Stimulated Brillouin Scattering During Electron Gyro-Harmonic Heating at EISCAT

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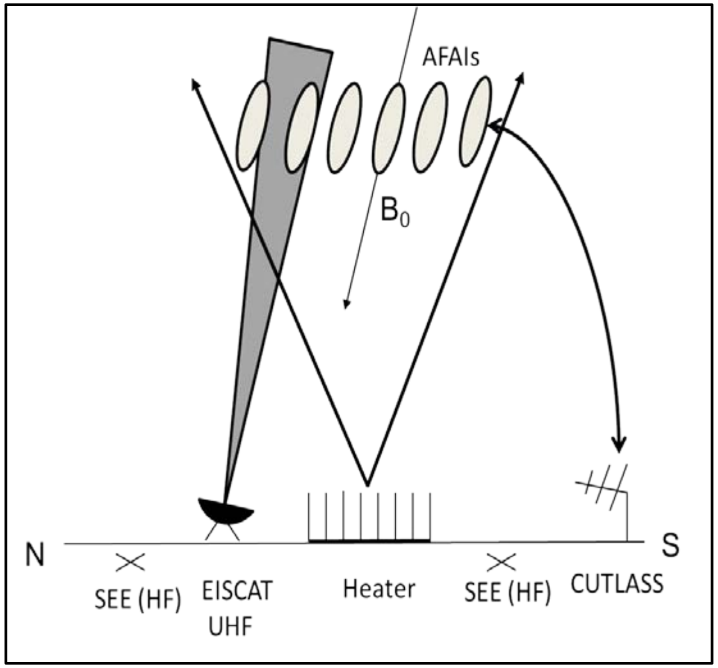
May 12- 14, VA, IES 2015

Outline

- **Introduction**
  - Background
  - Previous observation of SBS at HAARP
  - Required power for SBS generation at HAARP
  - Comparison of HAARP and EISCAT HF heater
- **Experimental observations at EISCAT (2012 July campaign)**
  - Attempt to reproduce SBS at EISCAT
  - Observation of SBS/DP near the third electron gyro-harmonic;
  - SEE correlation with Electron Temperature and Field aligned irregularities as well as ion line;
- **Experimental observations at HAARP (2012 August campaign)**
  - Attempt to correlate narrowband SBS with wideband SEE near $3f_{ce}$;
- **Summary and conclusions**

Background

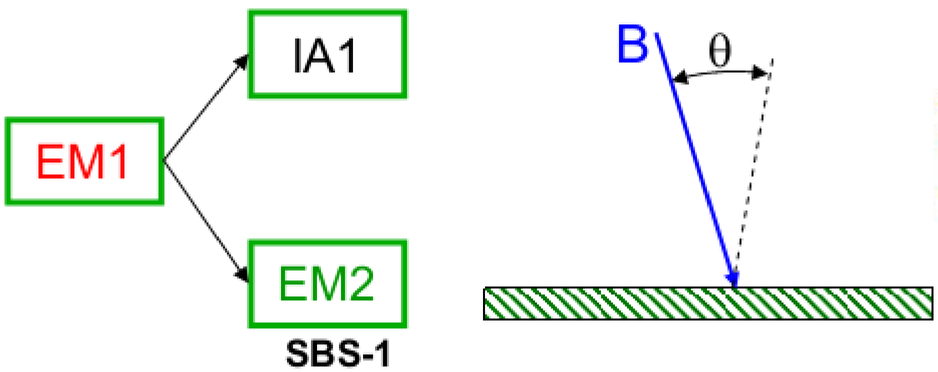
- Stimulated Electromagnetic Emission (SEE)
  - Secondary electromagnetic (EM) radiation generated during ionospheric pumping;
  - Measured sideband spectral features of the reflected signal on ground;
  - Studied in unmagnetized laser plasma interaction;
- SEE as a new diagnostic tool for nonlinear processes associated with heating
- SEE provides diagnostics of ionospheric parameters;
  - Enhanced optical rings and artificial layer formation tuned to electron cyclotron harmonics;
- SEE first predicted by Stenflo and Trulsen [1978];
- SEE first observed experimentally by Thide et al. [1982] at EISCAT;
- SEE studied extensively at HAARP after 2007;

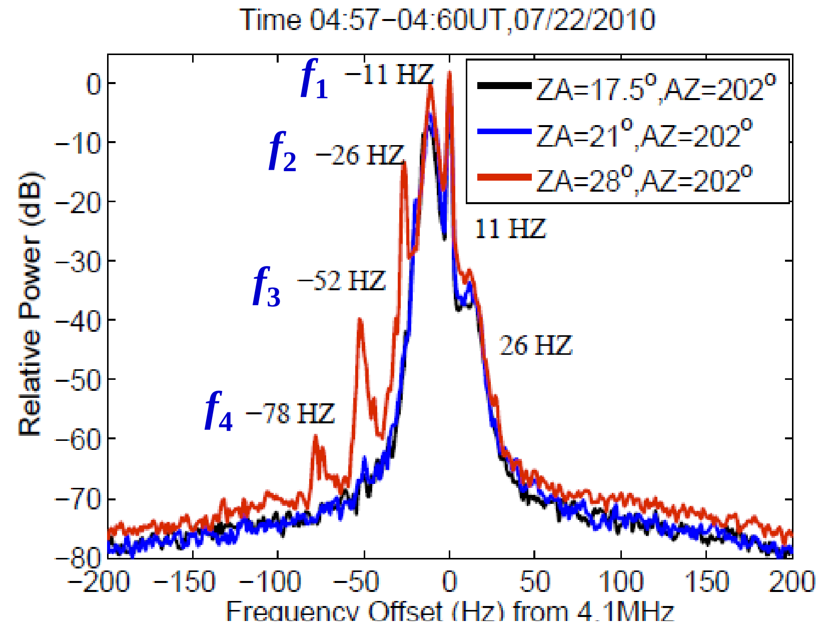


I: Previous observations of SBS at HAARP

(Near the **third** electron gyro-harmonic **3fce**)

- **Simulated Brillouin Scatter (SBS)**

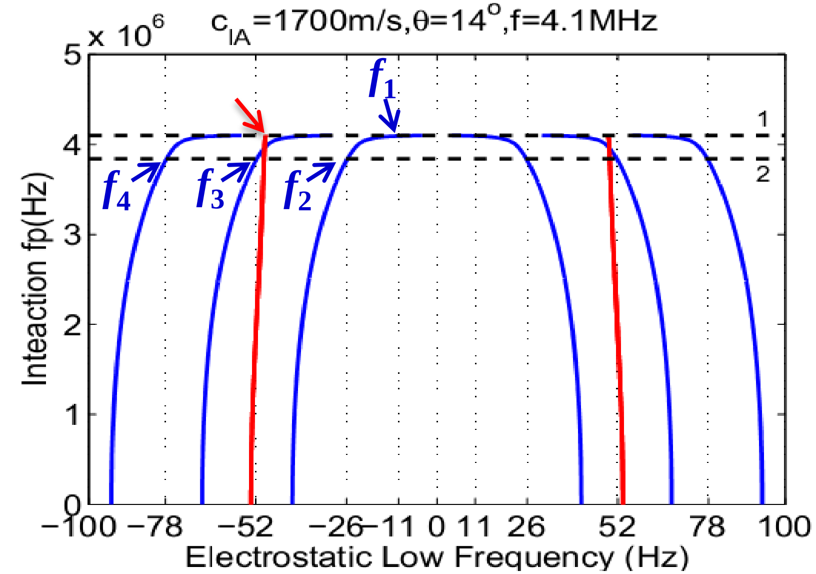




❑ Norin et al., [2009] observed the IA emission lines f_1 and f_2;

❑ Bernhardt et al., [2009] observed IA lines f_2 for electron temperature and Bernhardt [2010] observed IA line f_1 and EIC lines $f_3 \sim 47$ Hz for ion species;

