Introduction to heating experiments

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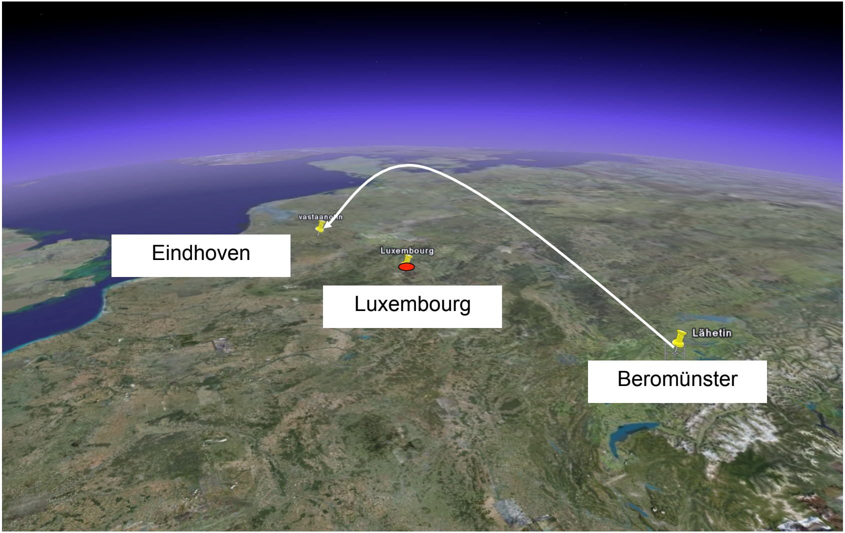
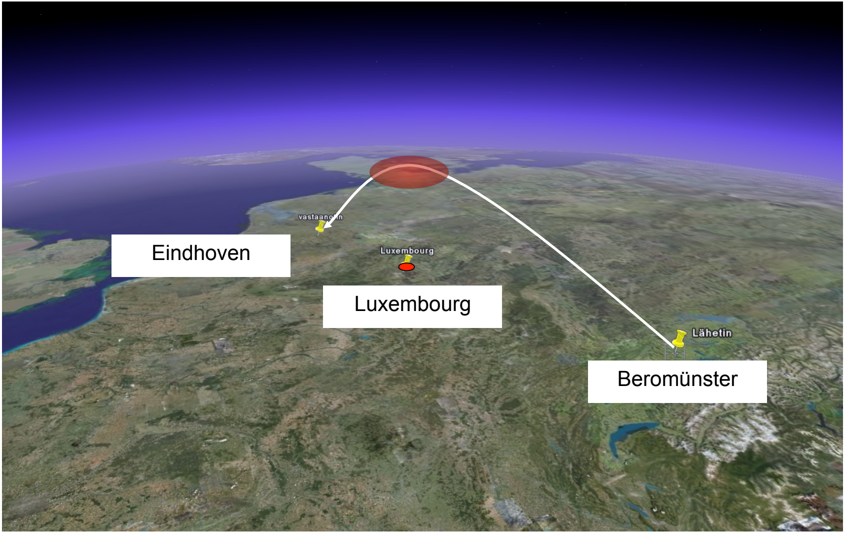
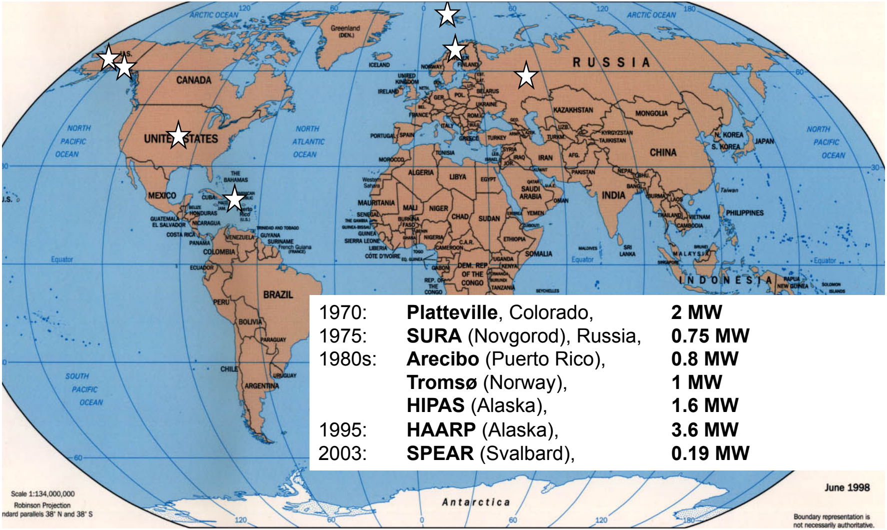
Early history: Luxembourg effect 1933



