oscillations (equation (A10)) keeps down the energy flux in the short scales increases due to conversion of long-scale waves on short-scale density oscillations (equation (A10)).
more efficient for the SLT development and hence DL. This is consistent with the greater NC power at MZ than that at vertical (Figure 5), alike the aforesaid MZ effect at low powers.

4.3. Langmuir Turbulence in the UH Layer

So far, the SLT development is implied near the turning point \( h_s \), i.e., at and between \( h_0 \) and \( h_{\text{mz}} \). However, SLT can also develop in the UH layer even at low powers [Mishin et al., 2004]. First, the OTSL\(_{\text{H}}\) [Kuo et al., 1997] of the primary UH waves with the r.m.s. amplitude \( \sim 0.1 – 0.3 \) V/m excites oblique short-scale Langmuir waves. These are transferred into long scales via parametric interactions, e.g., induced scattering on ions. The resulting wave condensate is subjected to the modulational instability leading to the SLT regime, albeit weaker than near \( h_s \), in the overdense ionosphere (see Appendix A). This mechanism was instrumental in explaining airglow in the underdense ionosphere at MZ at low powers [Mishin et al., 2005b]. As the OTSL\(_{\text{H}}\) is facilitated at \( f_0 > sf_{ce} \) (\( s \geq 3 \)), the contribution of the SLT acceleration in the UH layer is to be greater above the gyroresonance than below. This helps to explain the emergence of DL [Sergeev et al., 2013], faster descent speeds in Figure 6, and intensification of 427.8 nm emissions [Gustavsson et al., 2006] at \( f_0 > 4f_{ce} \).

Similarly, Samimi et al.’s [2014] numerical simulations at \( f_{\text{hr}} < 2f_{ce} \) and \( T_e \geq 3T_n \) show that the IAPD instability in the UH layer is associated with caviton collapse and concomitant electron acceleration along \( B_0 \), i.e., in line with the SLT processes. This agrees with the DL development in Figure 8b that starts almost immediately in the underdense ionosphere, where the modulational instability is prohibited until the UH becomes overdense \( (\nu_{pe}^{(\text{DL})} \geq f_0) \). Note also that cyclotron acceleration [e.g., Dimant et al., 1992; Kuo, 2015, Figure 1] can contribute to the DL formation at small \( |2f_{ce} − f_0| \), as with intensified optical emissions at \( h_0 \rightarrow h_{gr} \) for low powers [Mishin et al., 2005a; Kosch et al., 2007a].

It seems natural to explain the presence of two descending ion line layers at \( f_0 = 4.5 \) MHz (Figure 7a) by the concurrent excitation of SLT near \( h_{\text{mz}} \) and \( h_{\text{sh}} \). Indeed, the height difference \( h_{\text{mz}} − h_{\text{sh}} \approx 4 \) km (at the scale height \( h_s = 50 \) km) is close to the observed one at 20\% and 50\% of full power and at the beginning of descent at full power. The weaker signal in the lower layer is consistent with the weaker SLT energy in the UH layer [Mishin et al., 2004]. Let us assume that two temperature profiles, with peaks near \( h_{\text{mz}} \) and \( h_{\text{sh}} \), overlap in such a way that the temperature peak is formed between the layers. Then, the asymmetry in the Doppler-shifted spectra in each layer can be understood in terms of propagation of short-scale, \( k > k_c \), ion acoustic waves along \( \nabla T_e \). Though in this case the heat flux instability is not necessary, it can also contribute to the asymmetry.

4.4. Quenching and Persistence at the Terminator

Mishin and Pedersen [2011] suggested the thermal self-focusing instability near the plasma resonance to be the cause of kilometer-scale bright filaments in the March 2009 experiment, as Kosch et al. [2007b] for low powers. According to theory [e.g., Guzdar et al., 1998], kilometer-scale filaments grow initially and in \( \sim 10 \) s break into smaller-scale sizes (tens to hundreds of meters). During descent, the plasma resonance at \( h_0 \) descends by several kilometers in \( \sim 10 \) s, thereby precluding breaking into small scales. However, in the persistent layer at the terminus \( h_{\text{sh}} \), small-scale irregularities can fully develop for \( f_0 \) well under \( 2f_{ce}(h_{\text{sh}}^*) \) and scatter the HF beam, thereby quenching the SLT-related ionization and thus the DL. As soon as the layer decays and irregularities fade out, the artificial plasma can be created again, resembling the quenching and reappearance of the DL in Figure 8c. On the other hand, the instability is suppressed when \( f_0 − sf_{ce} \) tends to zero [e.g., Mjølhus, 1993; Starodubtsev et al., 2007, Figure 6j], in agreement with the DL’s persistence at \( h_{\text{sh}}^* \) in November 2009 (Figures 8a and 8b).

