

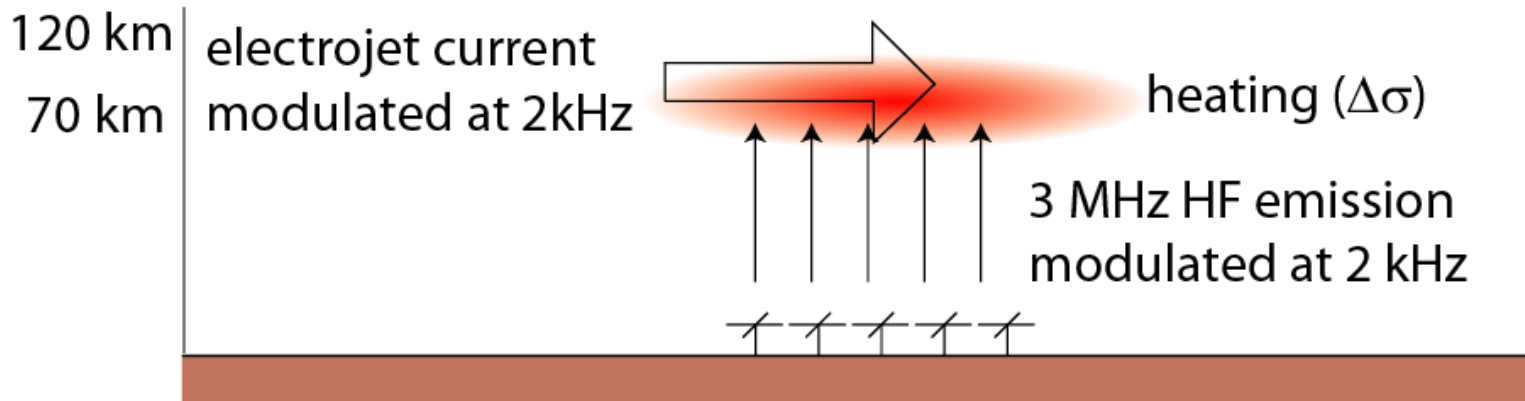


Ionospheric modification and ELF/VLF wave generation by HAARP

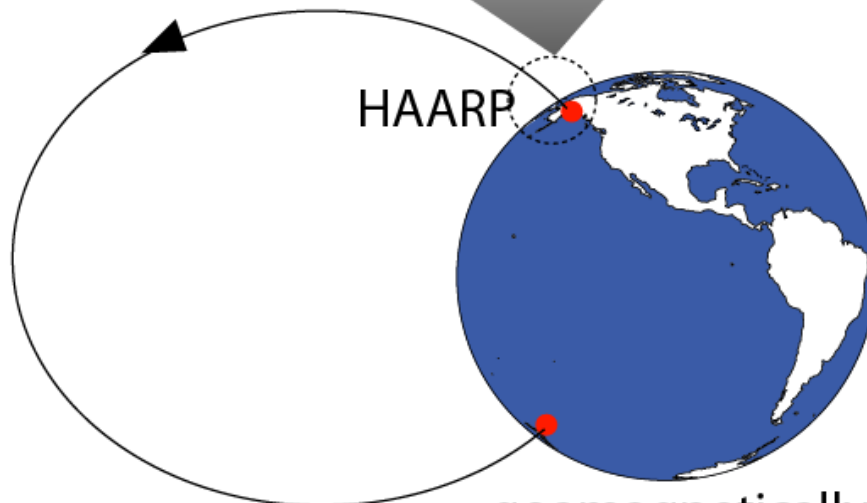
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January 7, 2006