Early history: Luxembourg effect 1934

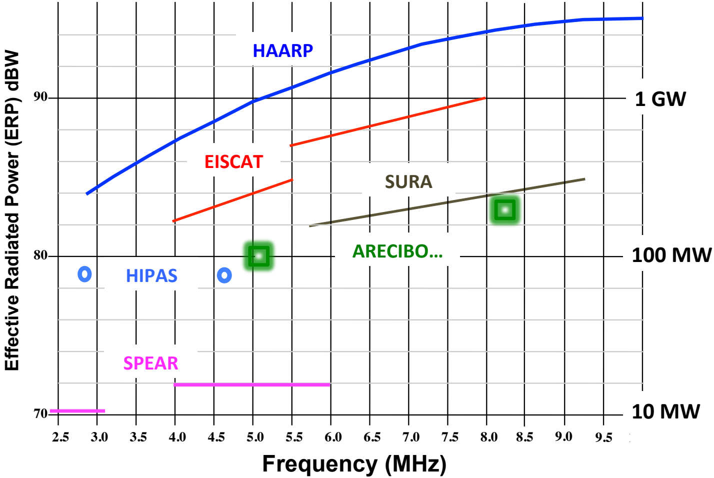


Heating facilities: POWER to the people!

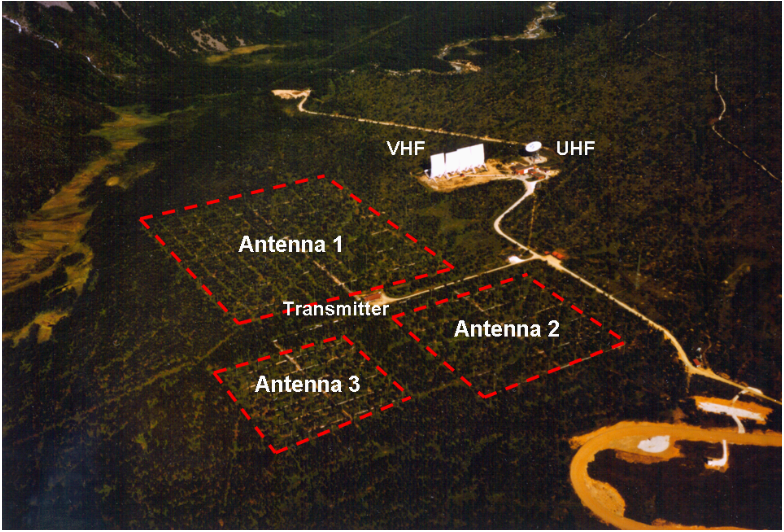


1970:	**Platteville**, Colorado,	**2 MW**
1975:	**SURA** (Novgorod), Russia,	**0.75 MW**
1980s:	**Arecibo** (Puerto Rico),	**0.8 MW**
	Tromsø (Norway),	**1 MW**
	HIPAS (Alaska),	**1.6 MW**
1995:	**HAARP** (Alaska),	**3.6 MW**
2003:	**SPEAR** (Svalbard),	**0.19 MW**

Heating facilities: ERP to the people!



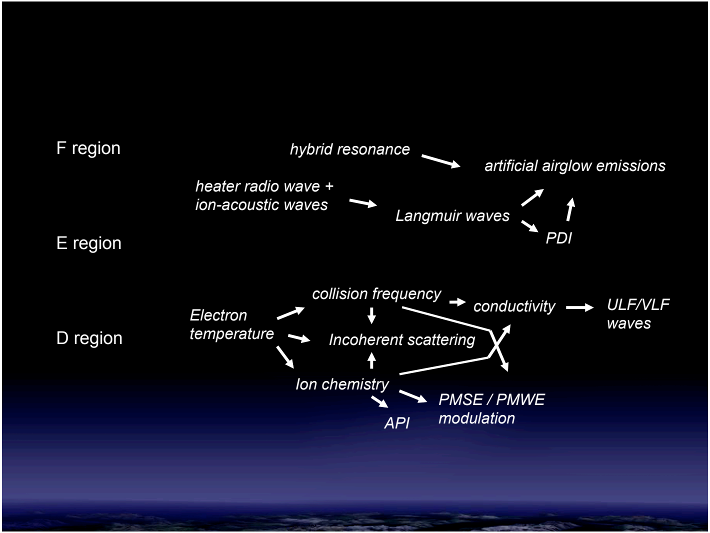
Heating facilities: EISCAT, Norway



Heating facilities: Arecibo, Puerto Rico

Heating facilities: HAARP, Alaska

Some science applications



Heating effect in collisional plasma: Appleton equation

Refractive index n of the plasma for the radio wave is given by the Appleton equation