A remark is in order. Even though our main object, the DL, is not related to the persistent IL layers near \( h_0 \) at MZ-6 for MZ and vertical injections (Figure 1), this phenomenon is significant enough to be discussed. We suggest that such layers are related to Z-mode waves that are efficiently generated by resonant scattering of the pump wave off cavitons in the SLT regions, such as in Figure 11, and also off FAI or LH cavitons near \( h_{\text{sh}} \) [Mishin et al., 2001]. After reflection on the topside, the Z-mode reaches the height of transformation into Langmuir waves slightly below \( h_0 \) and farther south to MZ [cf. Gelinas et al., 2003, Figure 12]. As the \( Z \rightarrow L \) (linear) conversion process is also very efficient, the SLT development in this layer is expected [e.g., Mishin et al., 2001]. The high wave energy, such as around the downward radio window in Figure 9, makes the elevated \( T_e \) observed at MZ-6 [Dhillon and Robinson, 2005] not surprising. Then, the heat flux instability in the heated plasma provides an explanation of the asymmetric IL spectra at MZ-6 (Figure 2).
5. Conclusion

The salient features of HF-driven plasma turbulence and descending layers of freshly ionized plasma in high-power heating experiments have been summarized. The overall data relate DL to the development of strong Langmuir turbulence, which is revealed by the specific spectral features of incoherent radar backscatter and stimulated electromagnetic emissions. We have performed numerical investigation of (linear) propagation of O-mode waves for 1-D and 2-D HF radio beams at various incidence angles, along with the SLT development and DL formation in the 1-D approximation. The swelling factor of a 2-D beam exceeds that of a 1-D beam by about 2 dB, while the characteristic scale length of the swelling pattern at MZ is about twice that at vertical. The greater extent of the SLT region near MZ than that at vertical appears to make HF beam pointings in MZ more efficient for electron acceleration and DL. The presence of the ambient suprathermal (photo)electron population facilitates the SLT acceleration. The consequences of the photoelectrons in the sunlit ionosphere are the decreased DL formation threshold, the greater DL speeds at weaker MUIR signals and stronger NC powers, the gap between the overshoot and persistent PL/IL signals, and the decay of the persistent DL at the terminus after sunlit-to-dark transition.

The data suggest that the SLT persistence near the plasma resonance during descent is the consequence of mitigation of anomalous absorption in the UH layer. In particular, parametric UH interactions mitigate anomalous absorption for heating frequencies outside the forbidden band and also generate Langmuir turbulence in the UH layer. The presence of the second SLT region is consistent with two layers of the MUIR ion line backscatter at $f_0 > 3f_{ce}$, as are the emergence of DL, faster descent speeds, and intensification of 427.8 nm emissions at $f_0 > 4f_{ce}$. The DL persistence at the terminal altitude depends on how close the heating frequency is to the local gyroharmonic. The large altitudinal spread of the IL/PL layers and the cloud-like structure of the DVH layers indicate the presence of short-scale density oscillations. These can be produced in the heated plasma by burned out collapsing cavities and the heat flux-driven instability. The latter leads to the asymmetry between downshifted and upshifted shoulders in the IL spectra and limits the field-aligned heat conductivity.

Overall, the concept of an ionizing wavefront created by accelerated suprathermal electrons agrees with the data. More careful studies, both experimental and numerical, are needed in order to detail the processes involved. Future modeling at various pump frequencies should include parametric interactions in the upper hybrid layer, scattering of the radio beam off cavities, thermal self-focusing and heat flux instability effects, and the resulting SLT acceleration in the plasma resonance and upper hybrid layers in a self-consistent manner.

Appendix A: Langmuir Turbulence and Related Effects

We present a heuristic description of plasma turbulence driven by pump waves of the amplitude $A_p$, and frequency $\omega_0 \approx \omega_{pe} \gg \omega_{ce}$ near the plasma resonance $h_0$. It is based on the Zakharov equations describing slow processes after “filtering out” the fast (HF) variations [e.g., Zakharov, 1984]. So the Langmuir field is presented via potentials $\psi = \text{Re}(\Psi(r, t)e^{-i\omega_0 t})$ and $E_j = -\nabla\psi$, with slowly varying $(\frac{d}{dt} \ln |\Psi| \sim \Omega \ll \omega_{pe})$ amplitudes $\Psi$ and $A_j = -\nabla\Psi$. The pump wave near $h_0$ is polarized mainly along $\mathbf{B}_0$, i.e., $|\mathbf{E}_1| \gg |\mathbf{E}_2|$. Then, the ponderomotive force is almost the same as in isotropic plasma, $\mathbf{F}_p = -\nabla W_p/2\omega_{pe}$ accurate to $|\mathbf{E}_2|/|\mathbf{E}_1|$. Here $W_p$ is the energy density of the total, pump and electrostatic, HF wavefield. Its quantitative measure is the dimensionless parameter of nonlinearity $w_2 = W_p/n_0 T_e$. Another key parameter is the frequency mismatch $\tilde{\omega}_j$ (2), since two HF oscillations with frequencies $\omega_0 \approx \omega_j$ exert the ponderomotive force at the beat frequency $\Omega = \omega_0 - \omega_j$.

For $\rho_0 = P_0/P_{DL} \geq 1$, we get from equation (4) the pump amplitude $A_0 = E_0(\theta_0) = 0.5\chi_0 \sqrt{\rho_0}$ at $h_0 = 220$ km. Taking $f_0 = 3$ MHz ($n_e \approx 10^6$ cm$^{-3}$), $T_e = 0.2$ eV, $l_0 = 40$ km, and $\chi = 14^\circ$ gives at vertical $l_0 \approx 75$ m, $E_0 \approx 12\sqrt{\rho_0}$ V/m, and $\omega_0 = E_0^2/(8\pi n_0 T_e) \approx 0.2\rho_0$. In the $j$th Airy peak within the Spitze, the frequency mismatch is $\tilde{\omega}_j = \omega_{j} - (h_0 - h_{j})/l_0$, where $\omega_{j} = \omega_0(h_0) \approx l_0/2\chi \sim 10^{-3}$, while $\omega_0 \approx \alpha_{j} \omega_0 (\alpha_j \approx 0.36 \rightarrow 0.16$ at $h_j/l_0 \approx 10 \rightarrow 40)$. For $\omega_0 >> \omega_{j}$, the frequency mismatch can be disregarded, at least in the first few Airy maxima.