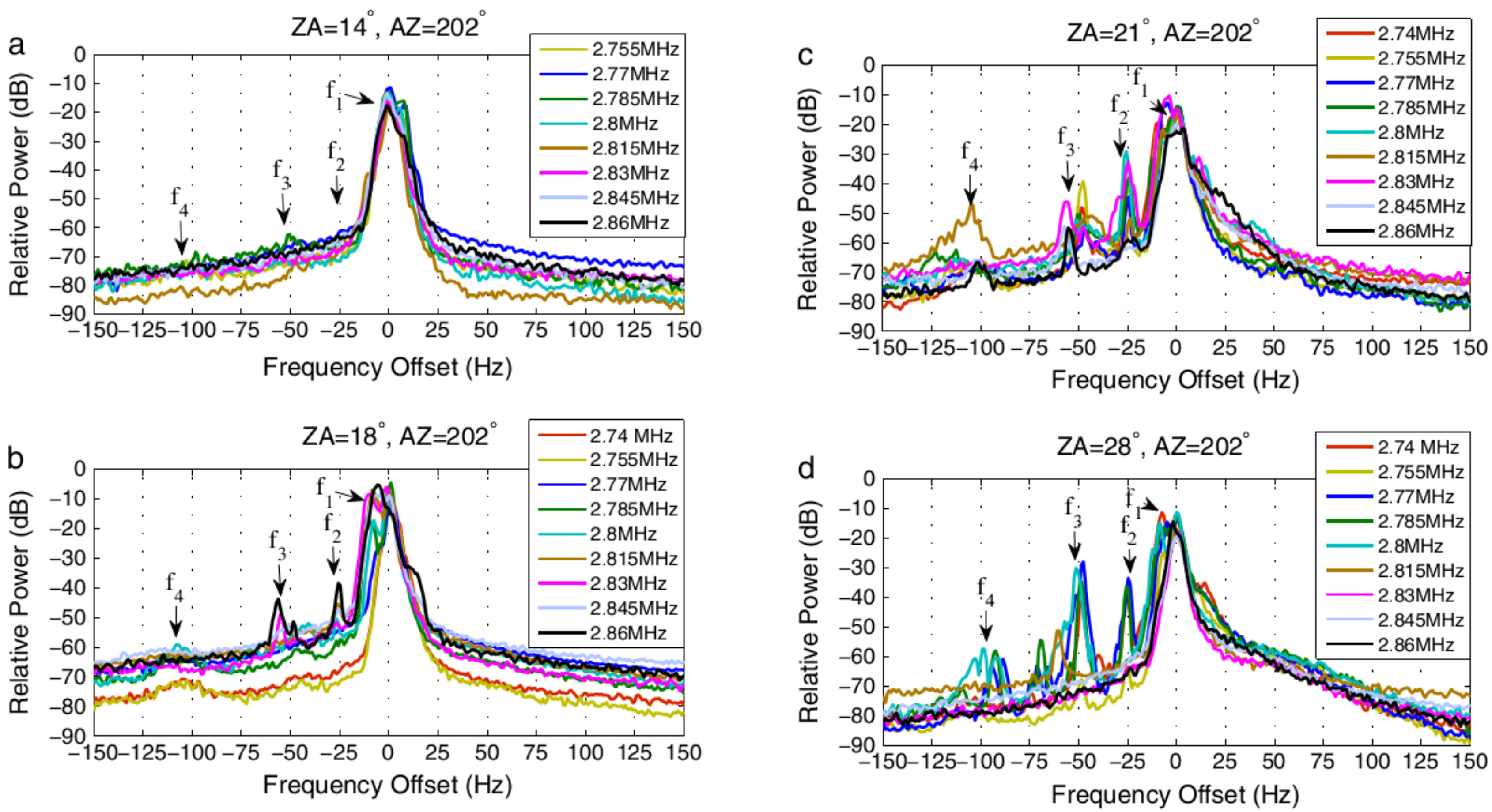
❑ Fu et al. [2013] observed the $f_3 \sim 52$ Hz and f_4 ~78 Hz emissions and proposed that these emissions are generated due to ion acoustic wave cascading at the upper hybrid level ;



Wave Matching Condition

I: Variation of SBS with Beam Angles at HAARP

(Near the **second** electron gyro-harmonic **2fce**)



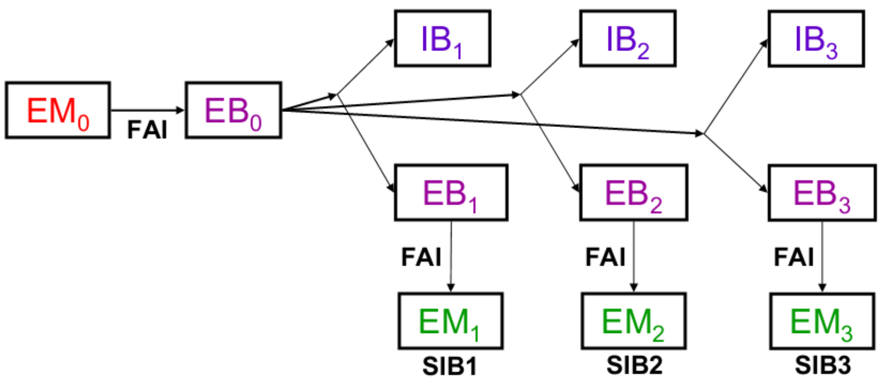
- **The amplitude of SBS** depends on the beam angle and pump frequency;
  (f_1 – (8 ~ 12) Hz, f_2 =– (25 ~ 27) Hz, f_3 =– (48 ~ 54) Hz, and f_4=– (96 ~108) Hz);
- **For pumping near electron gyroharmonic**, more SBS features occur as the heater beam is tilted from the magnetic field;
- **The frequency offset of SBS (f_2, f_3)** depends on the pump frequency relative to electron gyroharmonic;

[Fu et al., 2013];

I: Variation of SBS with Pump Frequency at HAARP

(Near the **second** electron gyro-harmonic **2fce**)

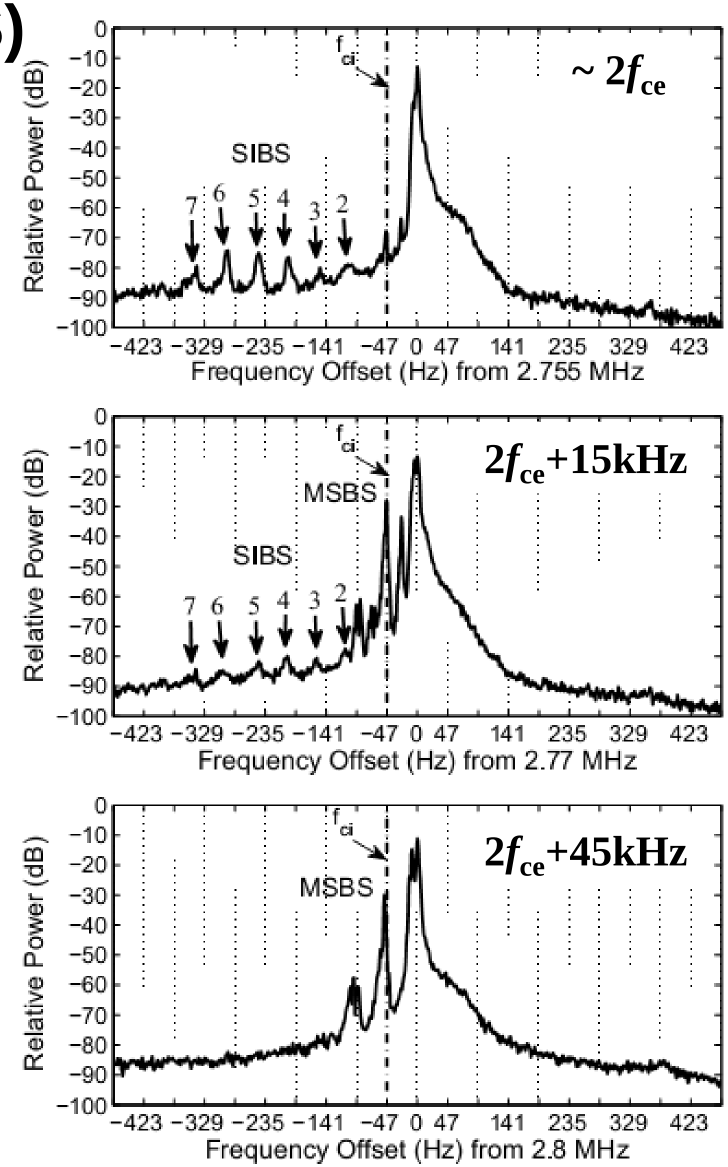
- **Stimulated Ion Bernstein Scatter (SIBS)**



- ❑ **SBS (f_2, f_3)** depends on pump frequencies sensitively far away from electron gyro-harmonics nf_{ce}.

- ❑ **SIBS** exists for the pump very close (typically within 10's of kHz) to electron gyro-harmonics nf_{ce};

- ❑ Calculations show SIBS exhibits a decreased threshold near electron gyro-harmonics.

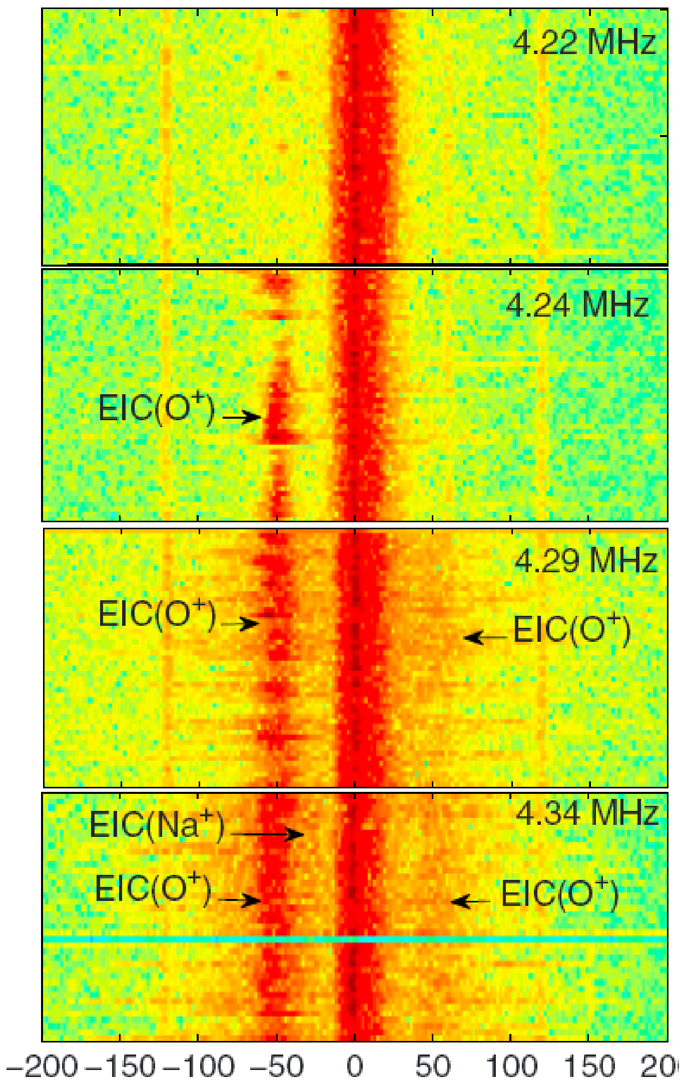


[Fu et al., 2013];