Generation of ELF/VLF waves



injected VLF wave



geomagnetically conjugate point



HAARP

High Frequency Active Auroral Research Program

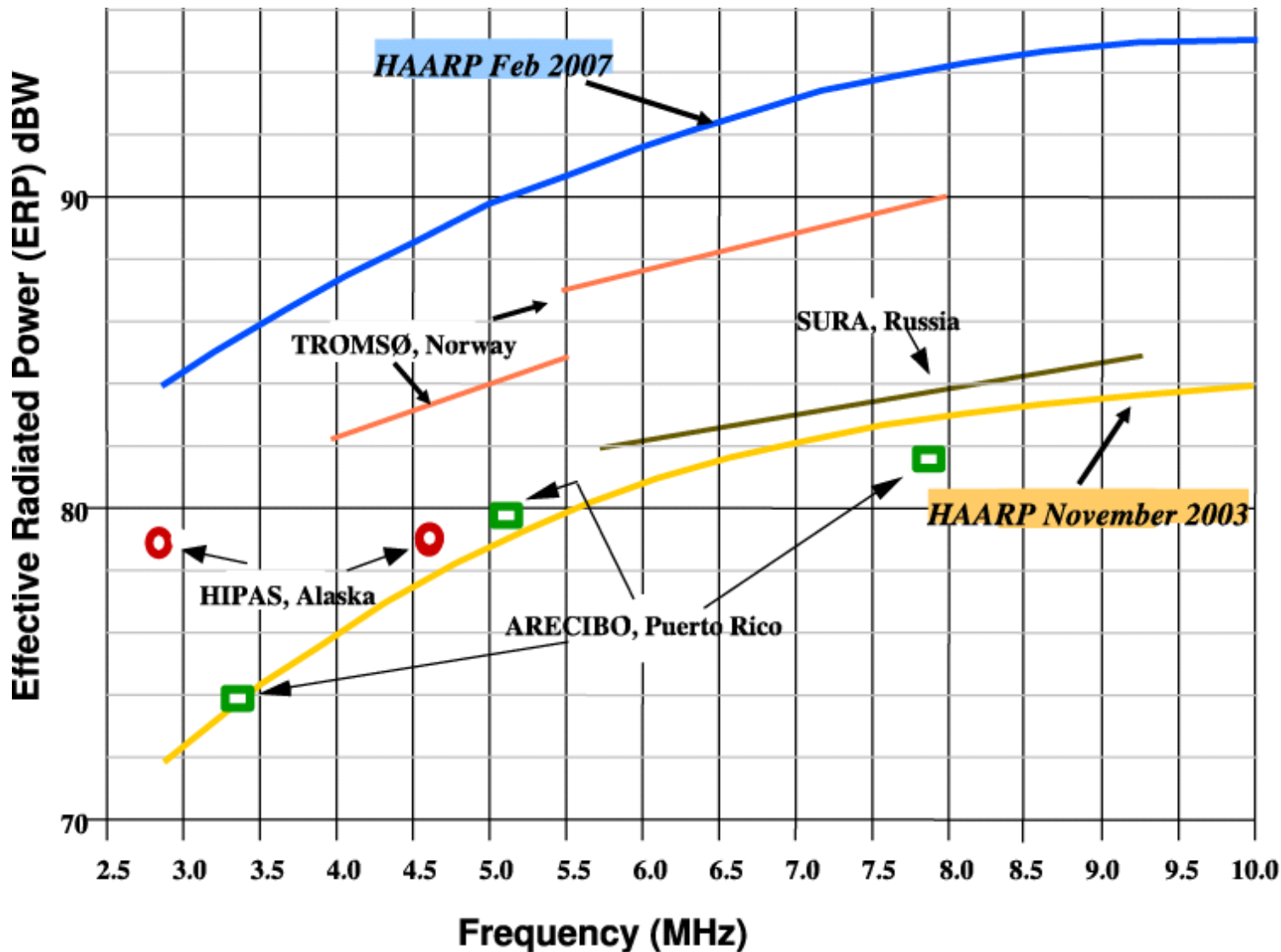


After upgrade in March 2006:

- **180 crossed dipole antennas**
- **3.6 MW power**
- **~2 GW effective radiated HF power (2.8-10 MHz) (lightning has ~20 GW isotropic ERP)**

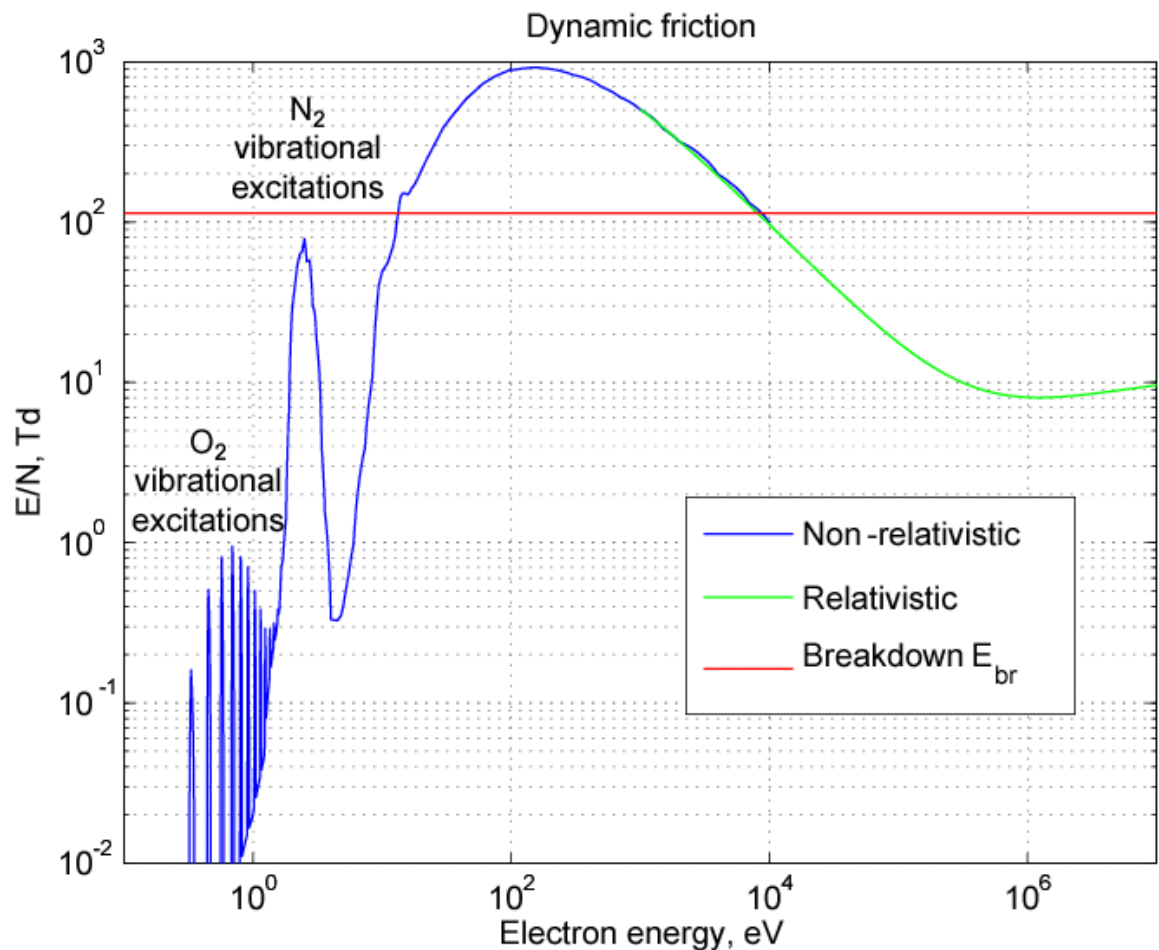


HAARP and other HF heating facilities





Important electron-molecule interaction concept: **Dynamic friction force**



$$F = \sum N \sigma_i(v) \Delta \epsilon_i$$

Inelastic processes:

- Rotational, vibrational, electronic level excitations
- Dissociative losses
- Ionization

$(E/N)_{br} = 130 \text{ Td}$ where $1 \text{ Td} = 10^{-21} \text{ V}\cdot\text{m}^2$



Kinetic Equation Solver (modified ELENDIF)

Time-dependent solution for $f(\mathbf{v},t) = f_0(\mathbf{v},t) + \cos\theta f_1(\mathbf{v},t)$
(almost isotropic)

Physical processes included in ELENDIF:

