REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
	New Reprint	-

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Electron gyro-harmonic effects on ionospheric stimulated Brillouin scatter	W911NF-11-1-0217
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
	206022

6. AUTHORS	5d. PROJECT NUMBER
W. A. Scales,, P. A. Bernhardt,, B. Isham,, E. Kendall,, S. J. Briczinski,, N. E. B. Fuentes,, O. Vega-Cancel	
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES	8. PERFORMING ORGANIZATION REPORT NUMBER
Inter American University of Puerto Rico - I P.O. Box 363255 San Juan, PR 00936 -3255	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	ARO
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)
	58966-EL-REP.8

12. DISTRIBUTION AVAILIBILITY STATEMENT

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13. SUPPLEMENTARY NOTES
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14. ABSTRACT

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15. SUBJECT TERMS
Brillouin, SBS, emission lines, pump frequency stepping, cyclotron, EIC, airglow, upper hybrid

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE	UU		Brett Isham
UU	UU	UU			19b. TELEPHONE NUMBER
					787-685-5223

Report Title

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Electron gyroharmonic effects on ionospheric stimulated Brillouin scatter

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Abstract Stimulated Brillouin scattering (SBS) and resonant phenomena are well known in the context of laser fusion, fiber optics, and piezoelectric semiconductor plasmas, as well as in various biological applications. Due to recent advances, active space experiments using high-power high-frequency (HF) radio waves may now produce stimulated Brillouin scattering (SBS) in the ionospheric plasma. The sensitivity of the narrowband SBS emission lines to pump frequency stepping across electron gyroharmonics is reported here for the first time. Experimental observations show that SBS emission sidebands are suppressed as the HF pump frequency is stepped across the second and third electron gyroharmonics. A correlation of artificially enhanced airglow and SBS emission lines excited at the upper hybrid altitude is observed and studied for second gyroharmonic heating. The SBS behavior near electron gyroharmonics is shown to have important diagnostic applications for multilayered, multi-ion component plasmas such as the ionosphere.

1. Introduction

Use of high-frequency (HF) heating experiments has been extended in recent years as a useful methodology for plasma physicists, wishing to remotely study the properties and behavior of the ionosphere as well as nonlinear plasma processes. Stimulated electromagnetic emissions (SEEs) are secondary electromagnetic waves excited by high-power HF electromagnetic waves transmitted into the ionosphere. The well-known SEE features with offset of 1 kHz up to 100 kHz from the pump wave frequency have been observed and studied in detail since the 1980s [*Leyser*, 2001]. Effects of stepping the pump through electron gyroharmonics on these broadband (well-known) SEE features have been studied extensively and can provide important diagnostic information [*Leyser et al.*, 1989; *Frolov et al.*, 2001; *Leyser*, 2001; *Sergeev et al.*, 2006]. An important step forward in ionospheric remote sensing techniques has begun after the recent update of the HF transmitter at the High Frequency Active Auroral Research Program (HAARP) facility. Increasing the maximum transmitter power up to 3.6 MW (effective radiated power (ERP)∼1 GW) has allowed studying parametric decay instabilities such as stimulated Brillouin scatter (SBS), responsible for narrowband SEE features, which were not possible a few short years ago. Recent observations of narrowband SEE emission lines (within 1 kHz of pump frequency) have caused a renaissance in the field of space science and remote sensing [*Norin et al.*, 2009; *Bernhardt et al.*, 2009, 2010; *Bordikar et al.*, 2013; *Mahmoudian et al.*, 2013a, 2013b; *Fu et al.*, 2013]. Sideband emissions of unprecedented strength have been reported during recent campaigns at HAARP, reaching up to 10 dB below the reflected pump wave. Such strong emissions are shifted by only a few tens of hertz from radio waves transmitted at several megahertz.