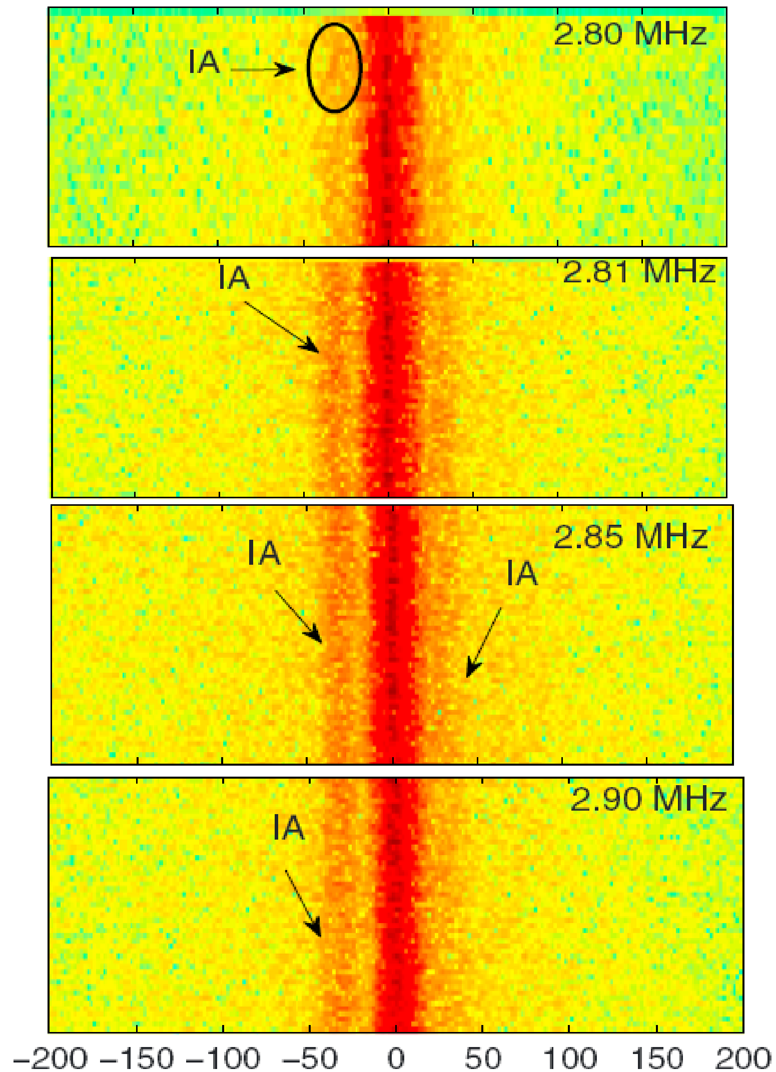
I: Variation of SBS with Pump Frequency at HAARP

(Near the electron gyro-harmonic)

- *Mahmoudian et al.* [2014] also verified enhanced IA (f_2) when pumping above 2fce and strong EIC(f_3) when pumping above 3fce using HAARP.



$3f_{ce} \sim 4.21$ MHz



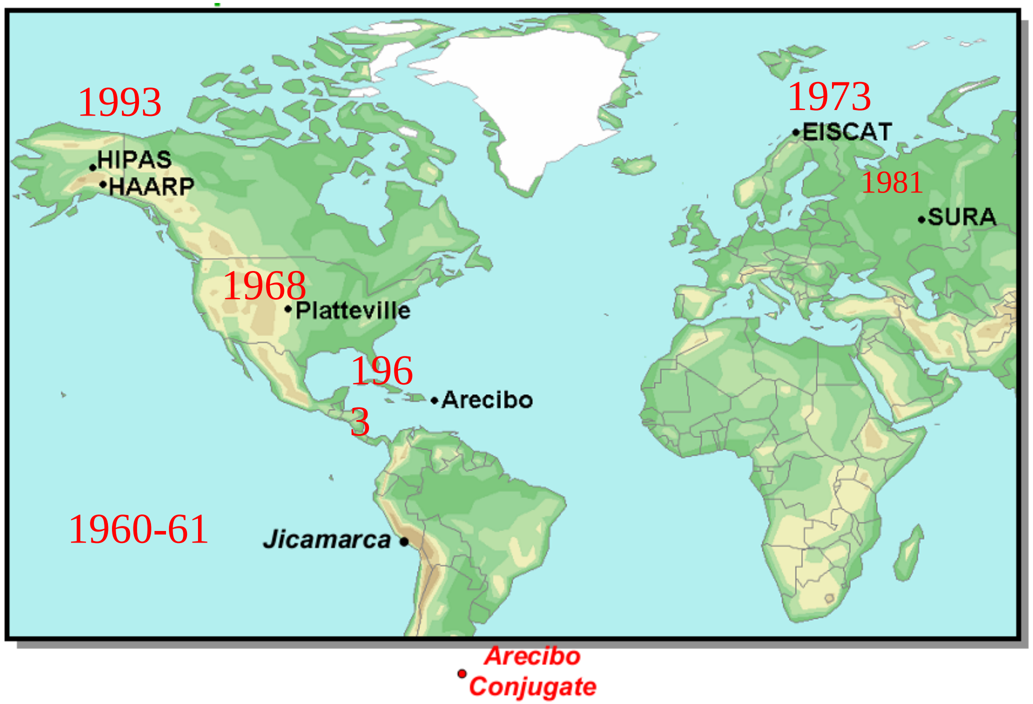
$2f_{ce} \sim 2.76$ MHz

I: Comparison of HAARP and EISCAT HF Heater

- ## Power Level and Frequency

The HAARP heater (High Frequency Active Auroral Research Program) directs a 3.6 MW signal (ERP up to 4GW), in the frequency range 2.8–10 MHz.

The EISCAT(European Incoherent Scatter Scientific Association) heater directs 1.2 MW signal (ERP up to 1GW) in the frequency range 3.85 - 8.00 MHz .



- ## EISCAT HF Transmitter

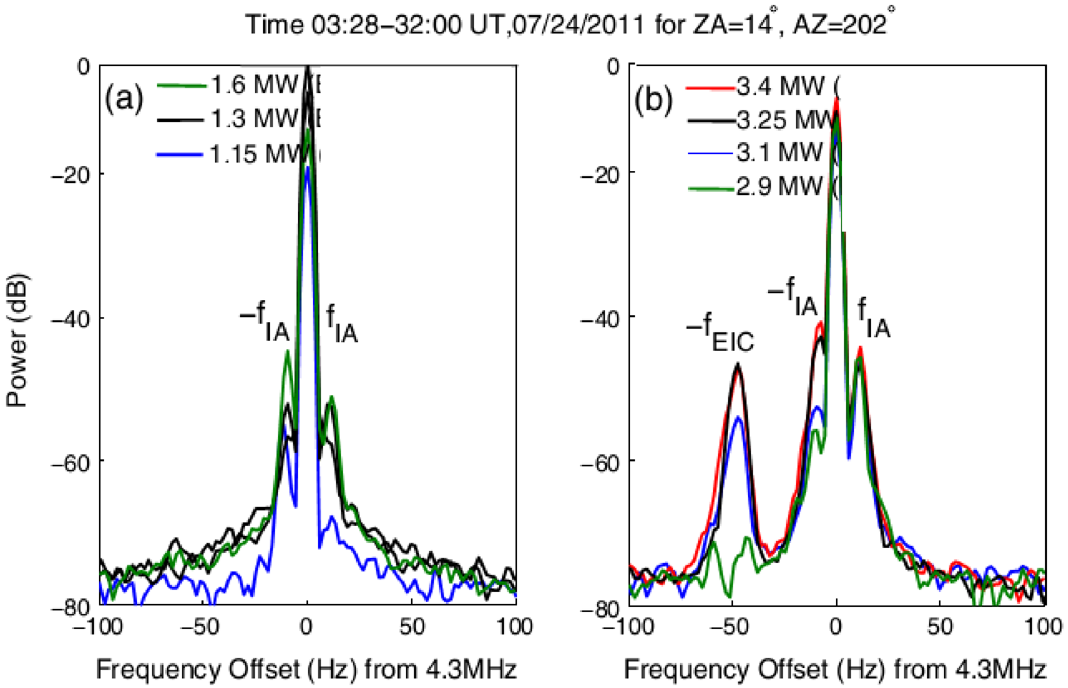
- Array 1 (Superheater): 5.5-8.0 MHz; 12x12 crossed dipoles, 384m square; 1020 kW total power
- Array 2: 4.0-5.5 MHz; 6x6 crossed dipoles, 270 m square; 1020 kW total power
- Array 3: 5.5-8.0 MHz; 6x6 crossed dipoles, 192 m square; 1020 kW total power
- HAARP can only match Superheater size in 1 dimension (317 m x 390 m)
  - –Other arrays matched by partial arrays at HAARP
- **In general, EISCAT ERP ~ 1/3 that of HAARP**

[Bernhardt, 2011; Pedersen, 2012]

I: SBS Power Threshold at HAARP

(Near the **third** electron gyro-harmonic **3fce**)

- **Successfully observed ion acoustic SBS1(f_1) at 8Hz using 1.15 MW (slightly less than 1/3 of HAARP power) and SBS2 (f_2) at 26Hz using 0.5 MW;**
- **Attempted to reproduce ion acoustic SBS1 and SBS2 using 1.2 MW EISCAT HF heater;**
- **Also examined potential to reproduce SIBS using EISCAT HF heater;**