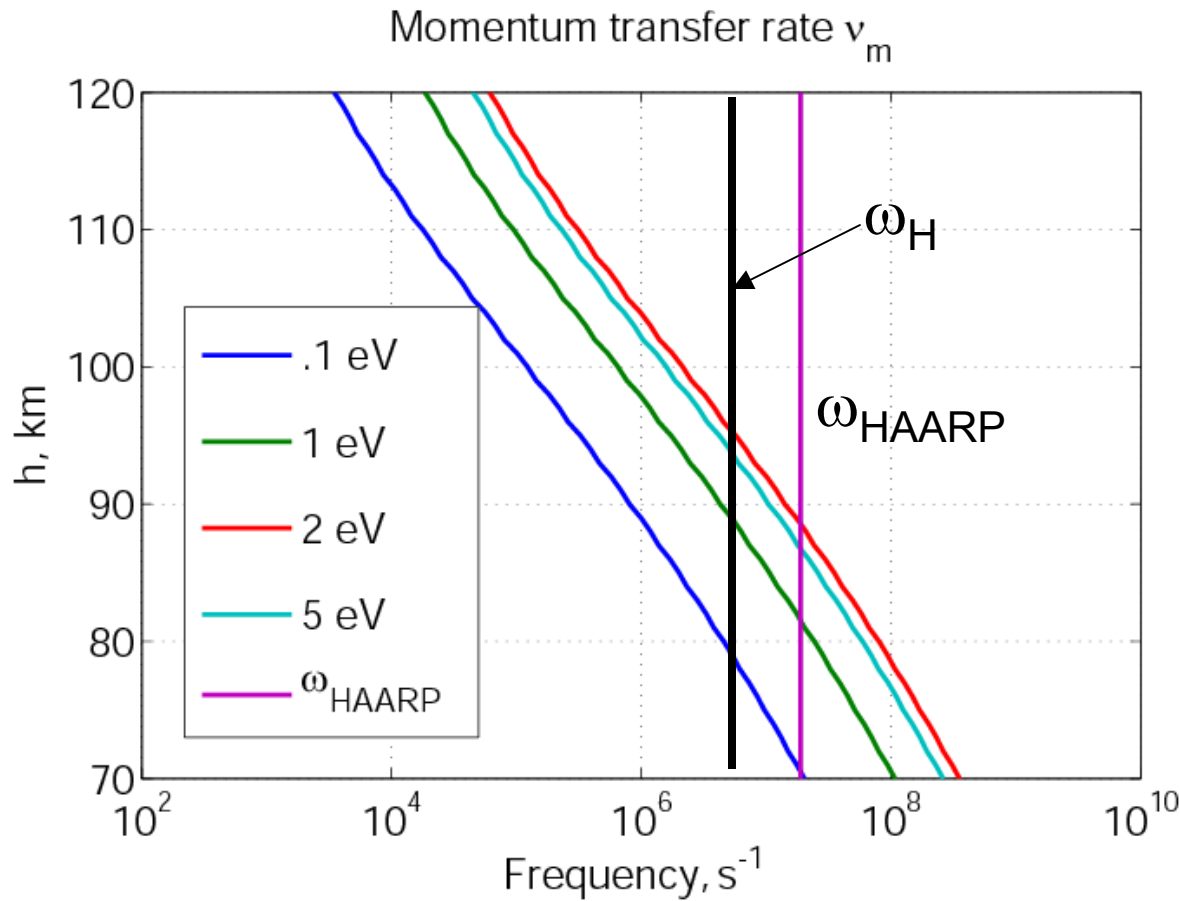
- Quasistatic electric field
- Elastic scattering on neutrals and ions
- Inelastic and superelastic scattering
- Electron-electron collisions
- Attachment and ionization
- Photon-electron processes
- External source of electrons

New:

- Non-static (harmonic) electric field
- Geomagnetic field



Importance of these processes



- The quasistatic approximation used by ELENDF requires $\nu_m \gg \omega$
- Geomagnetic field is also important: $\omega_H \sim 2\pi \times 1 \text{ MHz}$



Analytical solution

- **Margenau distribution**

$$f_0 = C \exp \left[-\frac{3m^3}{4Me^2 E^2 l^2} (v^4 + 2v^2 \omega_{eff}^2 l^2) \right]$$

where $l = v/v_m = (N\sigma_m)^{-1} = \text{const}$

- **Druyvesteyn distribution $\omega=0$**

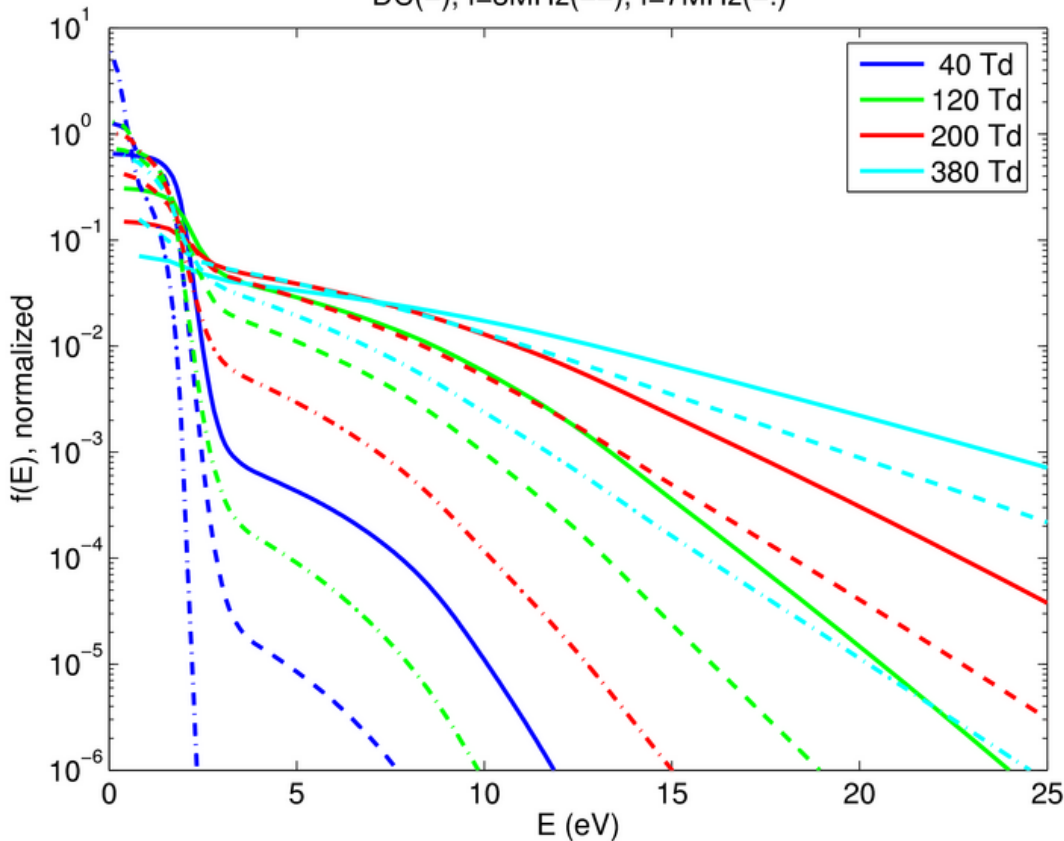
$$f_0 = C \exp \left[-\frac{3m^3 v^4}{4Me^2 E^2 l^2} \right]$$



Calculated electron distributions

Electron distributions for various RMS E/N
(in Td). $f > 0$ corresponds to extraordinary
wave ($f_H = 1$ MHz, $h = 91$ km)

DC(-), $f = 3$ MHz(--), $f = 7$ MHz(-.)