With the magnetic correction, the first Zakharov equation becomes [e.g., Shapiro and Shevchenko, 1984]

$$\left(i\frac{\partial}{\partial t} + \frac{3}{2}\alpha_{pe}^2 \alpha_j^2 \Delta \Psi - \frac{\alpha_{pe}^2}{2\alpha_{pe}} \Delta \left(\frac{1}{2} \nabla \cdot \mathbf{A} \right) \right) \Delta \Psi = \frac{\alpha_{pe}^2}{2} \nabla \cdot \left( \delta \nabla \mathbf{A} \right)$$

(A1)
where $\Delta$ is Laplacian and $A = A_1 + A_0$. As ions are unmagnetized, the second Zakharov equation for the slow ($\Omega \ll \omega_{pe}$) density variation $\delta n_i = \delta n_i / n_0$ remains

$$\left( \frac{d^2}{dt^2} - c_s^2 \Delta \right) \delta n_i = \frac{1}{16\pi n_0 m_i} \Delta A^2$$  \hspace{1cm} (A2)

We disregard collisional and convective damping, assuming $w_0 > \max(4\nu_e/\omega_{pe}, 2/k_{le}, \mu)$, where $k$ is the excited wave number.

Since $\omega_0/c < k_s = \sqrt{n}/3d_e$, the dipole approximation (a uniform oscillating field) can be used even at oblique incidence. At $w_0 \gg \omega_{pe}/\omega_{ce}$, the magnetic effect can be neglected. In the opposite limit, the modulational instability (MI) develops in a narrow cone $|\theta| \leq \frac{n_e}{w_0} \sqrt{w_0} < 1$ around $B_p$. The MI is inherently tied to the tendency of Langmuir plasmons to accumulate inside density depletions $\delta n_i < 0$ (hereafter, cavities). It develops when the excess of the HF pressure inside a cavity exceeds the thermal pressure disbalance $\delta p_e = n_0 T_e \delta n_i$ or

$$w_0 > w_{th} = 3k^2 r_D^2$$  \hspace{1cm} (A3)

As the HF pressure forces plasma out of a cavity, it deepens further and “attracts” yet more plasmons, thereby creating a positive feedback loop. In the supersonic, $w_0 > 3\mu$, regime, the growth rate maximizes at $k_{n_{f_D}} \approx \mu^{1/6}(w_0/3)^{1/3}$ and then reaches a plateau

$$\Gamma_{m}(k) \approx \omega_{pe}(\mu w_0/3)^{1/2}$$  \hspace{1cm} (A4)

The plateau at $k_m < k \leq k_{th} \approx r_D^2 \sqrt{w_0/3}$ dominates the phase volume of the pump-excited (primary) Langmuir plasmons.

At $|\delta n_i| > 3k^2 r_D^2$, plasmons are trapped so that intense localized wave packets are formed. Cavities with trapped Langmuir oscillations are termed Langmuir cavitons or simply cavities. Their evolution can be described using the following simple arguments [e.g., Sagdeev, 1979]. Undamped, undriven $(A_0 = 0)$ Zakharov equations conserve the total number of plasmons in cavitons

$$N \approx \int dr \ |E|^2 / 8\pi \omega_0 = \text{const}$$  \hspace{1cm} (A5)

As $|\delta n_i| < 1$, the integral (A5) yields $|E|^2 \propto l^{-d}$, where $d = 1, 2, 3$ is the dimension of cavities of the size $l$. The wavelengths of the trapped plasmons are also of the order of $l$, i.e., $k \sim 1/l$. As $k \propto |\delta n_i|^{1/2}$ (trapping), one has $l \propto |\delta n_i|^{-1/2}$, indicating that a deepening cavity narrows (collapses) as time progresses. Since $|\delta p_e| \propto |\delta n_i| \propto l^{-2}$ and $|E|^2 \propto l^{-4d}$, the thermal pressure will ultimately balance the HF pressure for $D = 1$, thus forming one-dimensional cavitons. In two (three) dimensions, the speed of collapse persists (accelerates) with time.