SEE lines within 100 Hz of the pump frequency produced by SBS process are the subject of this investigation. Specific focus is placed on investigating, for the first time, fundamental SBS behavior associated with stepping the pump frequency through electron gyroharmonic frequencies as well as new diagnostic capabilities. Parametric decay of an ordinary mode electromagnetic wave into an electrostatic wave and a scattered electromagnetic wave by SBS were observed for the first time in recent observations at HAARP [*Norin et al.*, 2009; *Bernhardt*, 2009, 2010; *Fu et al.*, 2013; *Mahmoudian et al.*, 2013b]. Depending on the angle between the wave normal direction and the background magnetic field vector, the excited electrostatic wave could be either ion acoustic (IA) or electrostatic ion cyclotron (EIC) [*Fu et al.*, 2013].

The IA dispersion relation can be written as [*Bernhardt et al.*, 2009]

$$\omega_{\mathrm{IA}}^2 = \frac{k_{\mathrm{IA}}^2 C_{\mathrm{IA}}^2 \cos^2\theta}{\left(1 - k_{\mathrm{IA}}^2 C_{\mathrm{IA}}^2 / \Omega_i^2\right)} \tag{1}$$

where $C_{\mathrm{IA}} = \left(\left(\gamma_e T_e + \gamma_i T_i\right)/m_i\right)^{1/2}$ is the ion acoustic velocity with $\gamma_e = 1$ and $\gamma_i = 3$, k_{IA} is the IA wave number, and Ω_i denotes ion gyrofrequency. The angle θ is between the wave normal direction and the background magnetic field vector. The EIC wave frequency is determined from [*Bernhardt et al.*, 2009]

$$\omega_{\mathrm{EIC}}^2 \cong \Omega_i^2 + \frac{k_{\mathrm{EIC}}^2 C_I A^2 \sin^2\theta}{\left(1 - k_{\mathrm{EIC}}^2 C_{\mathrm{IA}}^2 / \Omega_i^2\right)} \tag{2}$$

It should be noted that equations (1) and (2) are derived assuming $|k_L C_{\mathrm{IA}}| < \Omega_i$, a collisionless plasma, and also for one ion species. As can be seen in this equation as well as the matching condition for SBS instability [*Bernhardt et al.*, 2009; *Mahmoudian et al.*, 2013b], the EIC frequency is just above the ion gyrofrequency f_{ci}. Considering that each ion species has unique gyrofrequency due to mass difference, EIC lines can be distinguished based on their frequency offset relative to the pump frequency.

The received SBS SEE spectra are distinguished by their frequencies. IA emission lines appear with a frequency offset of 10–30 Hz [*Bernhardt et al.*, 2009] and EIC emission lines with frequency offset of 50 Hz (for O$^+$ ions) from the pump frequency [*Bernhardt et al.*, 2010; *Mahmoudian et al.*, 2013b]. According to the SBS matching conditions, emission lines originating near the HF reflection and UH resonance altitude appear with different frequency offsets in the SEE spectra [*Bernhardt et al.*, 2010; *Mahmoudian et al.*, 2013b]. The electron temperature in the modified ionosphere can be measured using the IA line shifts in the SEE data. The frequency offset of EIC lines relative to the pump frequency has been proposed as a sensitive method for determining ion species. First, validation is a component of this work.