- Effective electric field is smaller than in DC case:

$$E_{eff} = \frac{E}{\sqrt{1 + \left(\frac{\omega_{eff}}{v_{m,eff}}\right)^2}}$$

$$v_{m,eff} / N = 2 \times 10^{-13} s^{-1} m^3$$

$$\omega_{eff} = \omega \pm \omega_H$$

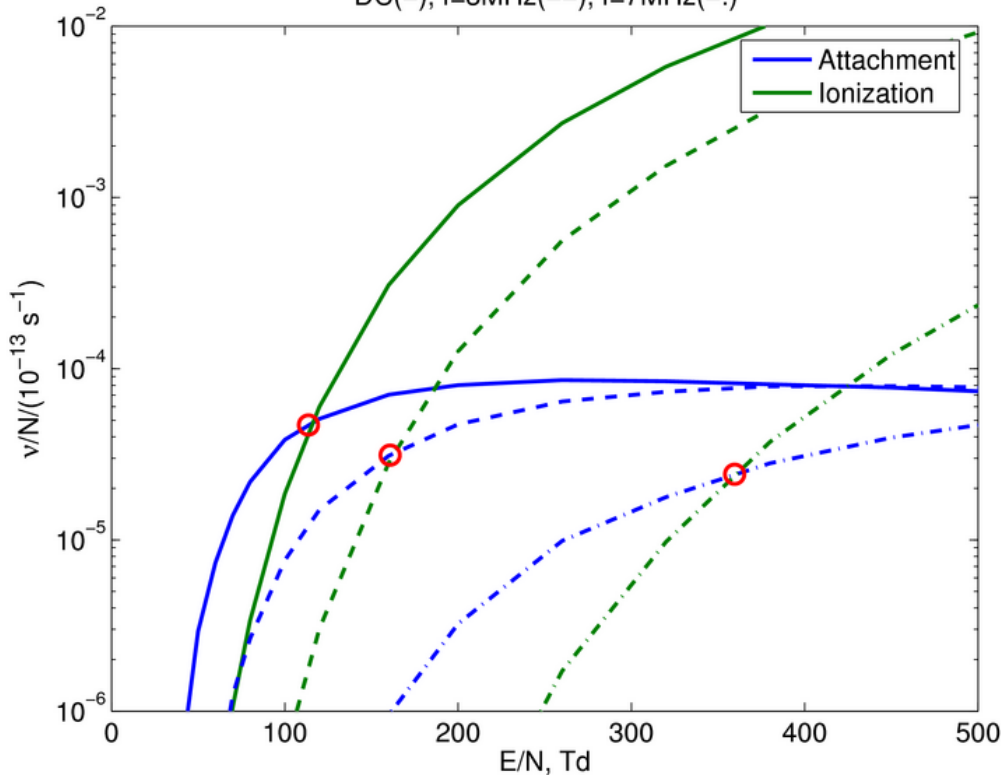
- + ordinary
- extraordinary



Breakdown field (used for the estimate of $v_{m,eff}$)

$h = 91$ km, extraordinary, $f_H = 1$ MHz

DC(-), $f=3$ MHz(--), $f=7$ MHz(-.)



- Breakdown occurs when $v_{ion} > v_{att}$
- The point of breakdown (shown with ●) shifts up in oscillating field

$$\frac{E_{br}}{N} \approx \left(\frac{E_{br}}{N} \right)_{DC} \sqrt{1 + \left(\frac{\omega \pm \omega_H}{N \times 2 \times 10^{-13} \text{ s}^{-1} \text{ m}^3} \right)^2}$$

- $f(v)$ at ionization energy (~ 15 eV) is most important



HF wave propagation

- **Power flux (1D), including losses:**

$$\frac{dS}{dz} = -\alpha(S, z)S$$

$$\alpha = 2 \operatorname{Im} k + \frac{2}{R}$$

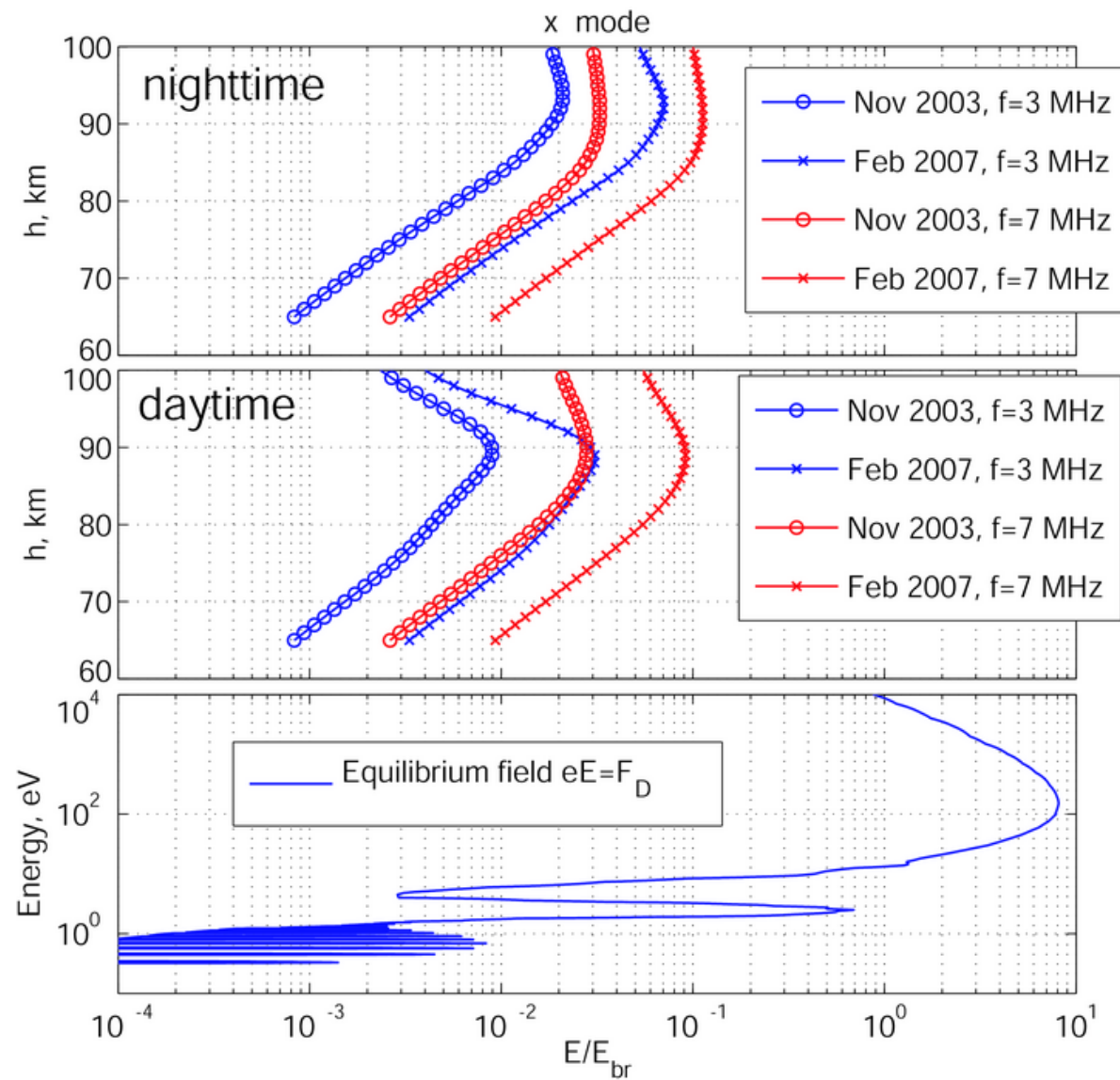
$$k = \frac{\omega}{c} \sqrt{1 + \frac{i\sigma}{\omega\epsilon_0}}$$