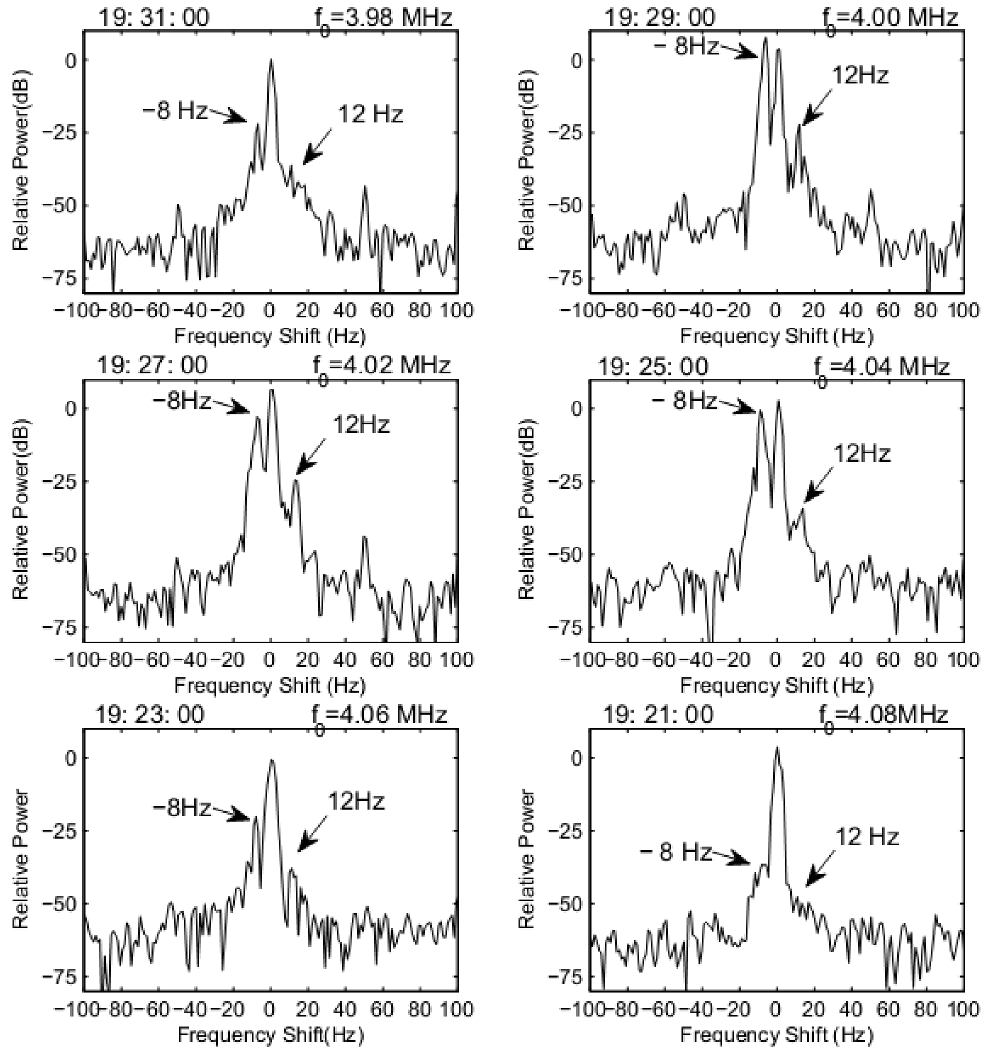


[Mahmoudian et al, 2013]

II: First experimental observation of SBS at EISCAT

(Near the **third** electron gyro-harmonic **3fce**)

- The ion acoustic emission lines shifted by 8 ~ 12Hz from the pump are observed for the pump frequency near the third electron gyro-harmonic.
- The amplitude of the down-shifted ~ 8Hz ion acoustic line is larger than the upshifted ~ 12Hz ion acoustic line .
- These main features of ion acoustic emissions reported in this paper agree quite well with SBS lines originating near the reflection resonance region previously observed at HAARP.



[Fu et al, 2015 under review]

Narrowband SEE below 100 Hz

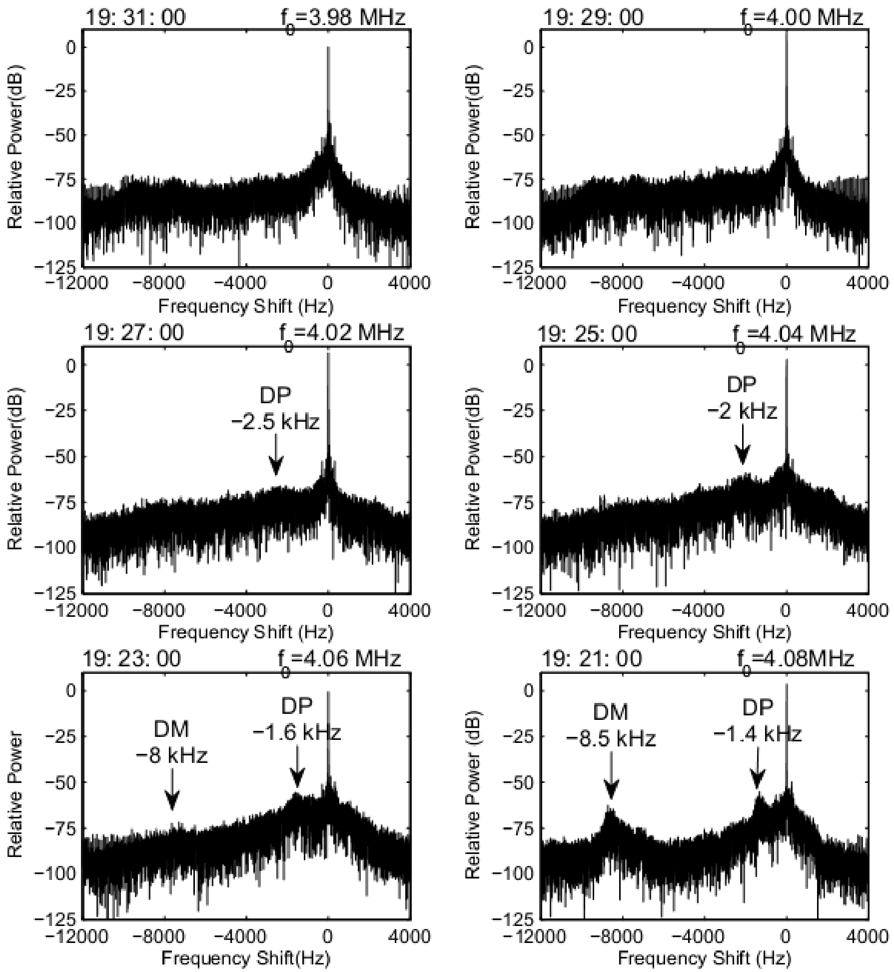
II: Experimental observation of DP at EISCAT

(Near the **third** electron gyro-harmonic **3fce**)

- The downshifted peak DP at approximately ~ 2kHz develops for pump frequencies close to 4:04MHz;

- The DP frequency offset drops approximately from −2.5 kHz to −1.5 kHz as the pump frequency approaches 3fce, consistent with previous experimental observations (Stubbe, 1994).

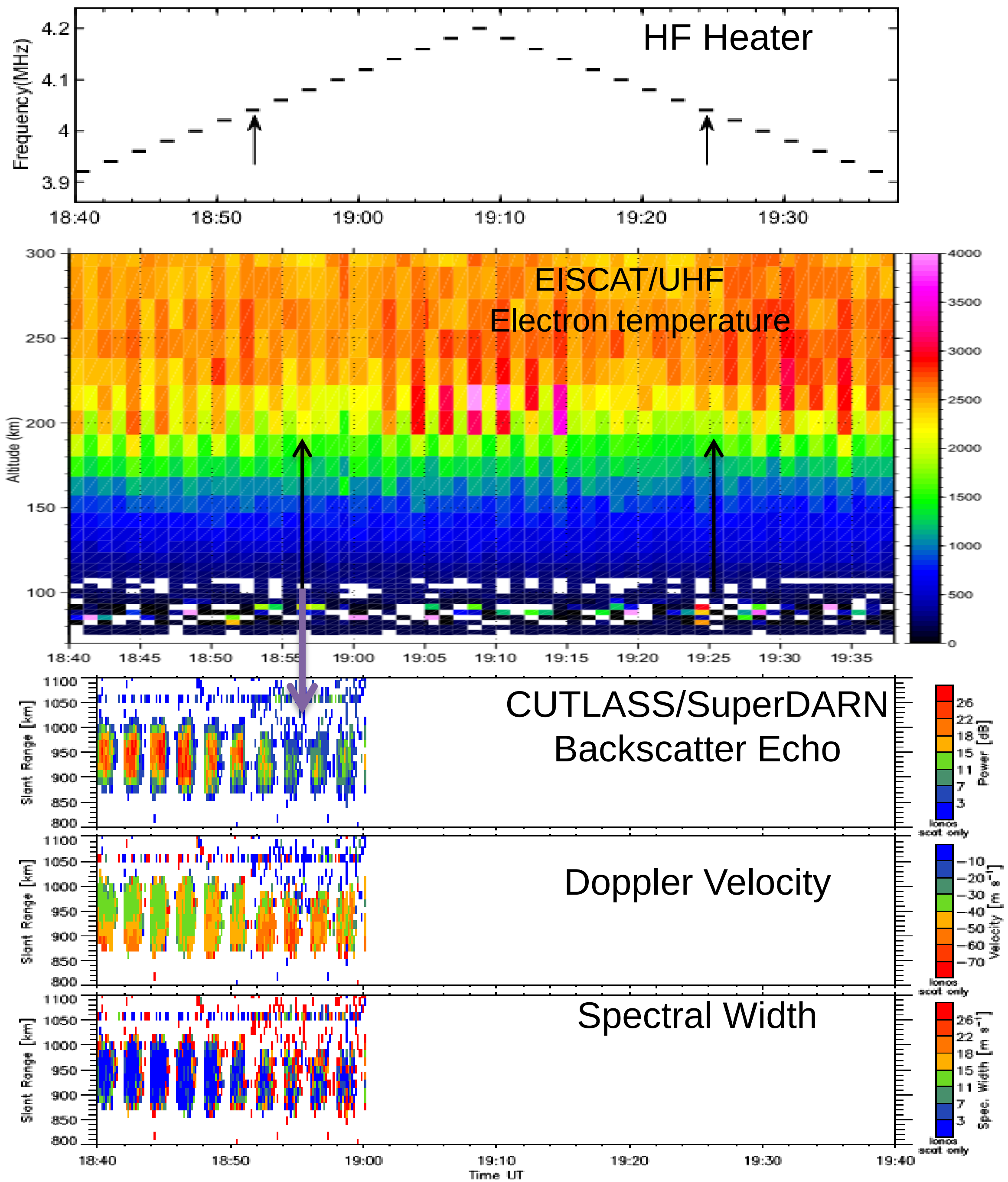
- If the pump frequency increases further above electron gyro-harmonic, the downshifted maximum DM spectral line (Leyser et al., 2001) at approximately 8 − 8.5kHz below the pump frequency appears in the lower sideband spectrum.