$$n^2 = 1 - \frac{X}{1 - iZ - \frac{(Y\sin\alpha)^2}{2(1-X-iZ)} \pm \sqrt{\frac{(Y\sin\alpha)^4}{4(1-X-iZ)^2} + (Y\cos\alpha)^2}},$$

where the normalised frequencies are

$$X = \frac{\omega_{pe}^2}{\omega^2} = \frac{N_e e^2}{\epsilon_0 m_e \omega^2}, Y = \frac{\omega_{ge}}{\omega} = \frac{eB}{m_e\omega} \text{and } Z = \frac{\nu_{en}}{\omega}.$$

Heating effect in collisional plasma: energy absorption

When the complex refractive index $n = \Re(n) + i\Im(n)$, given by the Appleton equation, is applied to the plane wave equation

$$E(r,t) = E_0 \exp\left[i\omega\left(t - nr/c\right)\right]$$

we get a decaying wave in a case of $\Im(n) < 0$:

$$E(r,t) = E_0 \exp\left[i\omega\left(t - \Re(n)r/c\right)\right] \exp\left(\omega\Im(n)r/c\right).$$

Heating effect in collisional plasma: energy absorption

Since the intensity of the wave $I \propto E^2$,

$$I(r) = \frac{ERP}{4\pi r^2} \exp\left(\frac{2\omega}{c}\int_0^r \Im(n)dr\right),$$

and the absorbed energy per time unit and per volume is

$$Q = -\frac{dI_{abs}}{dr} = -2\omega\Im(n)I/c.$$

This is the energy gain from the wave to the plasma due to collisions between electrons (accelerated by the wave) and neutrals.

Heating effect in collisional plasma: electron energy budget

In the ideal gas, the mean electron energy is

$$E = \frac{3}{2} k_B T_e.$$

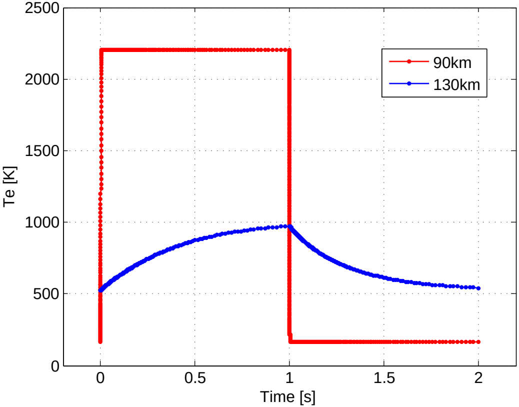
By differentiating this with respect to volume and time, we get

$$\frac{dT_e}{dt} = \frac{2}{3k_B N_e}(Q - L) = \frac{2}{3k_B N_e}\left(\frac{-2\omega \Im(n) I}{c} - L\right).$$

Here $L = \sum L_X\left([X], N_e, T_n, T_e\right)$ denotes the sum of electron energy loss processes by excitations of $\mathrm{O_2}$, $\mathrm{N_2}$ and O (Stubbe ja Varnum, 1972).

Example result: 1s on/off heating, T_e/T_i

ERP=600 MW, $f = 5.423$ MHz, O-mode



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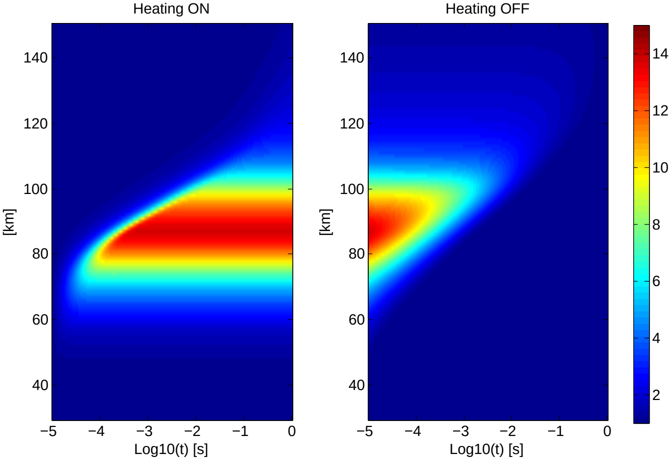