- **HF conductivity (ordinary/extaordinary)**

$$\sigma_{o,x} = -\frac{2e^2}{3m} \int \frac{\epsilon^{3/2}}{v_m - i(\omega \pm \omega_H)} \frac{\partial}{\partial \epsilon} \frac{n}{\epsilon^{1/2}} d\epsilon$$



Calculated HF electric field



- Normalized field, E/E_{br} is shown

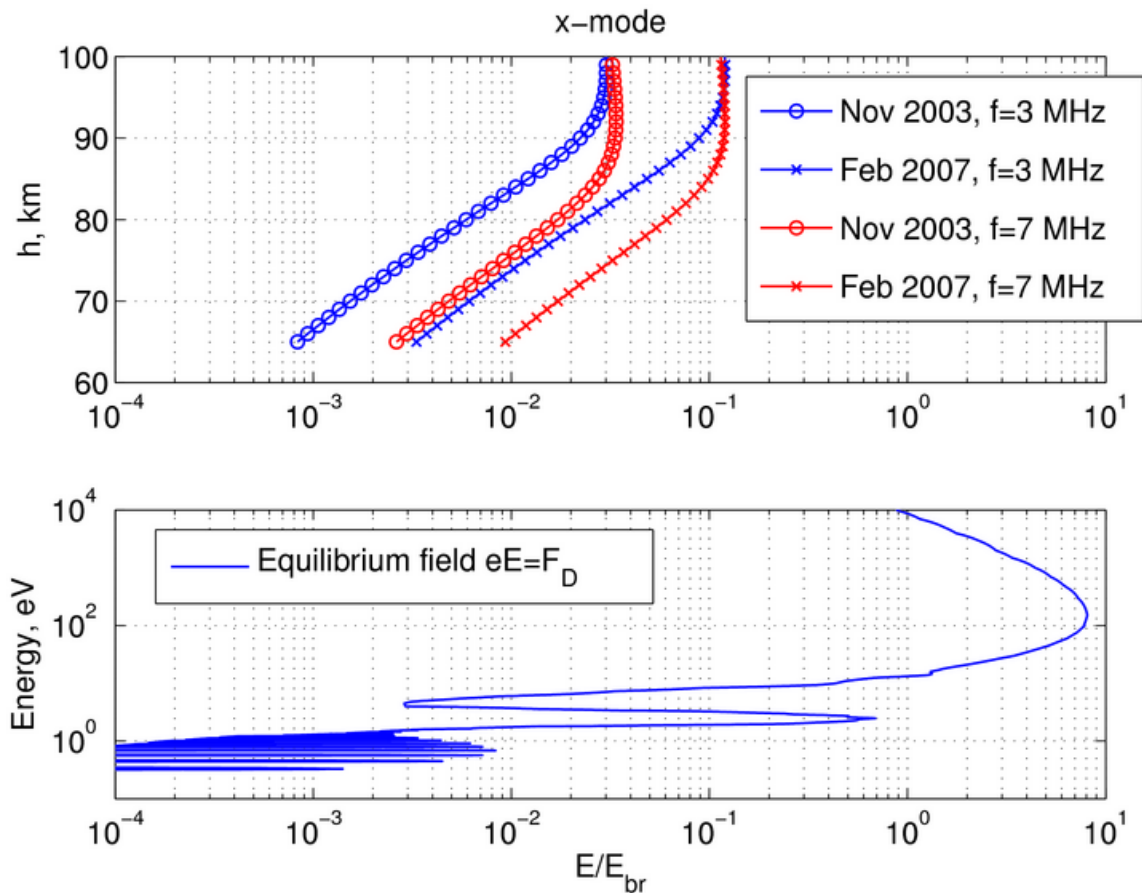
- For comparison, we show the dynamic friction function

- The N_2 vibrational threshold or breakdown field are not exceeded for current or upgraded HAARP power



Is breakdown achievable at all?