Wideband SEE below 10 kHz

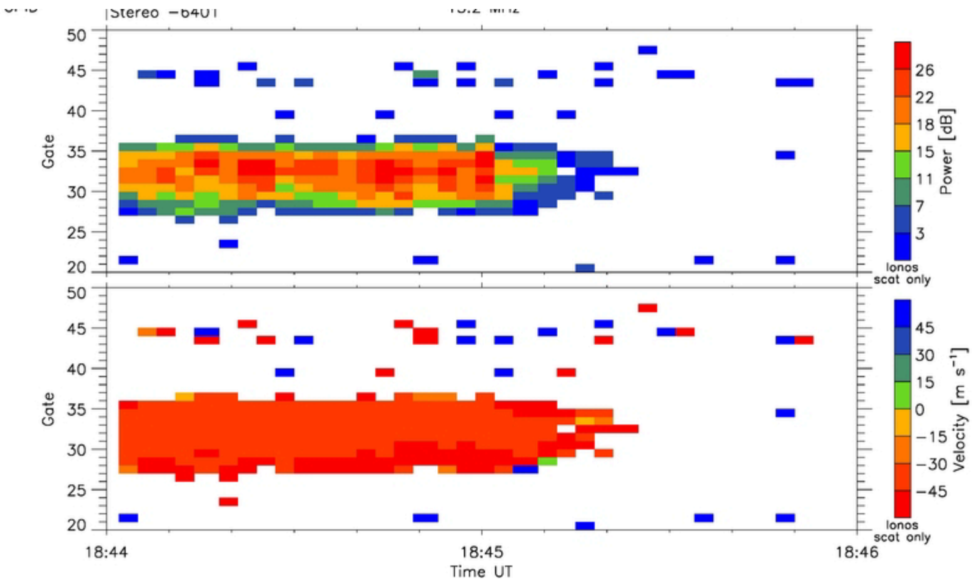
II: SBS correlation with electron temperature and field aligned irregularities

- Frequency stepping near 3fce;
- Electron temperature is minimized and field aligned irregularities FAIs echoes are suppressed while the ion acoustic SBS is observed mostly due to less absorption;
- HF pump induced Doppler velocity can reach a value −50 m/s, which corresponds to a frequency approximately 5Hz. The negative Doppler shifts are likely due to the plasma expulsion associated with the heating.
- The spectral width of HF signals mostly locate below 5m/s;



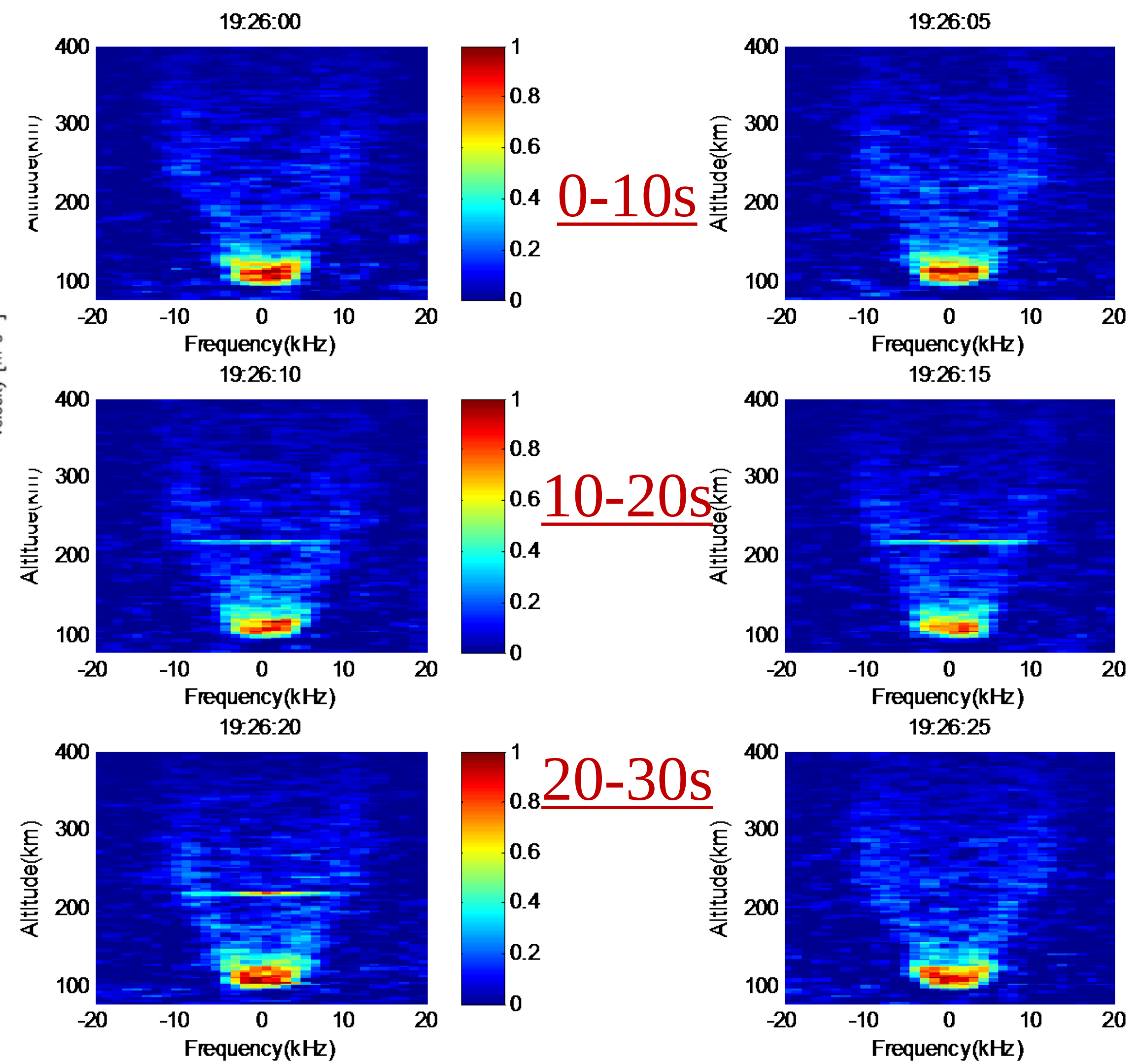
II: Temporal evolution of SBS, FAIs and Ion lines

FAIs evolution in a 1min on, 1min off duty cycle



- The rise time of FAIs less than 10s;
- The ion line enhancement arises in less than 30s, mostly less than 5s;
- SBS does not involve FAIs directly but involve ion acoustic wave;