Incoherent scatter spectrum

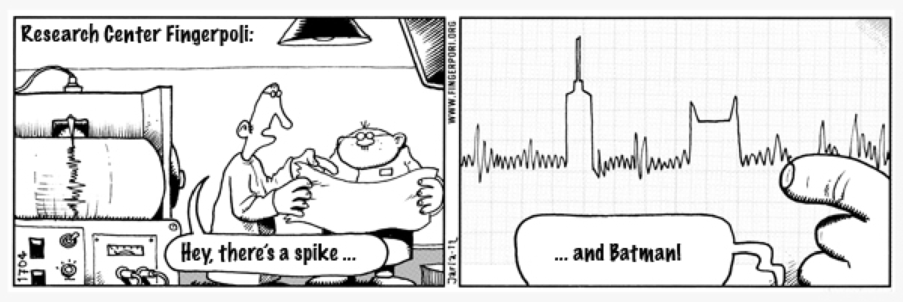


Figure : Fingerpori, HS, 7 September 2012

Incoherent scatter spectrum

The spectral density of the incoherent scattering is

$$\sigma(\omega_0+\omega)d\omega = \frac{N_e r_e^2 d\omega}{\pi} \frac{\left(|y_e|^2 \frac{\sum_j n_j \Re(y_j)}{\omega - \mathbf{k}\cdot\mathbf{v}_{dj}} \left| \sum_j \mu_j y_j + i\lambda_D^2 k^2 \right|^2 \frac{\Re(y_e)}{\omega - \mathbf{k}\cdot\mathbf{v}_{de}} \right)}{\left(\left| y_e + \sum_j \mu_j y_j + i\lambda_D^2 k^2 \right|^2 \right)}.$$

Here

- $n_j = N_j/N_e$ and $\mu_j = n_j T_e/T_j$ (densities and temperatures),
- $\lambda_D = (\epsilon_0 k_B T_e/N_e e^2)^{1/2}$ (Debye length)
- $k = 2\pi/\lambda$ (wave number).
- y_j (admittance function ... the next slide)

Incoherent scatter spectrum: Admittance function y_j

The admittance functions for the species j are

$$y_j = \frac{i + (\theta_j - i\psi G_j)}{1 - \psi G_j}.$$

Here the Gordeyev integral (asymptotic expansion) can be written as

$$G_j(\theta_j - i\psi_j, \phi_j, \alpha) = \int_0^\infty e^{-i(\theta - i\psi))t' - \phi^{-2}\sin^2 0.5\phi t' - 0.25t'^2 \cos^2\alpha} dt',$$

where α is the angle to the **B** and ...

$$\theta_j = \omega\zeta_j, \phi_j = \frac{eB}{m_j c}\zeta_j, \psi_j = \nu_j\zeta_j, t' = t/\zeta_j, \zeta_j = \frac{1}{k}(m_j/2k_B T_j)^{1/2}.$$

Incoherent scatter spectrum: Inputs

What is needed for calculating the IS spectrum?

- Radio wave parameters: ω, $\mathbf{k}$
- Plasma composition, temperatures, ion masses, coll. frequencies and drift velocities: N_j, T_j, m_j, ν_j and $\mathbf{v_j}$
- Magnetic field $\mathbf{B}$

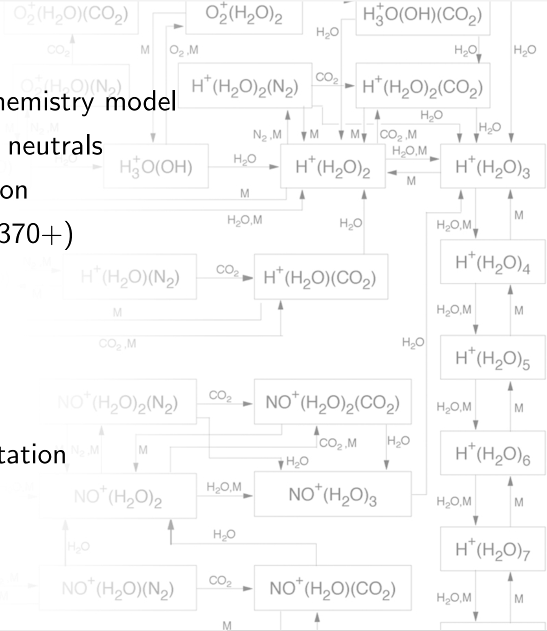
Sodankylä Ion (and neutral) Chemistry model (SIC)