2. Experimental Observations

2.1. Frequency Stepping Near $3f_{ce}$

On 9 August 2012 the HAARP facility (geographical coordinates 62.39°N, 145.15°W) was operated near the third electron gyroharmonic frequency $3f_{ce}$ between 10:44 and 10:55 UT (1 h after sunset). According to the theory, SBS should also be excited by the *X* mode. But in none of our experiments we could excite SBS with *X*-mode heater. The pump beam was pointed at the magnetic zenith (202° azimuth, 14° zenith). The transmitter frequency was tuned near the local $3f_{ce}$ at $f_0 = 4.15$ MHz for the first 60 s of the heating cycle and increased in 10 kHz steps every 30 s between 10:44 and 10:55 UT. The pump frequency was increased up to 4.35 MHz during this experiment. Digisonde data show a primary ionospheric *F* layer between 250 and 350 km but also a patchy sporadic *E* layer between 100 and 130 km. The primary ion constituent in the main *F* layer is O$^+$. Previous observations have shown the association between sporadic ion and sporadic neutral sodium and other metal layers. Typically, the sporadic *E* layer is believed to be composed of metallic ions (with dominant abundance by Na$^+$, Mg$^+$, and Fe$^+$) [*Mathews*, 1998; *Kopp*, 1997]. According to the ionogram data, the altitude of *F* layer HF reflection was around 250 km during this experiment. The International Geomagnetic Reference Field model provides the magnetic field strength and direction in the upper atmosphere over HAARP. The magnetic field near the HF reflection altitude is estimated to be $|B| = 50{,}163.4$ nT which results in $3f_{ce} \sim 4.21$ MHz. The ion gyrofrequency for oxygen ions (O$^+$) is $\Omega_{\mathrm{O}} \sim 48$ Hz, in the altitude ~ 120 km, sodium ions (Na$^+$), $\Omega_{\mathrm{Na}} \sim 37$ Hz, magnesium (Mg$^+$) $\Omega_{\mathrm{Mg}} \sim 34$ Hz, calcium (Ca$^+$) $\Omega_{\mathrm{Ca}} \sim 20$ Hz, and iron (Fe$^+$) $\Omega_{\mathrm{Fe}} \sim 14$ Hz. The frequency overlap between the EIC (Fe$^+$) and IA line makes observation of this line difficult. SEE measurements from four different sites located at different geographic locations relative to the HAARP facility were employed to study the physical process of parametric decay instabilities in the ionosphere and narrowband SEE features. The data collected from site 1 (62.18°N, 145.16°W) approximately 12 km south of HAARP are used in this paper.