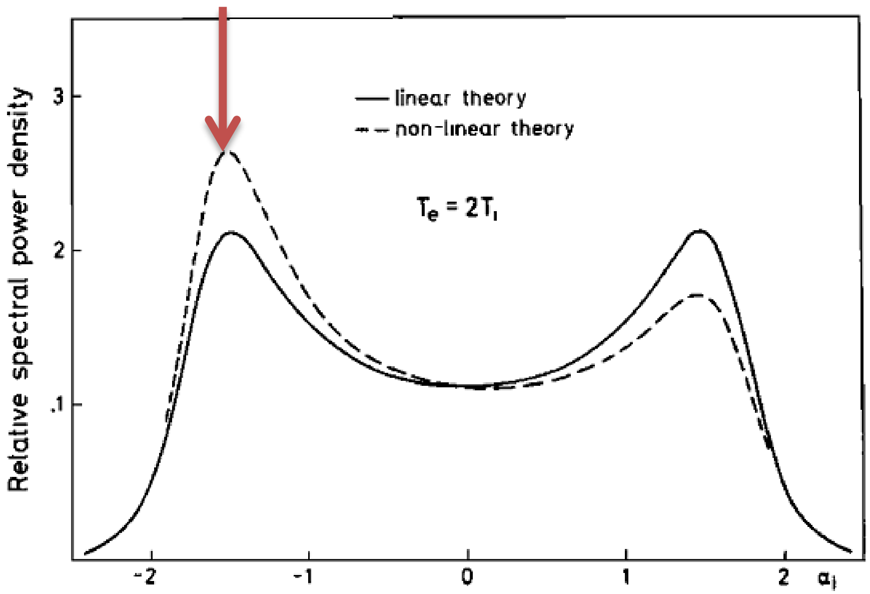
Pumping at 4.02 MHz for 1min



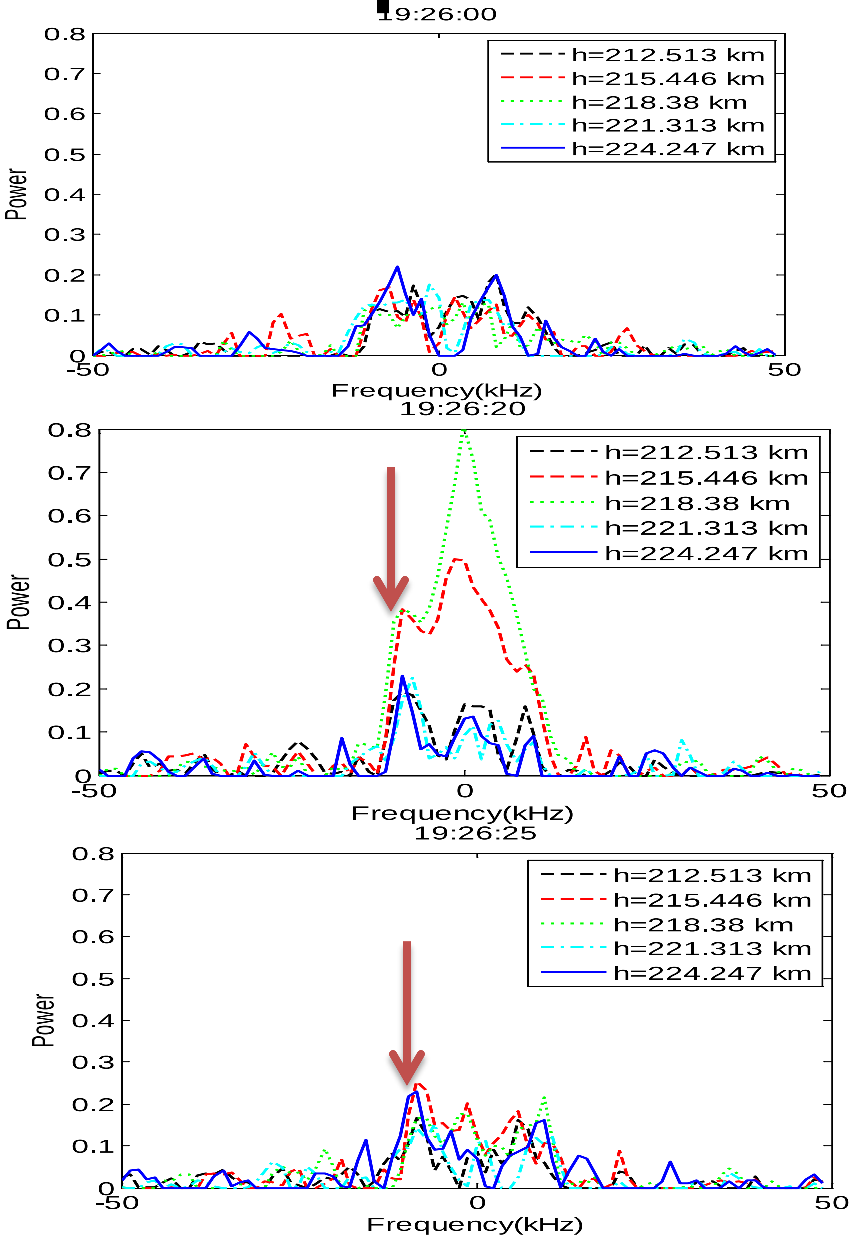
Measured Ion line Spectra versus height

II: Can SBS induced by HF heater cause asymmetry in the Ion Line Spectra?

- Fejer et al. (1978) predicted the stimulated Brillouin scattering by Jicamarca and Arecibo incoherent radars can cause an asymmetry in the double humped spectra of incoherent backscatter by enhancing the downshifted ion line and weakening the upshifted ion line;
- Experimental observation of SBS using the Jicamarca 50MHz incoherent scatter radar can cause 25 percent asymmetry, resulting in errors of 10 ~ 15 m/s in the measured velocity.;



[Fejer et al. ,1978]



Measured Ion line Spectra versus height

II: Summary comparison of SBS at HAARP and EISCAT

(Near the third electron gyro-harmonic 3fce)

EISCAT

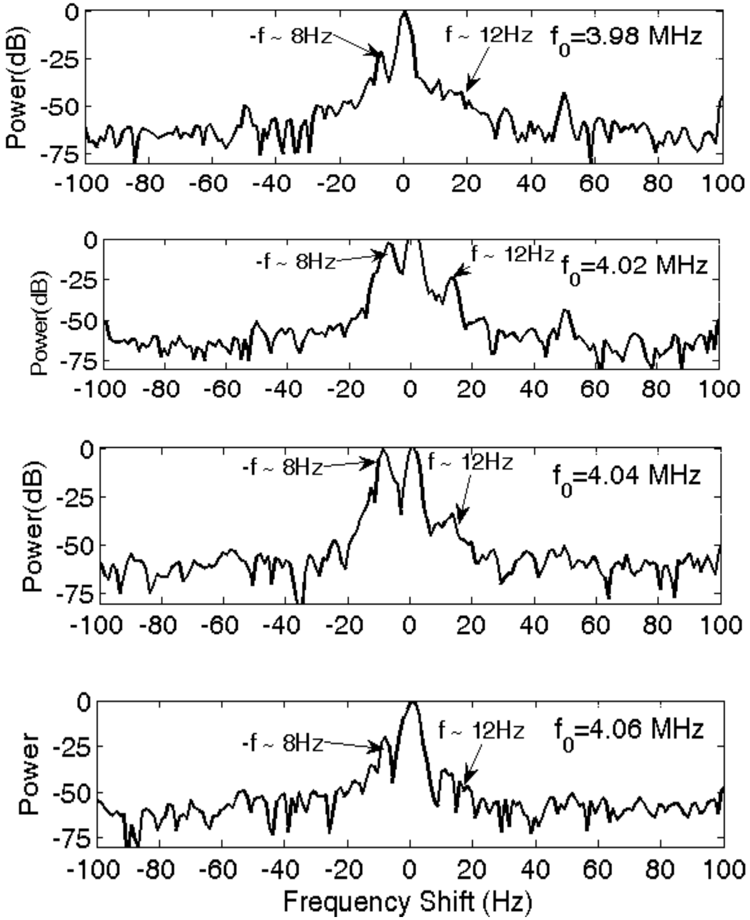


Fig. Measured frequency spectra of radio emissions from the EISCAT transmitter near $3f_{ce}$ for the magnetic zenith pumping during 19:20 -19:32 UT on July 3, 2012

HAARP

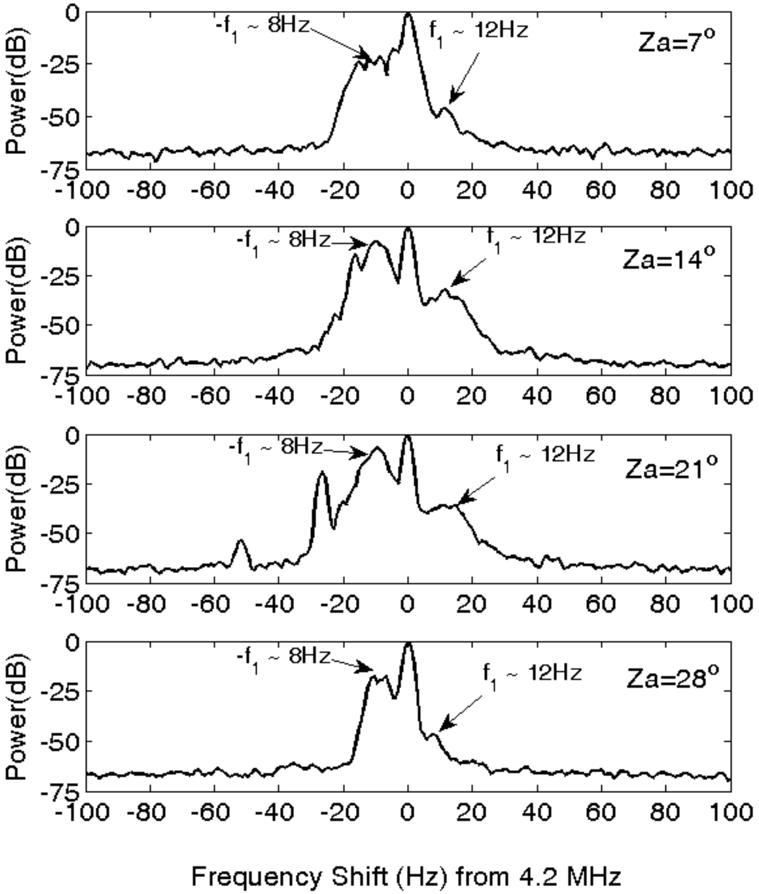
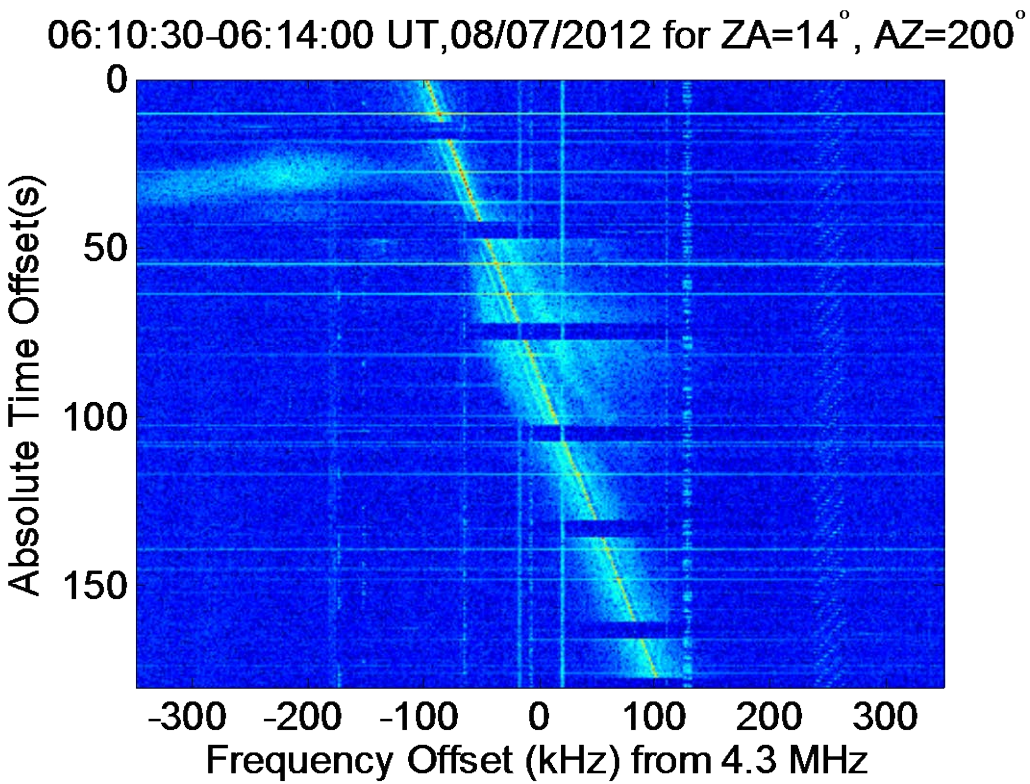