In the supersonic regime, the right-hand side of equation (A2) is $\Delta |E|^2 \sim \omega_{pe}^2 |E|^2 \propto |\delta n_i| |E|^2$, while the left-hand side becomes $d^2/dt^2 \sim (t_{w_p} - t)^{-2} \sim t^{-2}$, with $t = t_w - t$ and the time of collapse $t_{w_p}$. These give a self-similar solution $|E| \propto t^{-1}$ and $|\delta n_i| \propto t^{-2}$ \propto $t^{-d}$. It is valid also in the presence of external pumping, because the trapped plasmons become uncoupled from the pump in the course of collapse. The phase velocities of plasmons in collapsing cavitons decrease as $\sim \omega_{pe}/t \sim \tau^{-2/d}$. At some “absorption” size, $l < l_p \sim k_{uo}^{-1} \sim (3-5) r_D < 10 \text{ cm}$, plasmons are absorbed by electrons (the wave energy “burnout”) due to Landau and transit time damping. While the HF pressure in the cavition drops and collapse is arrested, a small group of suprathermal electrons gain energy. At $t_c \sim T_c$, an empty cavity $|\delta n_i| \sim k_{uo}^2 r_D^2$ relaxes within $\sim (k_{uo} c) \sim (3-5) \omega_{pe} \sim (5-9) 10^8 / \omega_0$. At $T_c > T_{se}$, short-scale ion sound waves at $\omega_{se} \sim k_{uo} c_{se}$, radiated by burned out cavities, tend to accumulate [Galeev et al., 1977].

The system ultimately reaches a dynamic equilibrium between the long-scale pumping and short-scale transfer by collapsing wave packets into the absorption interval $k > k_u$ [e.g., Galeev et al., 1977]. Here some plasmons are localized in randomly distributed cavitons at different stages of collapse, while others are free. The energy is pumped into cavitons in the long-scale source region, $k_l \leq r_D^{-1} \sqrt{w_0/3}$, with the energy density $W_L$ comprising the MI-excited long-scale waves. The energy balance equation in the source region is

$$dW_L / dt = v_{L_s} W_0 - \Gamma_m(W_L) W_{cav}$$  \hspace{1cm} (A6)
Here $W_{\text{can}}$ is the fraction of the energy in collapsing cavitons, $\nu_{ef} = \alpha_{ef} n_{\text{pe}} W_r / a_t$ is the effective dissipation rate of the pump energy, with a numerical coefficient $\alpha_{ef} \sim 1/3$. Since $\nu_{ef} > \Gamma_{\text{mz}}$, the saturated level of turbulent electric fields is smaller than during the initial stage (the SLT overshoot).

Between the source and absorption ($k_q \gg k_0$) regions lies the inertial interval, through which the energy is transported by collapsing cavitons. The spectrum in the inertial interval can be found assuming that the spectral energy flow $W_{\nu}^{(\text{in})} d\nu / d\nu$ is preserved. Substituting $k(t) \propto r^{-2/3}$ gives a power law spectrum $W_{\nu}^{(\text{in})} \propto 1/k^{1+2/3}$ and the total energy of short-scale waves at the absorption boundary $W_0 \approx W_{\text{can}} (k_q / k_0)^{2/3}$. In particular, for $W_{\text{can}} \sim W_r$ from equation (A6) one gets $w_r \approx 3 \mu^{-1} \alpha_{\text{ef}} W_{\text{mz}} \gg W_0$.

Since slow ($\Omega \sim \Gamma_{\text{mz}} \ll \omega_{\text{ce}}$) electron motion is magnetized, the cavitons at $|\delta N_s| \ll \alpha^2_{\text{ce}} / \omega^2_{\text{pe}}$ are pancake-like, with the dimensions [e.g., Shapiro and Shevchenko, 1984]

$$l_\parallel \sim k_{\parallel}^{-1} \sim r_D \sim |\delta N_s|^\frac{1}{2} \sim l_{\|^0} \quad \frac{\alpha_{\text{pe}} \nu_{\|}}{\omega_{\text{ce}}} \sim |\delta N_s|^\frac{1}{2}$$

(A7)

obtained by balancing the second and third terms in the left-hand side of equation (A1) and using the trapping condition $|\delta N_s| \sim k_{\parallel}^2 r_D^2 \sim r_{\|^0}^2$. The variation of the electric field in cavitons in the supersonic regime remains $|E| \sim r^{-1}$, and the self-similar solution is $l_{\|^0} \propto \nu_{\|} \sim |\delta N_s|^{-1} \propto \tau$. The initial dimensions of pancake-shaped cavitons are defined by equation (A7) with $|\delta N_s| \sim W_r$. Though the number of plasmons in collapsing “pancakes” decreases

$$N = \int d\nu_{\|} d\nu_{\perp} |E|^2 / 8 \pi \omega_{\|} \propto \sqrt{\tau}$$

(A8)

the radiated energy density is greater than $3r_{\|^0}^2 r_D^2$. So new cavitons of smaller scales emerge and collapse, thereby preserving the total energy flow toward the absorption region, $k_{\parallel} \geq k_0 \gg k_{\parallel} \sim r_{\|^0} \sqrt{W_r}$. The density variation $|\delta N_s|$ in collapsing cavitons can reach $\alpha^2_{\text{ce}} / \omega^2_{\text{pe}}$ at $l_{\|^0} \sim k_q$. Then, symmetric ($l_{\|^0} \sim l_{\|}$) cavitons with $W_{\text{sym}} = W_r \propto |\delta N_s| \sim W_r$ continue to collapse, preserving trapped plasmons until the energy burnout. The corollary to the above is that the 1-D description of SLT is deficient for weakly magnetized plasma, especially at large pump powers. In particular, much greater pumping is required in 1-D to achieve the same short-scale wave energy (the acceleration rate).