The variation of SEE SBS lines with pump frequency stepping from 4.15 MHz to 4.36 MHz in 10 kHz steps is shown in Figure 1. According to the matching condition for SBS, IA lines excited at the reflection altitude due to O$^+$ should appear with a frequency offset ~ 10 Hz and EIC lines due to O$^+$ and Na$^+$ appear near $f_{ci}(\mathrm{O}^+) \sim 49$ Hz and $f_{ci}(\mathrm{Na}^+) \sim 36$ Hz. The figure represents the average of spectra over the entire heating cycle for each pump frequency. The pump frequency was at 4.15 MHz for 60 s. At 4.15 MHz, a strong EIC line is downshifted from the pump (Stokes), appearing in the spectrogram in the frequency band 30–54 Hz
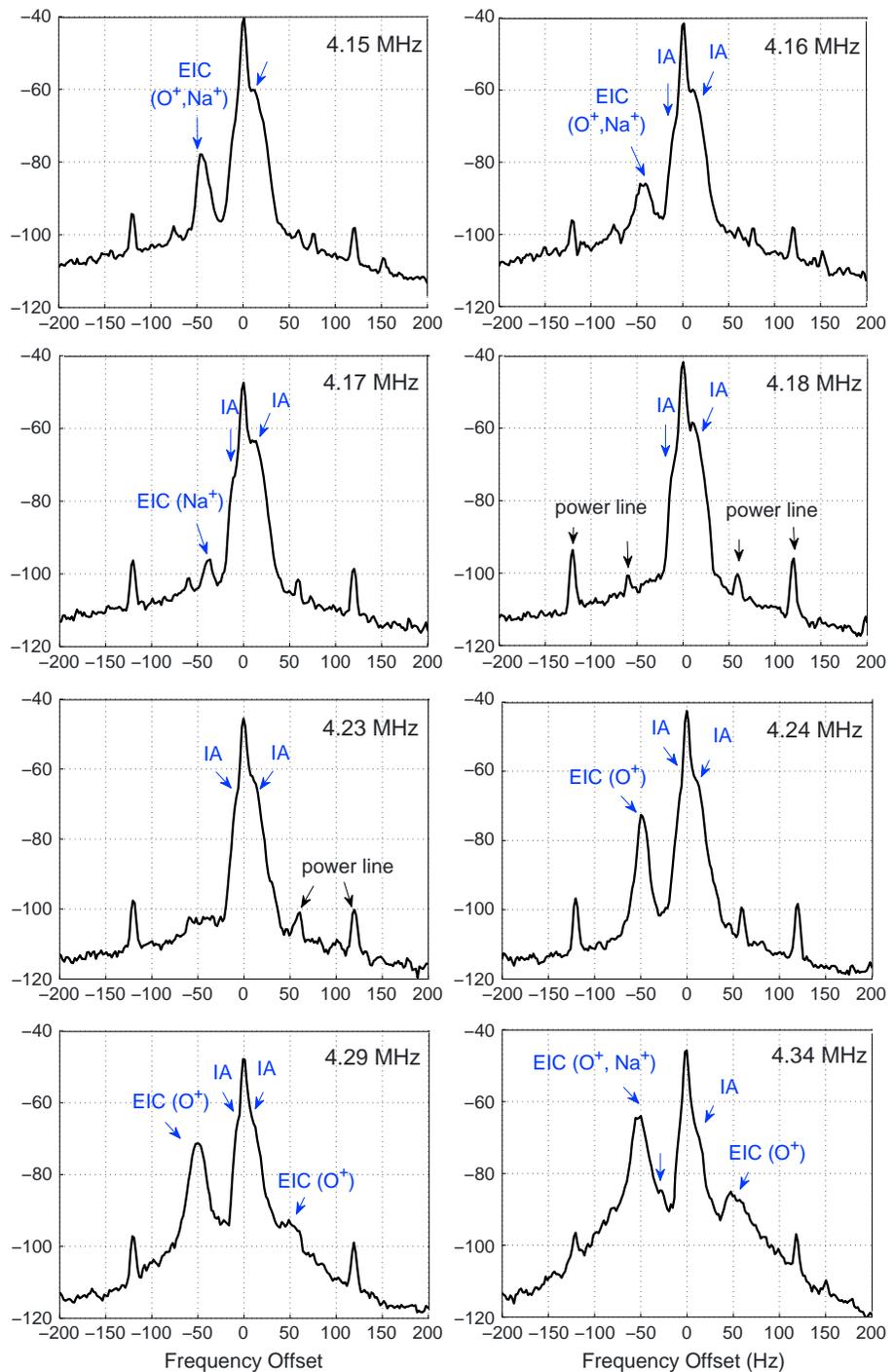
Figure 1. Experimental observations of stimulated Brillouin scatter (SBS) emission lines for pump frequency variation near $3f_{ce}$.

with a maximum around 47 Hz. This line is due to the EIC (O$^+$) mode in the primary F layer. Increasing the pump frequency from 4.15 MHz to 4.16 MHz and getting closer to $3f_{ce}$ decreases the strength of the EIC(O$^+$) line by 10 dB. A weak upshifted EIC (O$^+$) line can also be seen for a few seconds in the spectrum at $f_0 = 4.16$ MHz. At 4.17 MHz the EIC(O$^+$) line is absent; however, importantly, an EIC(Na$^+$) line downshifted 37 Hz from the pump frequency is now observed. Both EIC lines disappear from the spectra as the pump frequency gets closer to $3f_{ce}$. IA lines stay strong in the spectra and only become very weak for pump frequencies within 10 kHz of $3f_{ce}$. As the pump frequency increases above $3f_{ce}$, the SBS emission lines become stronger.
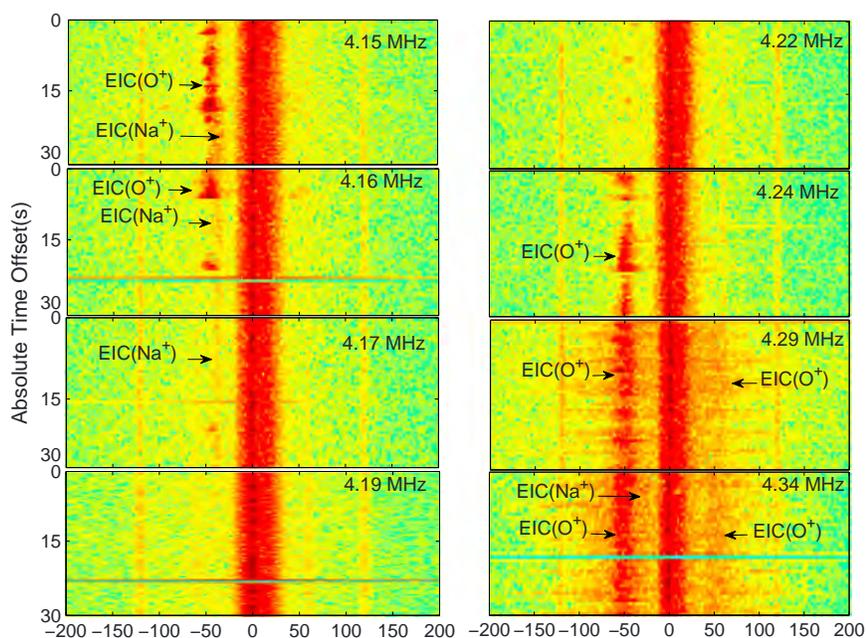
Figure 2. Time evolution of narrowband SEE spectra showing SBS spectral lines with pump frequency stepping near $3f_{ce}$. Note EIC lines are more constant for pump frequencies further above or below $3f_{ce}$.