Fig. Measured frequency spectra of radio emissions from the HAARP at 4.2 MHz relatively close to $3f_{ce}$ for different heater beam angles 14º (for the magnetic zenith) during 04:15-04:60 UT on July 22, 2010.

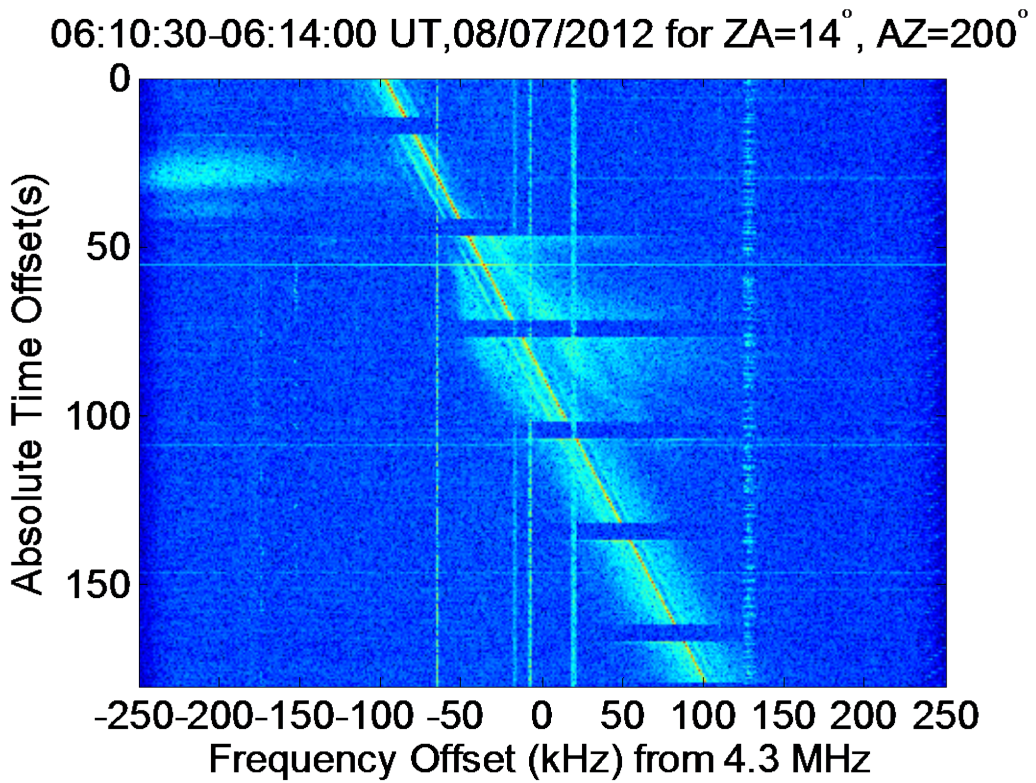
III: Wideband SEE results at HAARP

(2012 August Campaign, 08/07/2012)

- **Attempted to investigate narrowband SBS near 3fce and correlate with wideband SEE features for different heater beam angles using multiple sites SEE receiver at HAARP;**
- **However, the frequency sweeping rate is too fast to distinguish narrowband SBS within 100 Hz.**



Rivierview Site

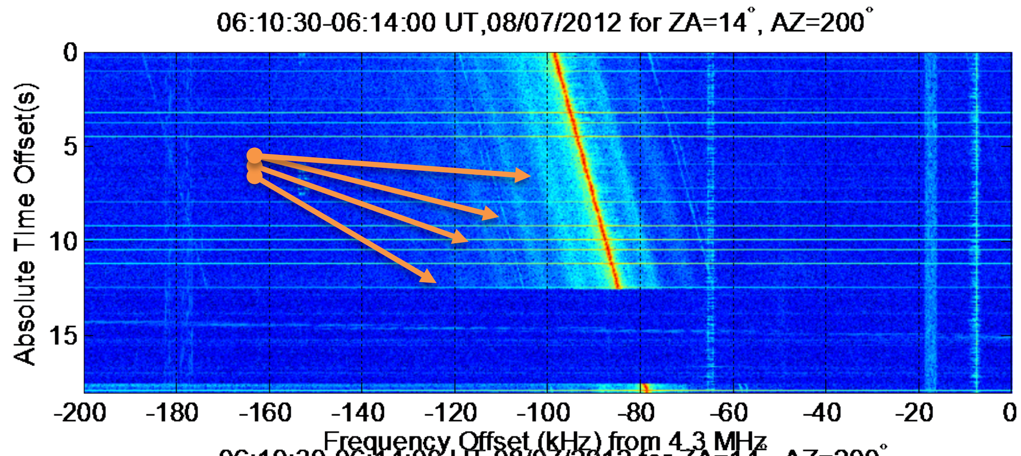


Chichina Site

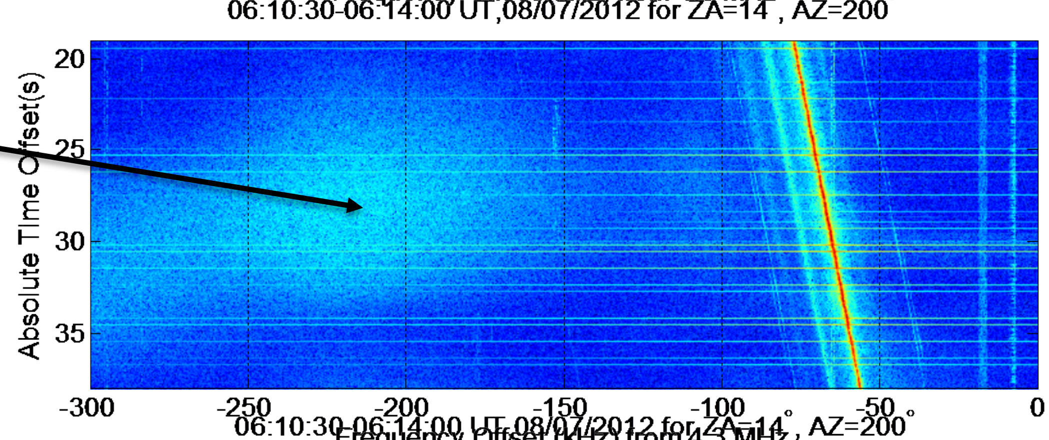
III: Wideband SEE Results at HAARP

(2012 August Campaign, 08/07/2012)

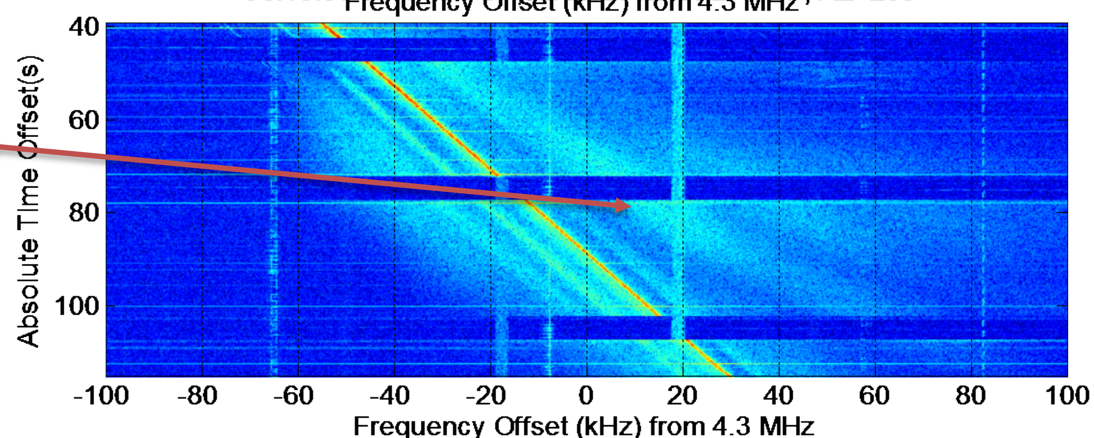
I: For pumping below 3fce
DM cascading at 8~9 kHz