Detailed 1-D time dependend chemistry model

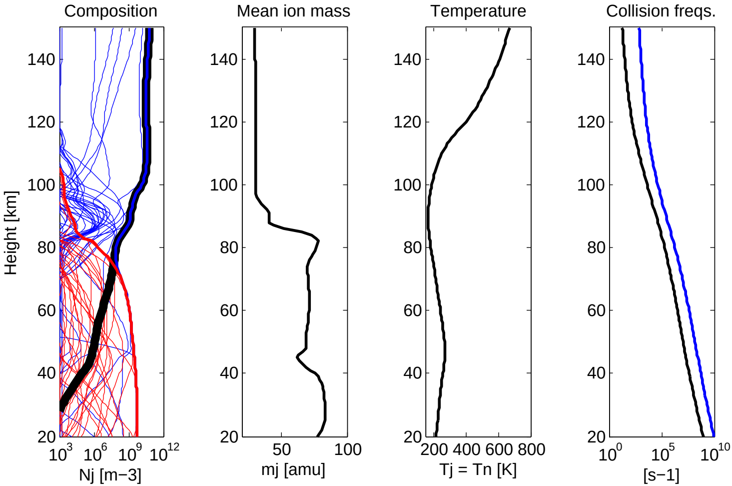
- 63 ions (27 negative) & 13 neutrals
- 20-150 km in 1 km resolution
- several hundred reactions (370+)
- vertical transport

Input

- MSIS
- solar EM flux
- proton and electron precipitation
- cosmic rays



Input profiles



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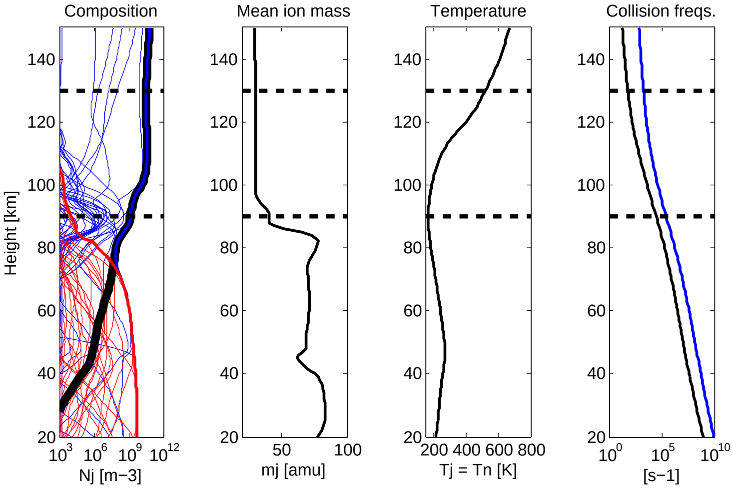
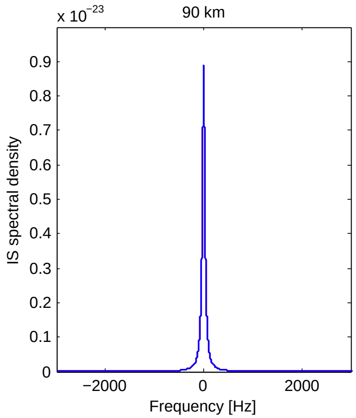
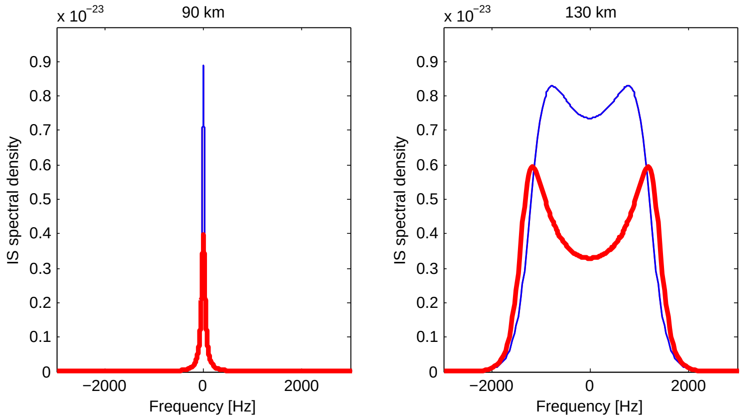