At 4.34 MHz a weak EIC (Na^+) with a peak near 36 Hz is observed. The EIC (O^+) line is about 20 dB below the pump power and 50 dB above the noise level. Spectra for pump frequencies 4.29 and 4.34 MHz show a well-developed downshifted EIC line (Stokes) and upshifted EIC (anti-Stokes) lines. These emission lines are persistent throughout the heating cycle.

Time evolution of EIC lines is illustrated in Figure 2. As can be seen, the strength of the EIC line is not constant during the pump heating at full power. While the strength of the IA line is consistent throughout the heating cycle, the strength of EIC lines varies. For pump frequencies $f_0 < 3f_{ce} - 30$ kHz and $f_0 > 3f_{ce} + 60$ kHz, excited EIC lines are persistent throughout the heating cycle. As the HF pump frequency approaches $3f_{ce}$ (from above or below), EIC lines become weaker and appear in the spectra only for a few seconds during the pump heating as a result of enhanced threshold. As can be seen in Figure 2, a weak EIC line near 37 Hz is observed for 4.15 MHz, 4.16 MHz, and 4.17 MHz, due to minor ion species Na^+. This is consistent with the ionogram measurements, which shows the presence of sporadic E layer before and during the experiment. According to the matching condition [*Mahmoudian et al.*, 2013b; *Fu et al.*, 2013], the EIC (O^+) line is produced by O^+ in the altitude range of 270 km, and the EIC (Na^+) is due to Na^+ around 120 km. These observations show the facility of tuning f_0 near the electron gyroharmonic to allow distinguishing one ion EIC line from the other.

2.2. Frequency Stepping Near $2f_{ce}$
A pump frequency stepping experiment near $2f_{ce}$ was performed from 10:30 to 10:43 UT on 9 August 2012. During this experiment the transmitter frequency was tuned at 2.7 MHz for 60 s and was increased in 10 kHz steps every 30 s. This experiment was repeated at 10:55 UT. The reflection altitude during this experiment was around 300 km for pump frequencies 2.7 to 2.9 MHz ($2f_{ce}$ ~2.76 MHz).