The above SLT scenario works for $w_r < 3k^2 r_D^2 \sim 10^{-2}$ or $w_0 > w_\text{sst} \approx 0.1 \sqrt{3} \mu^{-1} \sim 10^{-3}$. Otherwise, MI develops in the whole region from the pump to absorption so that in a steady state collapse plays a minor role and the energy flux through the inertial interval is reduced. In this superstrong regime, the energy balance becomes

$$\nu_{\|} W_r = 2 \sum_{k} \Gamma_{\|}(k) W_k \quad \text{at } w_0 > w_\text{sst} \approx 0.1 \sqrt{3} \mu$$

(A9)

with $\nu_{\|} \sim \alpha_{\text{pe}} \mu^{-1/3} (w_1 / 3)^{2/3} / \Gamma_{\text{mz}}$ and the Landau damping rate $\Gamma_{\|}(k)$ [Shapiro and Shevchenko, 1984]. Another limitation concerns the role of small-scale, $q \gg k_q$, density irregularities, $\delta N_s(r) = \sum_{\text{q}} \delta N_s^{(\text{q})} \exp(iq \cdot z)$. As a result of conversion, $l_{\|_q} \gg |\delta N_s| \to l_{\|_s}$, long-scale plasmons are transferred into the short scales. Therefore, the amount of the collapsing energy can be significantly smaller than that without small-scale irregularities.

For wideband random phase irregularities, $|\delta N_s| \sim 3q^2 r_D^2$, the conversion rate $\Gamma_{\|}$ is readily derived by averaging equation (A1) over the scale $\sim 2 \pi / k_q \gg 2 \pi / q$

$$\Gamma_{\|} \approx \sum_{q} \nu_{(q)} \frac{\langle |\delta N_s|^2 \rangle_{(q)}}{36q^2 r_D^2}$$

(A10)

to an accuracy of $\Gamma_{\|} \ll \nu_{(q)} \sim 3 \alpha_{\text{pe}} q^2 r_D^2$ [e.g., Mishin and Schlegel, 1994]. Here $\nu_{(q)}$ is the total (collisional + Landau) damping rate and $\langle |\delta N_s|^2 \rangle_{(q)} = \sum_{\text{q}} \langle \delta N_s^{(\text{q})} \delta N_s^{(\text{q})} \rangle_{(q)}$ is the phase-averaged spectral energy. Applying a similar procedure to the electromagnetic version of equation (A1) [e.g., Shapiro and Shevchenko, 1984], with either FAI near $h_{\text{sh}}$ [Mishin et al., 2001] or SLT cavitons near $h$, [Elisson, 2008] in the right-hand side, one can describe resonant scatter of electromagnetic waves into oblique Z- and O-mode waves.

At MZ, the swelling coefficient is smaller than $\Gamma_{\|}$ by a factor of $\approx 2$ in 1-D and $\approx 1.25$ in 2-D simulations (Figure 10). This does not inhibit the instability even at $p_{\|} \ll 1$, as long as equation (A3) is satisfied. However, it was so far implied that $w_0 > \tilde{\omega}_{\|}$. As follows from simulations (e.g., Figure 9), the value of $\tilde{\omega}_{\text{ms}} \approx -\Delta h_{\text{ms}} / 2l_s$ is of the order of $0.017 \approx \tilde{\omega}_{\|}$; this affects the instability development at smaller $w_r$. For small mismatches
For $\sqrt{\mu_0} w_0 > w_0$, the pump-driven modulational instability is inhibited, while PD$^2$ (or induced scattering at $T = T_0$) generates red-shifted plasmons at $k \sim k_c \sim \sqrt{\mu_0} w_0$. The waves in the resonance zone of the spectral width $\delta k \approx 2\mu^{1/2}/3d_e$ grow at the rate $\Gamma_{\text{ind}} \approx \alpha_{\text{pe}} w_0/\sqrt{\mu_0} > 0$ until at $\Gamma_{\text{ind}} \sim 10\Gamma_0$ they become unstable. In saturation, their pumping $\Gamma_{\text{ind}}(W_k)$ is balanced by their decay $\approx \Gamma_{\text{ind}}(W)$, with $W_k = \iiint d\omega \omega^2 |k|^2$. Therefore, their r.m.s. amplitude $\delta E_k \equiv A_k$ reaches $\approx A_0$. This process repeats itself in each further step, so the WT cascade spectrum consists of consecutive red-shifted peaks of the amplitudes $\approx A_0$ and widths $\sim \delta k_c$. The wave energy is evenly distributed ($W_k \approx W_0/\delta k_c$) over the WT spectrum with the total energy density $W_{\text{ind}} \approx W_0 \sqrt{\mu_0} / \mu \approx W_0$. Ultimately, plasmons converge in the region, $k \leq k_c \approx \mu^{1/2} W_0/2 \mu^{1/2} \approx k_0$, with the energy density $W_c \approx W_0 k_c/\delta k_c \approx 3\mu^{1/2} n_T^2$. The plasmon condensate is subject to MI, so the WT and SLT regimes coexist. For $w_0 > \mu$, the supersonic MI (equation (A4)) leads to the energy outflow in collapsing cavities $\sim \Gamma_{\text{ind}}(W_k) \Gamma_{\text{cav}}$. Balancing by the energy influx due to induced scattering, $\approx 2\Gamma_{\text{ind}} W_0$, gives $\Gamma_{\text{cav}} \approx \Gamma_{\text{in}} \ll \Gamma_c$.