Propagation with no absorption

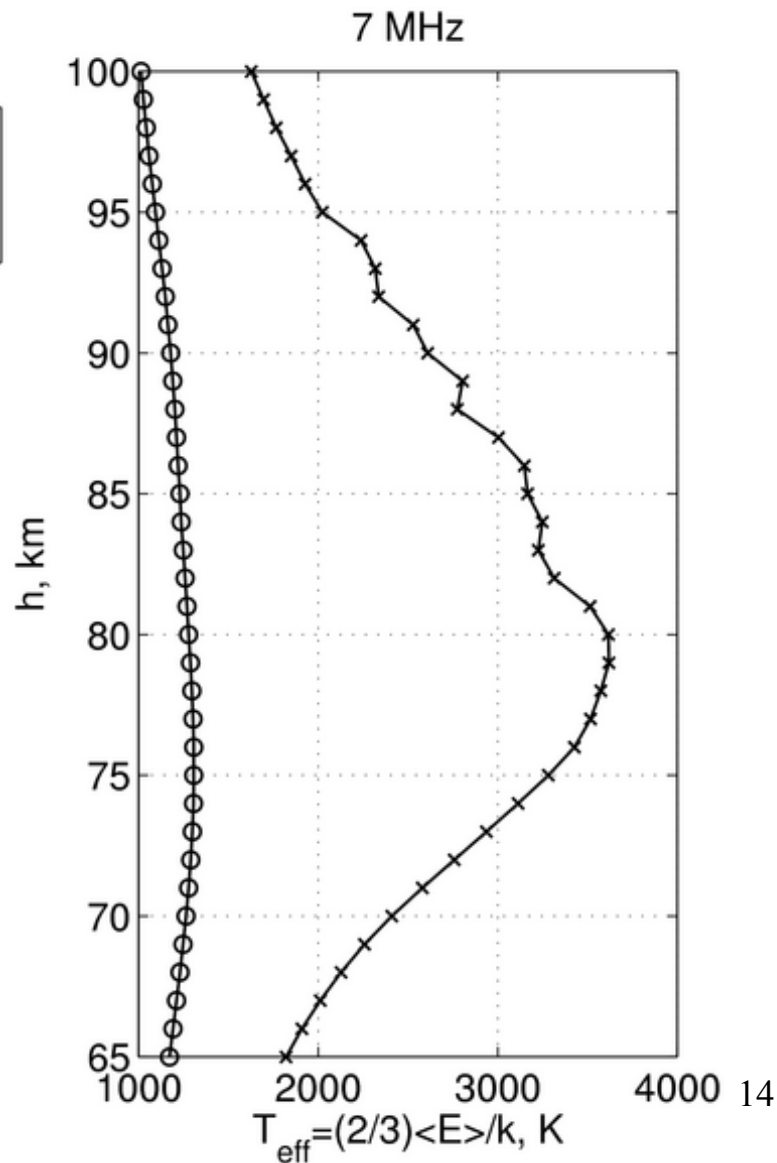
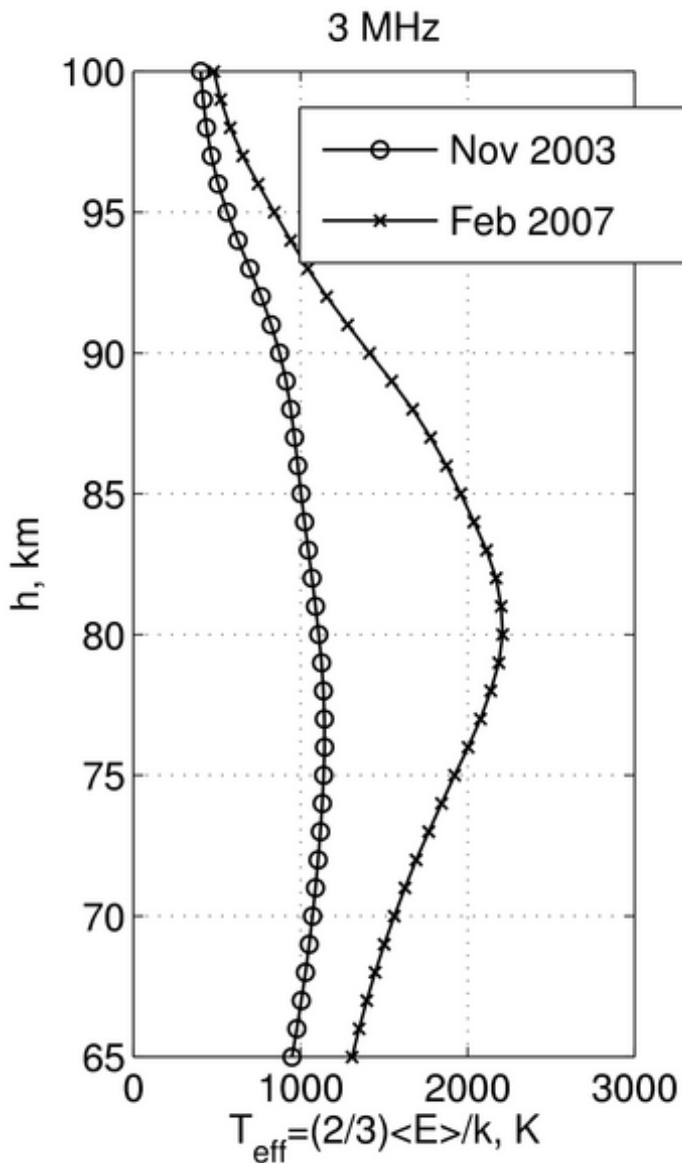


- The electric field can be higher in a non-steady state case
- Electric breakdown field with altitude:
 - Decreases due to thinning atmosphere
 - **But**, increases due to oscillations and magnetization.

$$\frac{E_{br}}{N} \approx \left(\frac{E_{br}}{N} \right)_{DC} \sqrt{1 + \left(\frac{\omega \pm \omega_H}{N \times 2 \times 10^{-13} \text{ s}^{-1} \text{ m}^3} \right)^2}$$



Temperature modification (daytime, x mode)