As illustrated in Figure 3a, no SBS emission line is seen in the spectrum at $f_0 \leq 2.8$ MHz. A weak IA line appears in the spectrum for $f_0 = 2.8$ MHz. According to the matching condition, SBS lines are due to the IA wave, excited at the UH altitude. These emission lines appear at a frequency shift around 27 Hz from the 2.81 MHz pump frequency at 10:36 UT. Coordinated optical and SEE observations were carried out in order to provide a better understanding of electron acceleration and precipitation processes. Multiple wideband narrow field systems at the HAARP site were used to observe 557.7 and 630.0 nm emissions from atomic oxygen corresponding to >4.17 and >1.96 eV electron energy, respectively. As shown in Figure 3, as the pump frequency is stepped above $2f_{ce} \approx 2.76$ MHz, the SEE IA lines generated at the UH altitude increase in strength as well as the optical emissions.
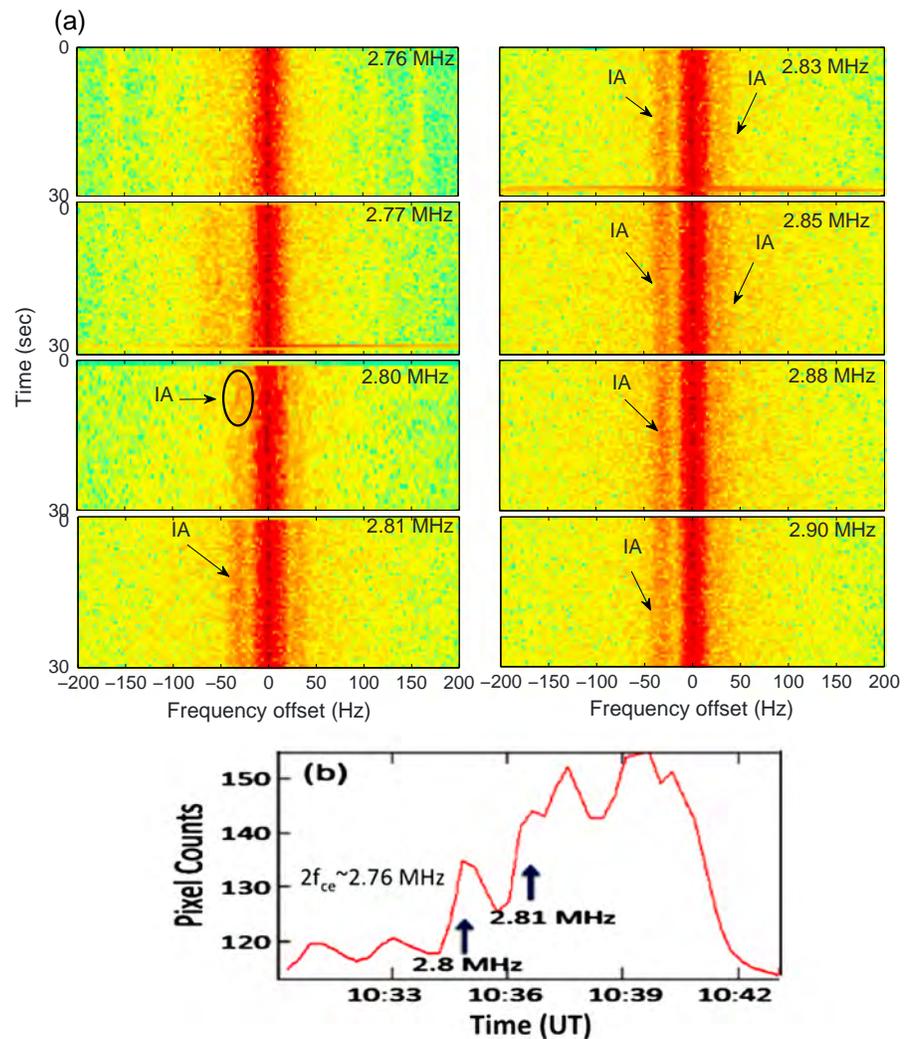
Figure 3. (a) Time evolution of spectrogram of SBS emission lines for pump frequency stepping near $2f_{ce}$ and (b) 630.0 nm intensities for the central region of the 19° field of view images over time.