Regardless of their source, the short-scale plasmons are absorbed by a small group of plasma electrons that form a non-Maxwellian high-energy tail $F_e(u)$. It is found from equation (7), with $\partial/\partial z = 0$ and $W_k$ determined from the energy balance in the absorption interval

$$\frac{dW_k}{dt} + \frac{d}{dk} W_k \frac{dk}{dr} = \Gamma_\alpha(k)W_k \quad (A11)$$

where $k(t) \sim r^{-2}$ and $\Gamma_\alpha(k)$ is the absorption rate.

A steady state solution of equations (7) and (A11) is a power law function, $F_e(u) = C_e \cdot u^{-b}$ at $u_{\text{max}} \geq \varepsilon \geq u_{\text{min}} \gg T_e$. Numerical modeling of 1D electron acceleration in a Maxwellian ($F_0 = F_{\text{M}}$) plasma yields $b \approx 1.5$, $T_{\text{M}}/T_e \approx 10^{-20}$ and the tail density $n_t = C_{\text{e},t} n_e \approx 10^{-3-4} n_e$ [Galeev et al., 1983; Wang et al., 1997]. The value of $n_t$ is mainly defined by the matching condition, $F_e(u_{\text{min}}) \approx F_{\text{M}}(u_{\text{min}})$. In the presence of the ambient ("seed") suprathermal population (e.g., photoelectrons), with $F_e(u_{\text{max}}) \gg F_{\text{M}}(u_{\text{max}})$, the absorption rate increases so that collapse is arrested at greater scales than in a Maxwellian plasma. As a result, the minimum energy of the tail electrons $e_{\text{min}} \ll e_{\text{in}}$, and $n_t$ significantly increases [Mishin and Telegin, 1986]. The obvious corollary is that many more energetic electrons are accelerated during daytime than would be at night [Mishin et al., 2004]. Thus, far, neither numerical SLT simulations include the ambient suprathermal population.

Eliasson et al.’s [2015] simulations show the SLT-driven DL at different incidence angles (see Figure 12). Mishin and Pedersen [2011] estimated the DL speed $v_D$ using the fact that accelerated electrons move along the magnetic field to form a stretched “tongue” of newly ionized plasma. Let $l_{\text{ion}}$ and $r_{\text{ion}}$ be the $|| B_0$ extent of the ionization region downward and the time for the plasma at $h_0(t) - l_{\text{ion}}$ to reach $n_t$, respectively. Here $n_t$ is defined by the resonance condition $f_{\text{pe}}(n_t) = f_D$. Assuming that the ionization rate $q_{\text{ion}} \approx n_t^{-1} \nu_{\text{ion}}$ greatly exceeds recombination and diffusion losses gives

$$\tau_{\text{ion}} \sim \left(1 - \frac{\delta t}{\delta n_t}\right) \left(\alpha_{\text{ion}}^{-1} \nu_{\text{ion}}^{-1}\right)^{-1} \sim 0.8 \left(\alpha_{\text{ion}}^{-1} \nu_{\text{ion}}^{-1}\right)^{-1} \quad (A12)$$

Here $\nu_{\text{ion}} = \alpha_{\text{ion}}^{-1} \sim C_{\text{e},t} e^{1-b} / (b-1)$ and $\nu_{\text{ion}} \approx 2 \cdot 10^{-8} \left(\left|N_e\right| + 1\right)$ is the mean ionization frequency, i.e., $\nu_{\text{ion}} = \iiint v_{\text{ion}}(v) F_e(v) v^2 dv$, at $\nu_{\text{ion}} \ll \epsilon_{\text{max}}$. As the ratio $\delta t = \nu_{\text{ion}} / \nu_e$ is small, the accelerated electrons undergo fast ionization, yielding $\nu_{\text{ion}} \sim \nu_{\text{ion}}^{1/2} / \nu_{\text{ion}}$. Here the frequency of inelastic collisions $\nu_{\text{ion}}(v) = (1 - 2\nu_{\text{ion}}) e^{-1}$ at $10^2 > \nu_{\text{ion}} > 1$. At altitudes well above the initial resonance $h_0$, the ambient density is low, $n_t \ll n_0$, and the speed of descent $v_D \sim l_{\text{ion}}^{-1} \tau_{\text{ion}}^{-1}$ becomes

$$v_D \sim \alpha_{\text{ion}}^{-1} \nu_{\text{ion}}^{-1} \cdot \nu_{\text{ion}}^{1/2} / \nu_{\text{ion}} \sim \alpha_{\text{ion}}^{-1} \cdot \nu_{\text{ion}}^{3/2} \quad (A13)$$