II: For pumping slightly below 3fce at 4.22 ~4.24 MHz
Droadband DE at ~150 kHz



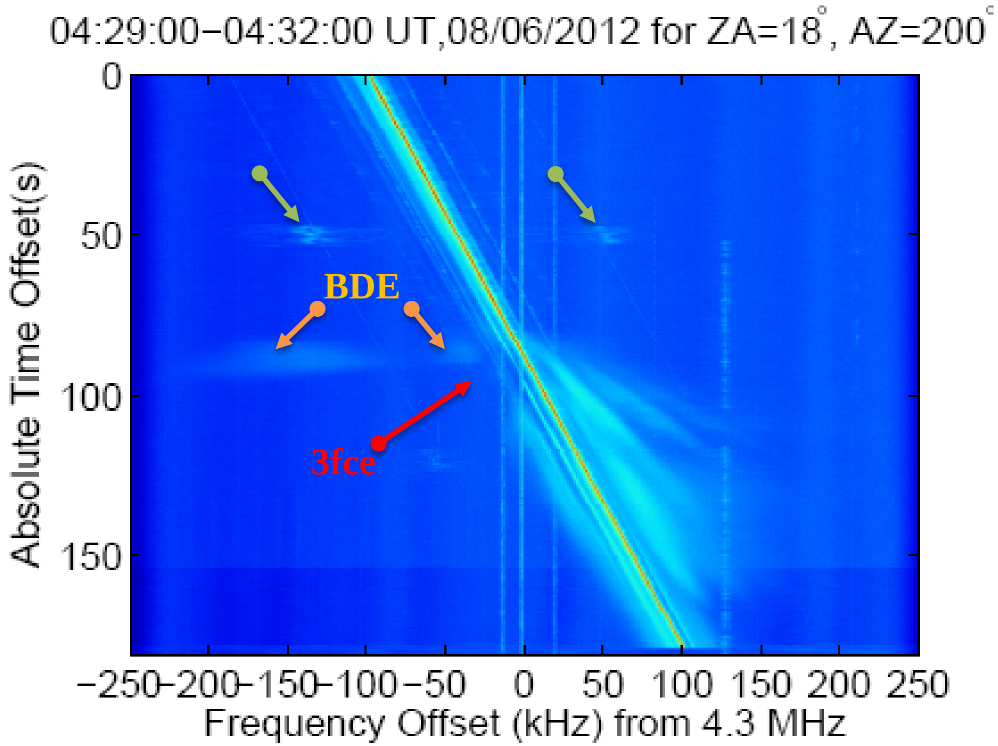
III: For pumping above 3fce at 4.27~4.32 MHz
BUM at 25 kHz



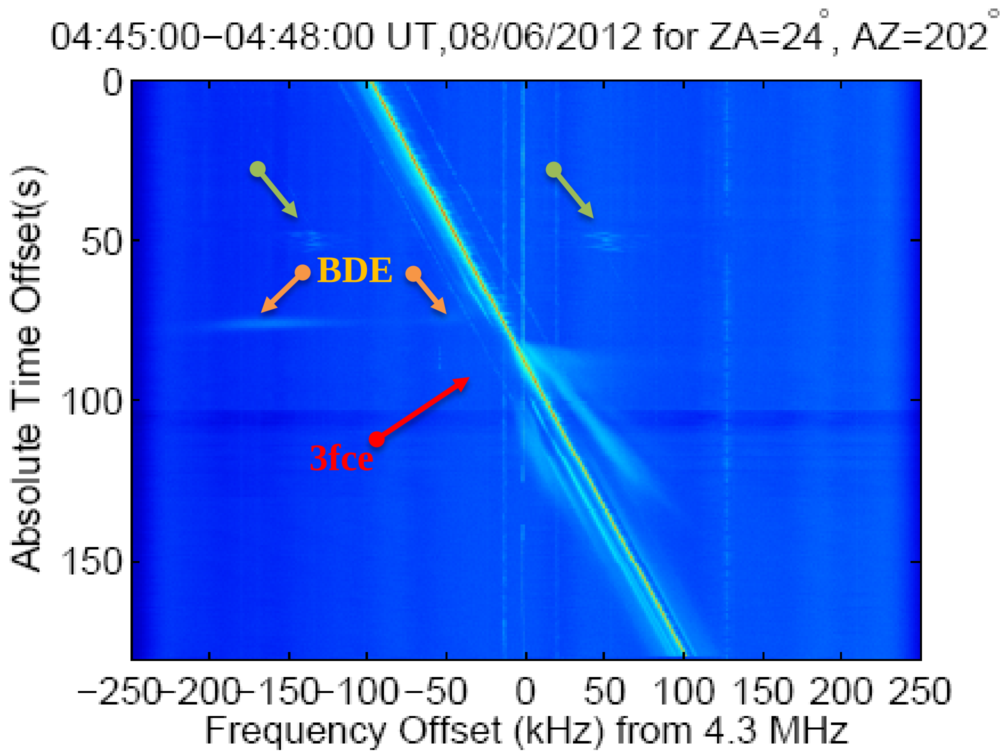
III: Wideband SEE results at HAARP

(2012 August Campaign, 08/07/2012)

- **Attempted to investigate narrowband SBS near 3fce and correlate with wideband SEE features for different heater beam angles using multiple sites SEE receiver at HAARP;**



Zenith Angle = 18°



Zenith Angle = 24°

Conclusion and Summary

- **SBS at EISCAT observed for the first time at 3fce**
  - The HF facility with ERP ~ 148MW, can generate SBS emissions at 8 ~ 12Hz near 3fce;
  - Agrees well with SBS at the reflection resonance region previously observed at HAARP;
- **Simantenously measurement of SEE features with electron temperature and field aligned irregularities near electron gyro-harmonic heating;**
  - SBS/DP strengthens near 3fce while electron temperature from EISCAT/UHF data and field-aligned irregularities from CUTLASS radar are suppressed;
- **Attempted to correlate narrowband SBS with wideband SEE features near 3fce for different transmitter beam angles using multiple sites SEE receiver at HAARP;**
- **These SEE spectral lines are important consequences of plasma waves near electron gyroharmonic in the wide band and narrowband SEE spectrum leading to unique ionospheric diagnostic information;**

Acknowledgement and Collaborations

- The authors would like to acknowledge Ingemar Haggstrom for EISCAT UHF radar at the EISCAT facility for technical support.
- HAARP Collaborations: W.A, Sclaes, A. Mahmoudian, M. Bordikar, A. Samimi, Virginia Tech
- HAARP Collaborations: P. Bernhardt, S. Brisinski, Naval Research Laboratory, Washington D.C
- HAARP Collaborations: M. McCarrick, Marsh Creek. LLC, Gakone, Alaska
- EISCAT Collaborations: M. Kosch, A. Senior, University of Lancaster, United Kingdom
- SuperDARN Collaborations: T. K. Yeoman, University of Leicester and J. M. Ruohoniemi, Virginia Tech, Bill Bristow, University of Alaska

The Brillouin scattering effect causes an asymmetry of the power spectrum of the incoherent backscatter in such a manner that the downshifted ion line is enhanced and the upshifted ion line is weakened. The total effect depends on the power of the transmitted radar pulse (the pump) and the height region along which the interaction of the pump with the downgoing incoherently backscattered waves takes place. This interaction is height-dependent because the power density of the pump and the ionospheric parameters involved, such as electron density and ion and electron temperature (N_e, T_i, and T_e), are functions of the height. The effect is weak, and a high-power radar pulse of reasonably long duration is desirable to allow both a long interaction time and a large height integral. A long integration time is also necessary to reduce the statistical error in the data. The following arrangement was chosen to achieve this. For detailed descriptions of the Jicamarca Radio Observatory near Lima, Peru, see *Bowles* [1967] or *Evans* [1969].

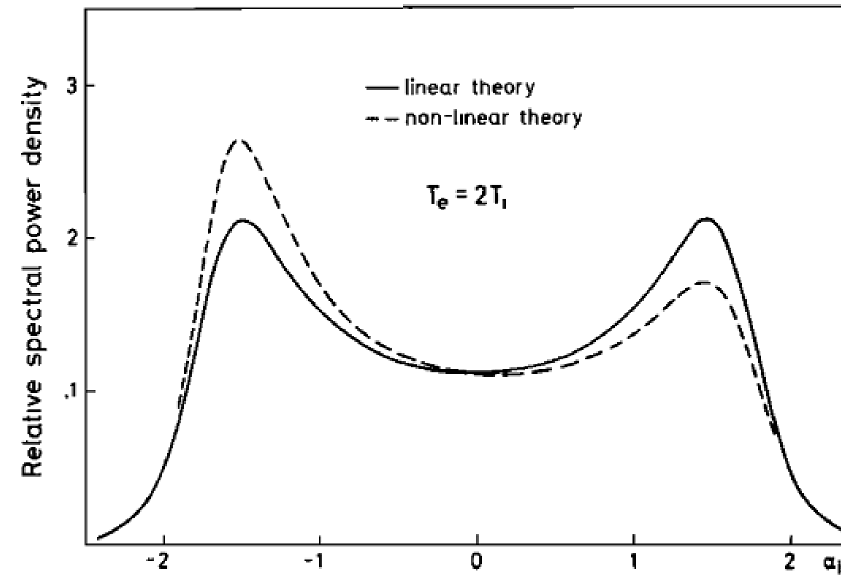


Figure 2. The calculated normal incoherent ba scatter spectrum for Jicamarca is shown by th solid line. The interrupted line shows the sp trum modified by stimulated Brillouin scatter A peak radiated power of 2 MW is assumed. The assumed pulse length is 3 msec and the calcul received spectrum 1.33 msec after the trailin edge of the pulse is shown.