It has been shown by *Bernhardt et al.* [2009] that electron temperature at the UH level can be determined using IA frequency offset. It should be noted that changes in the IA SBS frequency offset are a manifestation of ion-acoustic speed at the UH interaction altitude. The offset for pump frequencies 2.8, 2.83, 2.85, and 2.88 MHz are 29.38 Hz, 31 Hz, 33.19 Hz, and 32.2 Hz, respectively. The electron temperature obtained from equations (26) and (27) in *Bernhardt et al.* [2009] are $\sim$ 3200 K, 3562 K, 4083 K, and 3841 K. The variation of IA line offset and associated electron temperature with pump frequency correlates with that of the enhanced artificial airglow. The obtained T_e has uncertainty less than 200 K for frequency resolution $\sim$ 1 Hz. It should be noted that these calculations are valid for SBS lines excited at the UH level and for the transmitted wave near vertical incidence.

3. Discussion and Conclusions

According to the observations presented in this paper, the generation and strength of the SBS lines are strongly affected by proximity of the pump frequency to the electron gyroharmonic frequency $f_0 \sim sf_{ce} \pm \Delta f$. The SBS emission lines from experimental observations also depend on the angle between pump wave vector and background magnetic field in the interaction altitude. The experimental results show that there exists an asymmetry of the pumped plasma behavior with respect to the sign of Δf. It has been demonstrated that as the pump frequency approaches both $2f_{ce}$ and $3f_{ce}$, SBS lines are suppressed.

Strong SBS lines were observed for pump frequencies shifted above and below the second and third gyroharmonics. Upshifted EIC lines were also observed for $f_0 \sim 3f_{ce} + 100$ kHz. According to the observations, the EIC lines start to become strongly suppressed around 40 kHz below $3f_{ce}$ and reappear in the spectra for $f_0 \geq 3f_{ce} + (20–30)$ kHz. The IA lines become strongly suppressed within 10 kHz of $3f_{ce}$. The IA line becomes suppressed in a range ± 30 kHz from below to above $2f_{ce}$. Simultaneous SEE and airglow observations show that IA lines generated at the UH altitude appear in the spectra at the same time as enhanced optical emissions. The electron temperature at the UH level was determined using the IA frequency offset, and the variation with pump frequency shows correlation with the strength of artificial optical emissions. Our recent observations have also revealed a strong correlation of the IA SBS lines and the enhanced UHF radar ion lines [*Mahmoudian et al.*, 2014].

According to the matching condition for SBS process, various ion species produce an imprint in the SEE spectrum through emission lines at different offsets relative to the pump frequency as a result of their different masses. The first observation of an SBS EIC line produced by a minor ion species (Na$^+$) in the presence of sporadic E layer for pump frequency stepping near $3f_{ce}$ has been presented in this paper. The observations demonstrate the importance of tuning the pump frequency to distinguish one ion line from the other, demonstrating a potentially powerful remote sensing diagnostic utilizing SBS SEE lines. Therefore, the SEE technique during ionospheric heating can be used as a mass spectrometer to determine the minor species in the lower ionosphere. Considering that the frequency resolution is ~1 Hz for the current measurements, the EIC lines associated with minor ion species (Na and Ca) should be resolved from IA lines. This may be especially valuable for identification of metallic ions of meteoric origin in the E layer, because the composition of the lower ionosphere can be altered by meteorite ablation [*Mathews*, 1998; *Kopp*, 1997]. The strength, growth, and damping time of emission lines associated with Na may possibly be employed to study the role of ion molecular chemistry in the generation of sporadic Na$^+$ layers.

Stimulated Brillouin scatter from an incident light wave can propagate tens of kilometers without significant attenuation in optical fibers. This is an efficient method of RF signal distribution over longer distances. On the other hand, SBS could be an undesired effect and prevent launching maximum power [*Kobyakov et al.*, 2010; *Zhu et al.*, 2007]. Recent studies have also shown the existence of SBS in biological tissues [*Brodin and Stenflo*, 2013]. Observations of SBS electron gyroharmonic effects in the ionosphere may have applications to ionospheric remote sensing, photonics, semiconductors, and biological science, or in any application where the enhancement or suppression of SBS may be important.

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