Comparison of Maxwellian and non-Maxwellian approaches

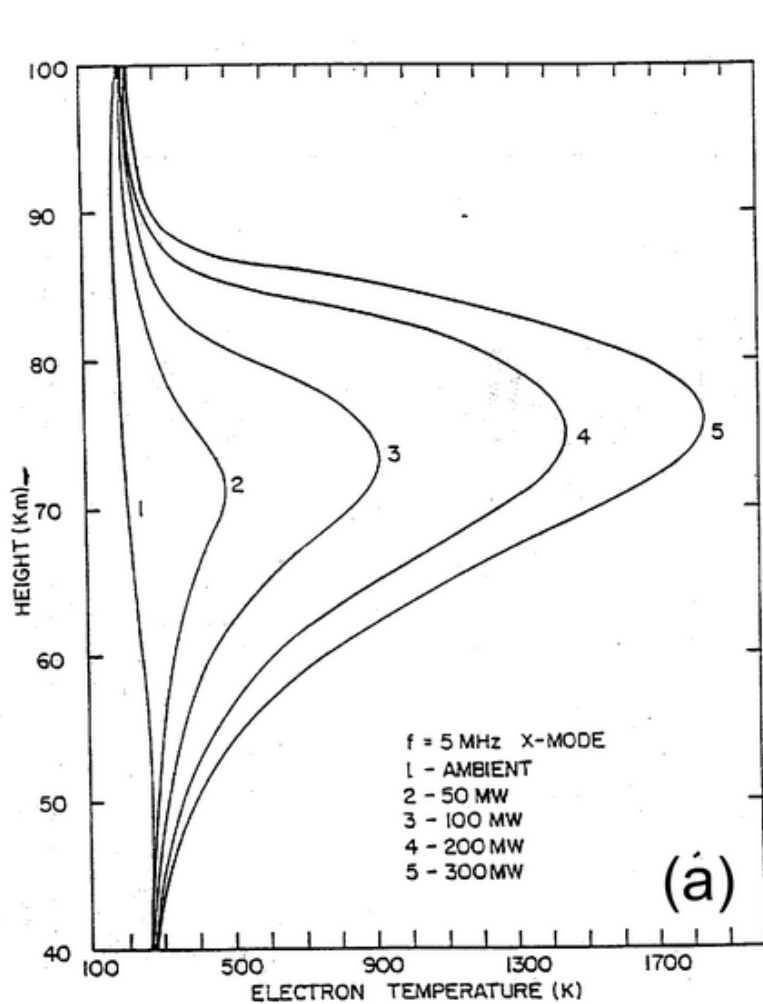
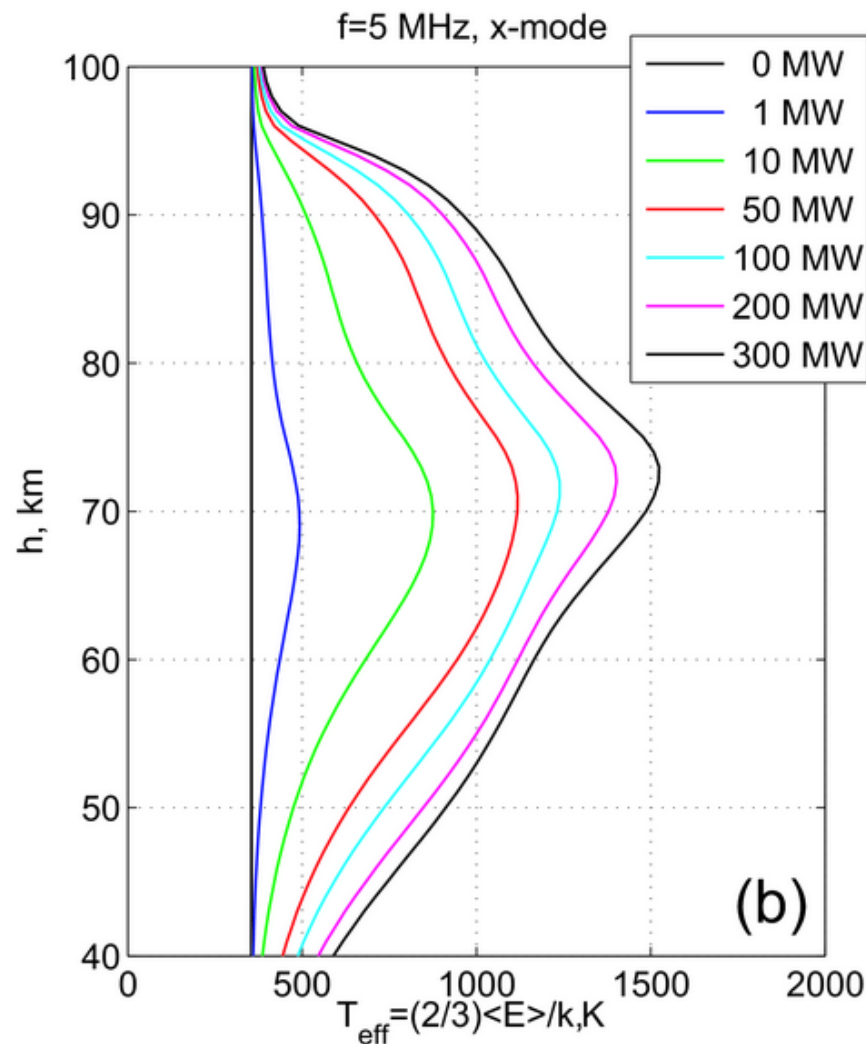


Figure 3.5 - Steady state electron temperature profiles for various heating powers.





DC conductivity changes (for electrojet current)



Conductivity tensor (DC)

- Conductivity changes due to modification of electron distribution
- Approximate formulas were used previously
- Pedersen (transverse)

$$\sigma_p = -\frac{2e^2}{3m} \int \frac{v_m \varepsilon^{3/2}}{\omega_H^2 + v_m^2} \frac{\partial n}{\partial \varepsilon} \frac{1}{\varepsilon^{1/2}} d\varepsilon \approx \frac{N_e e^2}{m} \left\langle \frac{v_m}{\omega_H^2 + v_m^2} \right\rangle$$

- Hall (off-diagonal)