As $\nu_{\text{ion}}^{3/2} \sim 10^8$ m/s, we get the value of $v_D < 10^2$ m/s for $\alpha_{\text{ion}}^{-1} \sim 10^{-4}$. Note that $v_D$ contains no direct dependence on the neutral density $N_e$, and hence predicts $v_D \sim \text{const}$, providing that $\alpha_{\text{ion}} \approx \text{const}$ along the path.
Let the ionizing front be initially created at some altitude $h_D^0$. Then, the seed suprathermal population at lower altitudes will be maintained by degrading earlier accelerated electrons, thereby supporting a self-similar process [Mishin and Pedersen, 2011]. As soon as the latter is broken, descent slows down and finally stops even for the same input. Apparently, as the scale length in the front decreases, $I_{\text{ion}}^0 \sim l_{\text{ion}} \sim N_e^{-1}$, the SLT extent $l_{\text{T}}$ and the electron transit time ($\sim l_{\text{T}}/u_{\text{max}}$) decrease as $\sim N_e^{-1/2}$, thereby limiting $\epsilon_{\text{max}}$ and thus $n_{\text{en}}$. Further, adding inelastic losses $\Sigma \epsilon_F(e) \approx -v_F(e)F(e)$ in the right-hand side of equation (7) puts additional bounds on $\epsilon_{\text{max}}$ at $h_D < 160$ km [Mishin and Pedersen, 2011]. That is, when $v_F(\epsilon_{\text{max}})$ exceeds the acceleration rate $m\Delta u_{\text{max}}/8\pi\epsilon_{\text{max}}$, the increase of $\epsilon_{\text{max}}$ stops [Volokitin and Mishin, 1979]. Another factor is that a stretched $\langle \parallel \mathbf{B}_0 \rangle$ tongue of the DL plasma affects the pump propagation [cf. Gurevich et al., 2002]. Apparently, this effect increases at low altitudes where $n_0(h_D) \ll n_e$ and the $O$-mode index of refraction is mainly defined by the DL plasma.

Thus, far, the plasma temperature is implied unchanged, which holds for time scales much shorter than the electron heating time $\tau_e \sim 0.1 \sim 1$ s. The perturbed electron temperature, $T_e = T_e^0 + \Delta T_e$ is derived from the heat balance

$$\frac{3}{2} n_e \frac{\partial}{\partial t} \Delta T_e = \nu_e W_e - v_e T_e \frac{\partial}{\partial t} \Delta T_e - \nabla \cdot q_e$$

(A14)

$$q_e \approx 6n_e T_e v_e K_e \text{sign}(\nabla \cdot T_e)$$

(A15)

Here $\nu_e W_e$ is the collisional (ohmic) heating rate, $q_e$ is the electron heat flux, $K_e = \lambda_T \nabla \cdot \ln T_e = \lambda_T/l_T$ is the Knudsen number, and $\lambda_T = v_e/l_T$. It is implied that $K_e \ll 1$ and $v_e \ll c_e$. The coefficient of inelastic losses at 220 km, $\gamma_F(T_e) \approx (0.3 - 1) \cdot 10^{-3} \cdot 10^{-2} - 1.5 \cdot 10^{-2}$ at $T_e \approx (0.15 - 0.22) - 0.38 - 0.43$ eV, is calculated using Majeed and Strickland [1997] tabulations. The thermal conduction balances $v_e W_e$ at $K_e = K_e = (w_e/6)^{1/2}$. At $K_e < K_e$, equation (A14) yields $\Delta T_e = \Delta T_{e0} \sim 2W_e/3n_0{T_e0}(T_{e0})$ or $T_{e0} \sim 0.35$ eV at $T_{e0} \sim 0.2$ eV and $W_e/n_0T_{e0} \sim 10^{-2}$. The steady state is achieved at $K_f = K_{e0} \sim K_{e0}(T_{e0})$.

If $T_{e0}$ exceeds $\sim 4T_e \approx 0.3 - 0.4$ eV and $K_e > 2\mu^{1/2}$, the heat flux-driven instability can develop in the heated region [e.g., Forslund, 1970; Mishin, 1974]. For $l_T \geq 1$ km, this condition is satisfied for $l_T \sim 100$ km. Far beyond the threshold, the saturated ion sound spectrum is close to $W_i \propto W_e \ln(1/k_i) \cdot k_i^{3} \sim k_i^{6}$ at $k_i \leq k \leq r_D^{-1}$ (the Kadomtsev-Petviashvili spectrum) [e.g., Kadomtsev, 1965]. Here the energy density $W_i \sim 10^{-2} - 3n_0T_{e0}$ with the spectral maximum at $k_{\text{max}}$ and a lower frequency cutoff at $k_{\text{min}} \sim (0.05 - 0.1)/T_D$ (see details and references in Mishin and Fiala [1995]). As far as the $k_i$ value is concerned, it varies from $\sim (0.2 - 0.3)/T_D$ to $\sim 0.6/T_D$ in different experiments and simulations where an energetic ion tail is formed. When the ion tail is absent, the spectrum maximizes just above the low-frequency cutoff and the waves are mainly field aligned.

The ion tail occurs at low ion-neutral collisions such as in the $F$ region. In this case, waves at $k < 0.6/T_D$ are highly oblique (angles $\theta$ up to $\sim \pi/2$), while those at $k \geq 0.6/T_D$ turn to be more field aligned. While waves propagate along $\nabla \cdot T_e$, i.e., downward above, and upward below, the temperature peak, their wave numbers decrease and may become detectable by UHF radars. Apparently, greater values of $K_e$ at higher altitudes favor the instability above the $T_e$ peak and thereby the upshifted shoulder in the excited IL Doppler spectra. Another important outcome of this instability is that the heat flux in turbulent plasma is reduced to $q_{\text{turb}} = \kappa_{\text{turb}} n_e T_e V_f$ with $\kappa_{\text{turb}}$ in the range $\sim 7.5\mu^{1/2}$ to $\approx \mu^{1/4}$ [Mishin, 1974; Bychenkov et al., 1988], thus severely limiting the heat transport at $K_e \gg 2\mu^{1/2}$.