Incoherent scatter ion line: 90 and 130 km

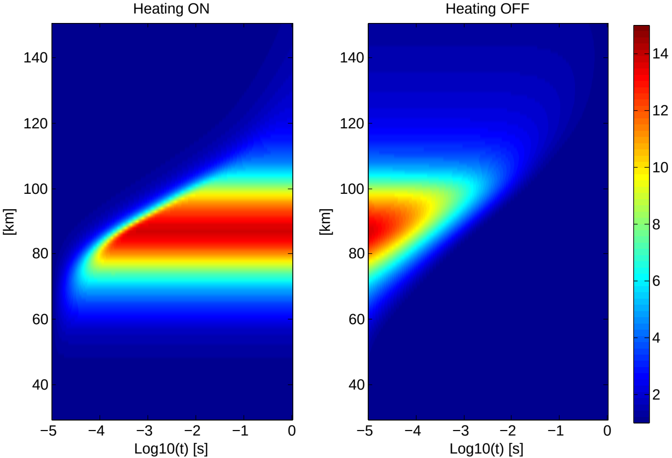


Incoherent scatter ion line: 90 and 130 km, $T_e = 2T_i$



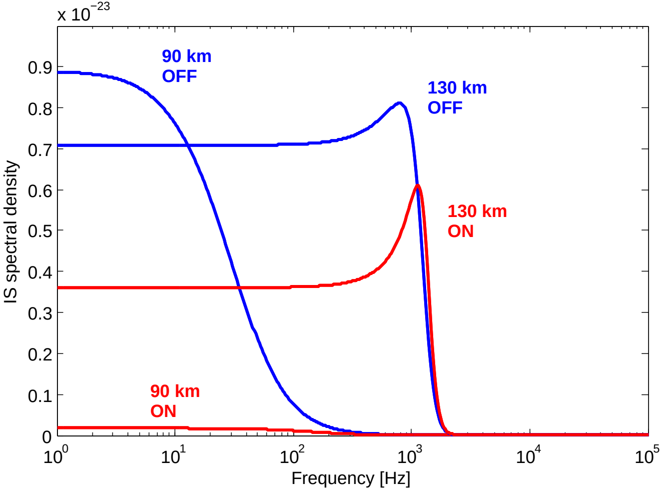
Example result: 1s on/off heating, T_e/T_i

ERP=600 MW, $f = 5.423$ MHz, O-mode



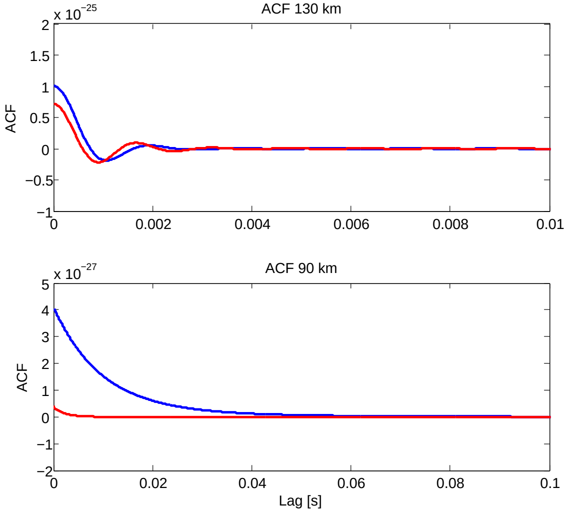
Example result: 1s on/off heating, the IS spectra

ERP=600 MW, $f = 5.423$ MHz, O-mode

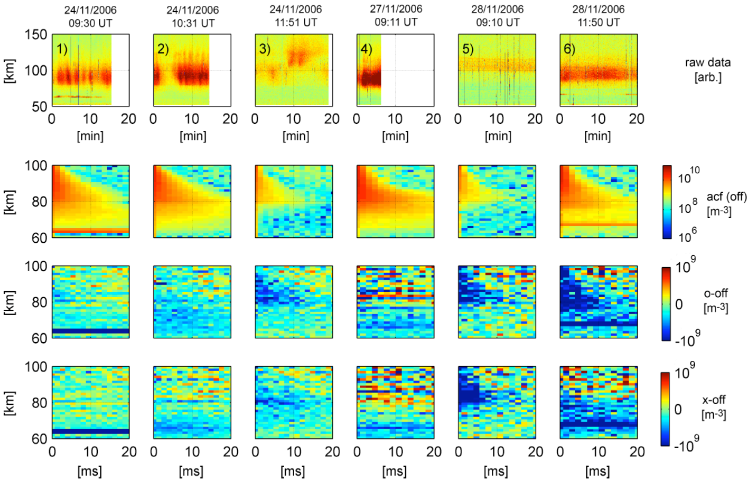


Example result: 1s on/off heating, the ACFs

ERP=600 MW, $f = 5.423$ MHz, O-mode



EISCAT campaign 2006



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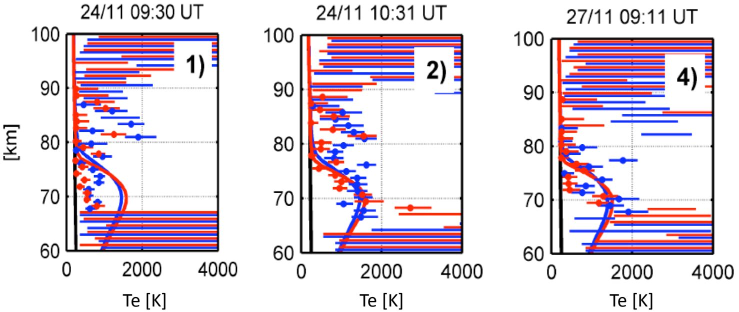
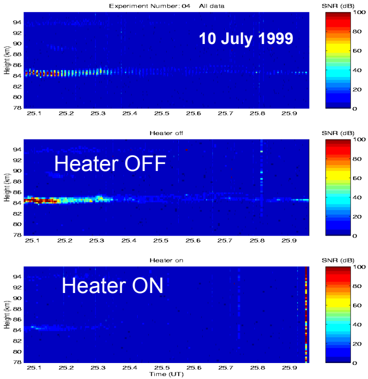
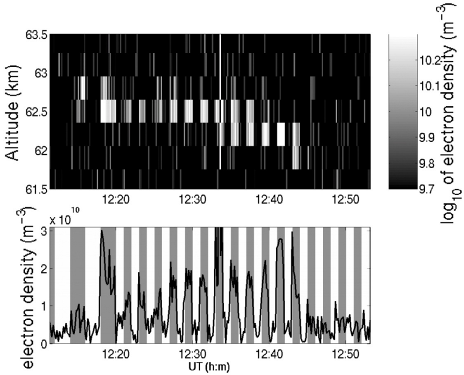


Coherent scattering: PMSE and PMWE

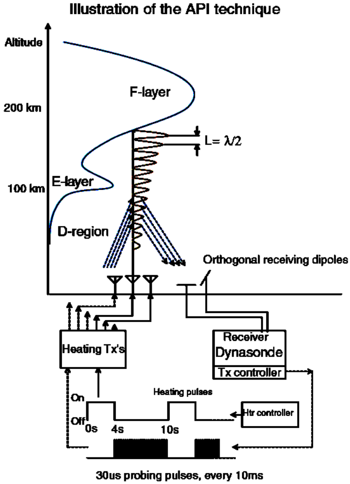
PMSE at 85 km

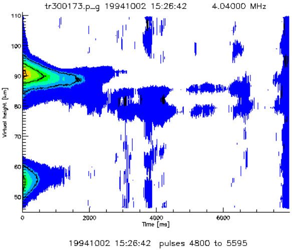


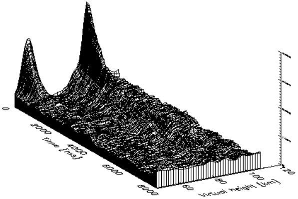
PMWE at 63 km



Coherent scattering: Artifical Periodic Irregularities (API)