**Notation**

- $B_0$ the ambient magnetic field
- BF layer the region of scattering from the bottomside $F$ region
- BUM broad upshifted maximum
- DM downshifted maximum
- DL descending layers
- DP the downshifted (SEE) peak
- DVH descending virtual height of reflection
- $E_A$ the first Airy peak amplitude
- $E_{\text{bump}}$ the threshold amplitude for the BUM generation
- $E_{\text{f}}$ the free space field
$E_m$ the input amplitude of the pump wave (section 3)

EB electron Bernstein waves

FAI field-aligned irregularities

$F_M$ the Maxwellian distribution

$F_0 = F_M + F_s$ the total ambient electron distribution

$F_s$ the distribution of ambient suprathermal electrons (e.g., photoelectrons)

$F_t(u)$ the accelerated tail distribution function (TDF)

$C_t$ the const in the power law approximation (equation (9))

IAPD ion acoustic parametric decay $UH/EB \rightarrow UH'/EB' + IA$

IL and PL ion and plasma lines

Knudsen number $K_T = \lambda_T \left[ \frac{\sqrt{\ln T_e}}{\nabla_{\parallel} \ln T_e} \right] = \lambda_T / l_T$

L and UH Langmuir and upper hybrid waves

LH and S lower hybrid and ion sound (ion acoustic IA) waves

Lo oblique (magnetized) Langmuir waves

MI modulational instability

MUIR the (HAARP) modular UHF incoherent scatter radar

NC narrow continuum

OTSI oscillating two-stream instability

$OTSI_{Lo}$ oscillating two-stream instability of the UH pump $UH \rightarrow UH \rightarrow Lo + \delta n_{st}$

$PD_L^O$ parametric decay $O \rightarrow L + S$

$PD_{uo/ub}^O$ parametric decay $O \rightarrow UH/EB + LH$

$PD_{uo/ub/L}^O$ parametric decay $UH/Lo \rightarrow UH'/Lo' + LH$

$P_0$ effective radiated power (ERP)

$P_{DL} \approx 400$ MW the threshold ERP for descending layers at $2f_{ce}$

Primary waves waves excited by the pump wave

SEE stimulated electromagnetic emissions

SLT strong Langmuir turbulence

SST superstrong (Langmuir) turbulence (equation (A9))

Striations FAI with depleted plasma density $\delta n_{st} < 0$

TPI thermal parametric instability

WT weak turbulence

$W_a$ the wave spectral energy density

$f_{pe}$ the plasma frequency within the DL

$h_0$ the reflection (plasma resonance) height at vertical

$h_A$ the first Airy maximum altitude

$h_D$ the descending layer altitude

$h_{gl}$ the altitude of the region of green line emissions

$h_{gr}$ the gyroresonance matching height, $sf_{ce}(h_{gr}) = f_0$

$h_{mx}$ the turning points at the magnetic zenith (MZ)

$h_{uh}$ the upper hybrid resonance height

$h_{ne}$ the altitude of the region of IL/PL radar echoes

$h_D^o$ the DL terminal altitude

$h_{xx}^0$ the start altitude of the descending feature $xx$ ($re, bum, gl$, etc)

$h_{xx}^*$ the terminal altitude of the descending feature $xx$

$l_0$ the scale length of the Airy (swelling) pattern at vertical

$l_0$ the scale length of the swelling pattern at oblique incidence

$l_{mx}$ the scale length of the swelling pattern at MZ

$l_{LT}$ the altitudinal extent of the SLT region

$l_n$ the density scale height

$l_t$ the electron temperature scale height

$n_e$ the critical plasma density defined by the resonance condition $f_{pe}(n_e) = f_0$

$n_{on}^i$ the density of the ionizing ($e > e_{ion}$) electrons $n_0 = P_0 / P_{DL}$

$r_D$ the Debye radius

$v_D$ the speed of descent

$v_{xx}$ the speed of the descending feature $xx$
w the dimensionless parameter of nonlinearity
\( w_0 \) the pump wave nonlinearity parameter
\( w_{\text{th}} \) the modulational instability threshold (equation (A3))
\( \Gamma_m \) the modulational instability growth rate (equation (A4))
\( \Gamma_e \) the conversion rate (equation (A10))
\( \Omega \) the frequency of slow oscillations
\( \alpha_{\text{ion}} \) the relative density of ionizing (\( e > \epsilon_{\text{ion}} \)) electrons
\( \Delta\mu_\text{b} \) the threshold value of \( \alpha_{\text{ion}} \) for DL
\( \epsilon_{\text{ion}} \) the ionization energy
\( \theta_0 \) incidence angles of the pump wave
\( \lambda_r \) the Spitzke angle
\( \lambda_T \) the resonant (Bragg scatter) wavelength
\( \mu \) the electron-to-ion mass ratio
\( \nu_{\text{in}} \) the frequency of inelastic collisions
\( \nu_{\text{ion}} \) the ionization frequency
\( \tau_{\text{st}} \) the growth time of striations
\( \tilde{h}_A \) the frequency mismatch between the pump and plasma frequencies
\( \tilde{h}_{\text{max}} \) the frequency mismatch at \( h_A \) and \( h_{\text{max}} \), respectively.

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