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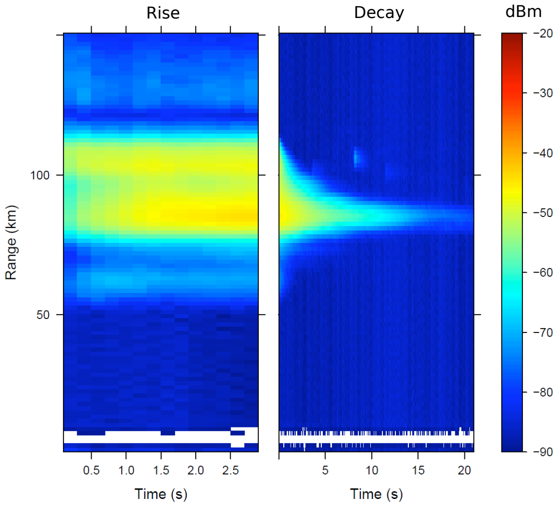
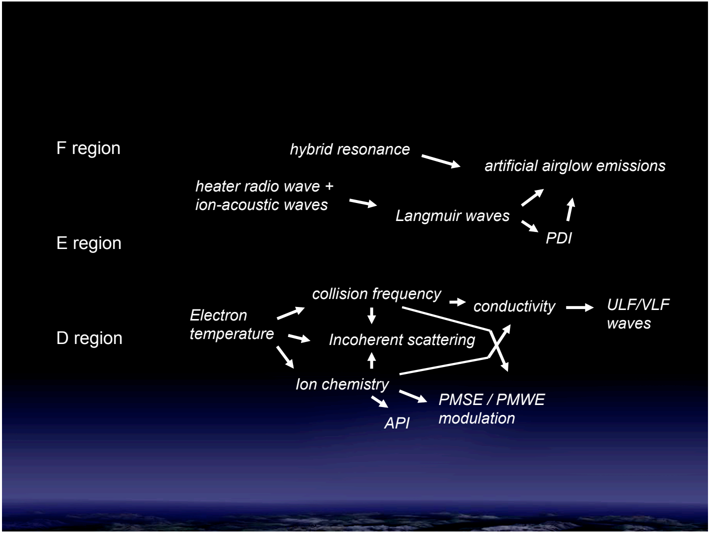


Coherent scattering: summary

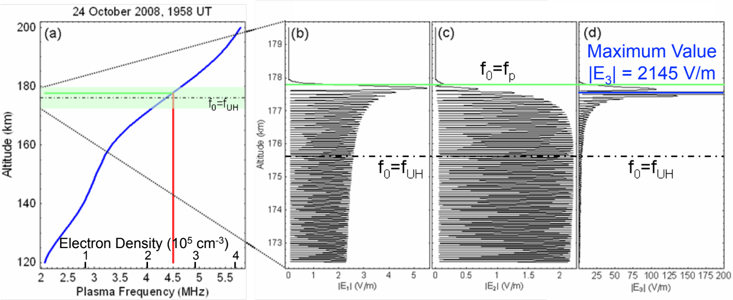
	API	PMSE/PMWE
Production	• standing wave • negative ion prod. • (dust charging?)	• turbulence • dust/ice charging • (negative ions?)
Loss	• detachment • (dust de-charging) • (diffusion)	• diffusion • dust de-charging • (detachment)
Heating	Forms the irregularities in the first place	Makes the echo *weaker* (+ builds the overshoot)
Lambda	55.3 m	0.32/1.34/5.35 m

Some science applications



Resonance heating

Full Wave Solution for EM Pump Wave at 4.5 MHz in the Ionosphere Over HAARP

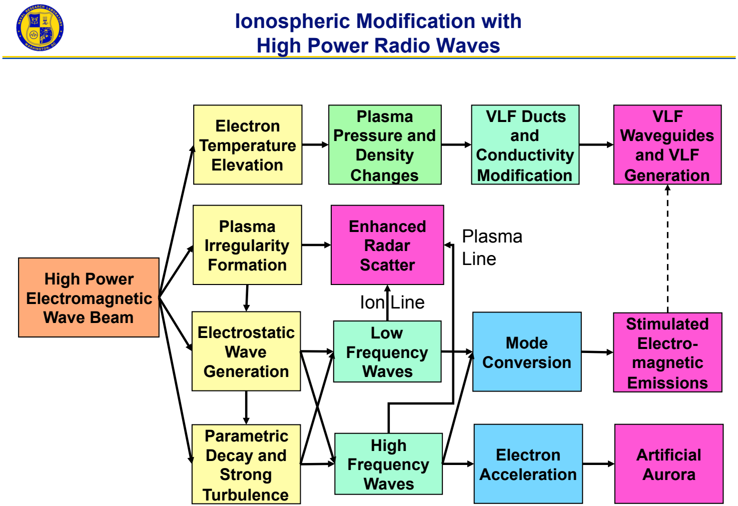


Horizontal Electric Fields

Vertical Electric Field

Large Increase in Electric Field Just Below Reflection Altitude where EM Wave Frequency = Plasma Frequency

Resonance heating



Resonance heating: artificial airglow

EISCAT Enhanced Airglow, Bjorn Gustovson, IRFU