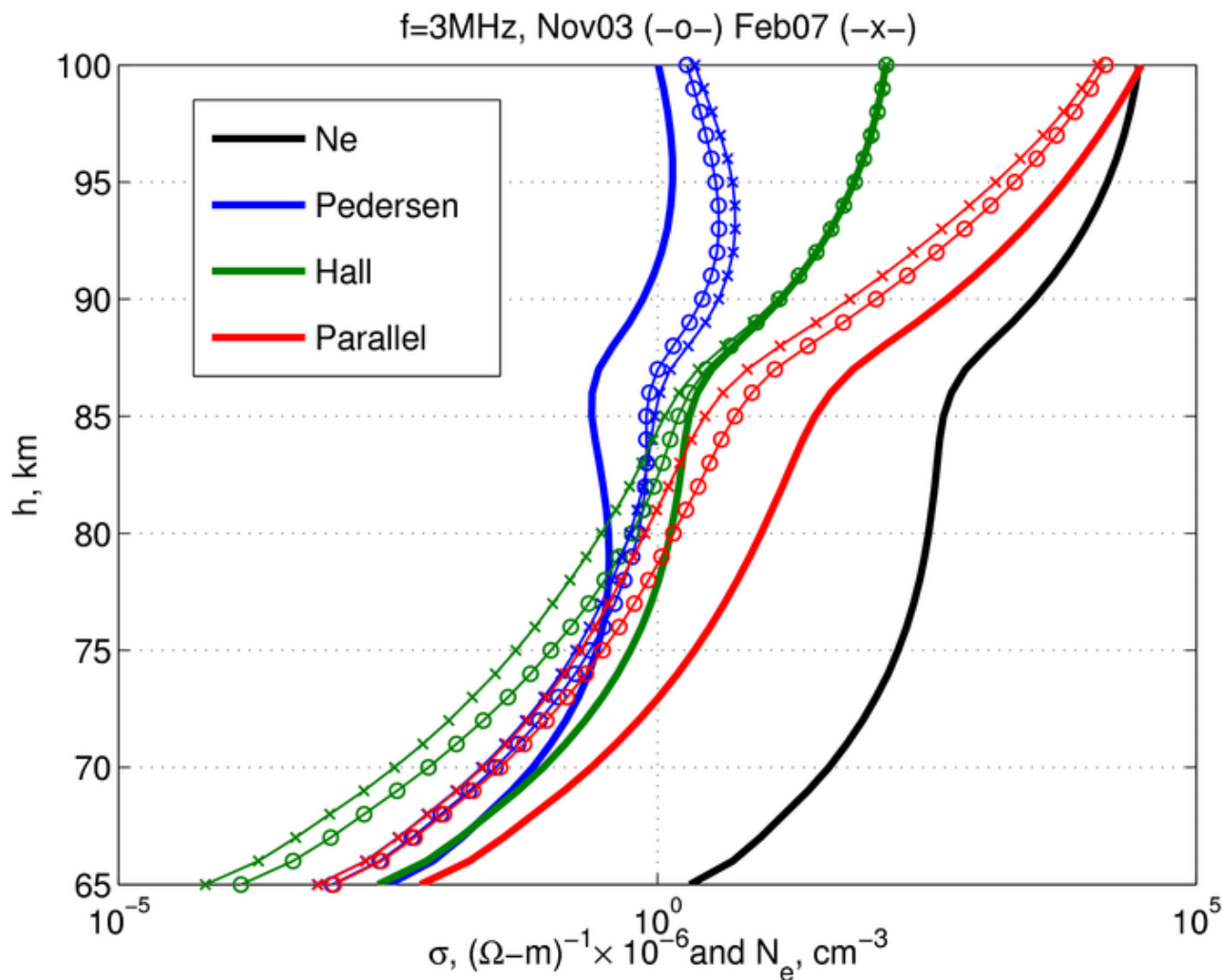
$$\sigma_h = -\frac{2e^2}{3m} \int \frac{\omega_H \varepsilon^{3/2}}{\omega_H^2 + v_m^2} \frac{\partial n}{\partial \varepsilon} \frac{1}{\varepsilon^{1/2}} d\varepsilon \approx \frac{N_e e^2}{m} \left\langle \frac{\omega_H}{\omega_H^2 + v_m^2} \right\rangle$$

- Parallel

$$\sigma_z = -\frac{2e^2}{3m} \int \frac{\varepsilon^{3/2}}{v_m} \frac{\partial n}{\partial \varepsilon} \frac{1}{\varepsilon^{1/2}} d\varepsilon \approx \frac{N_e e^2}{m} \left\langle \frac{1}{v_m} \right\rangle$$



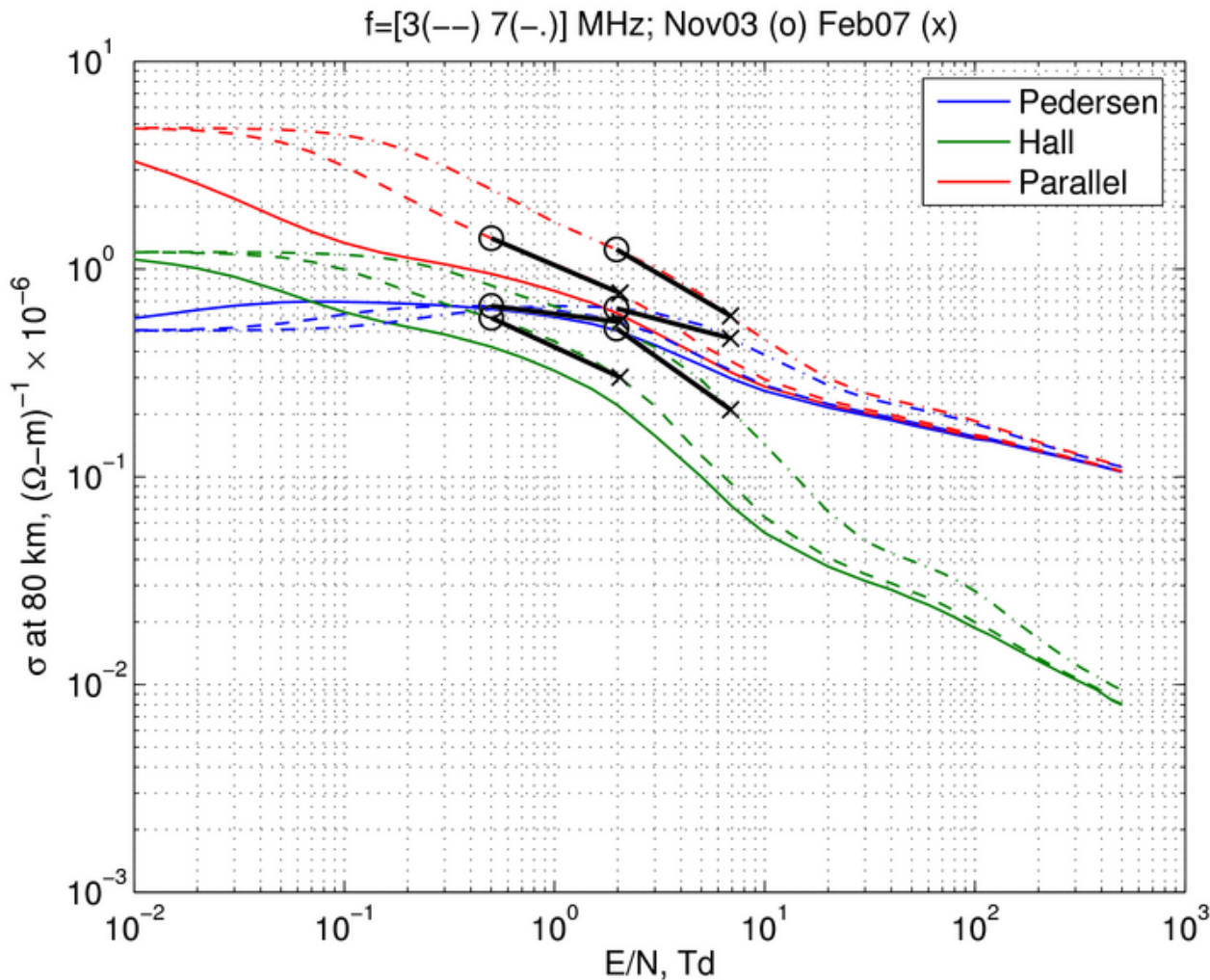
Conductivity modification



- Pedersen conductivity is increased
- Parallel conductivity is decreased



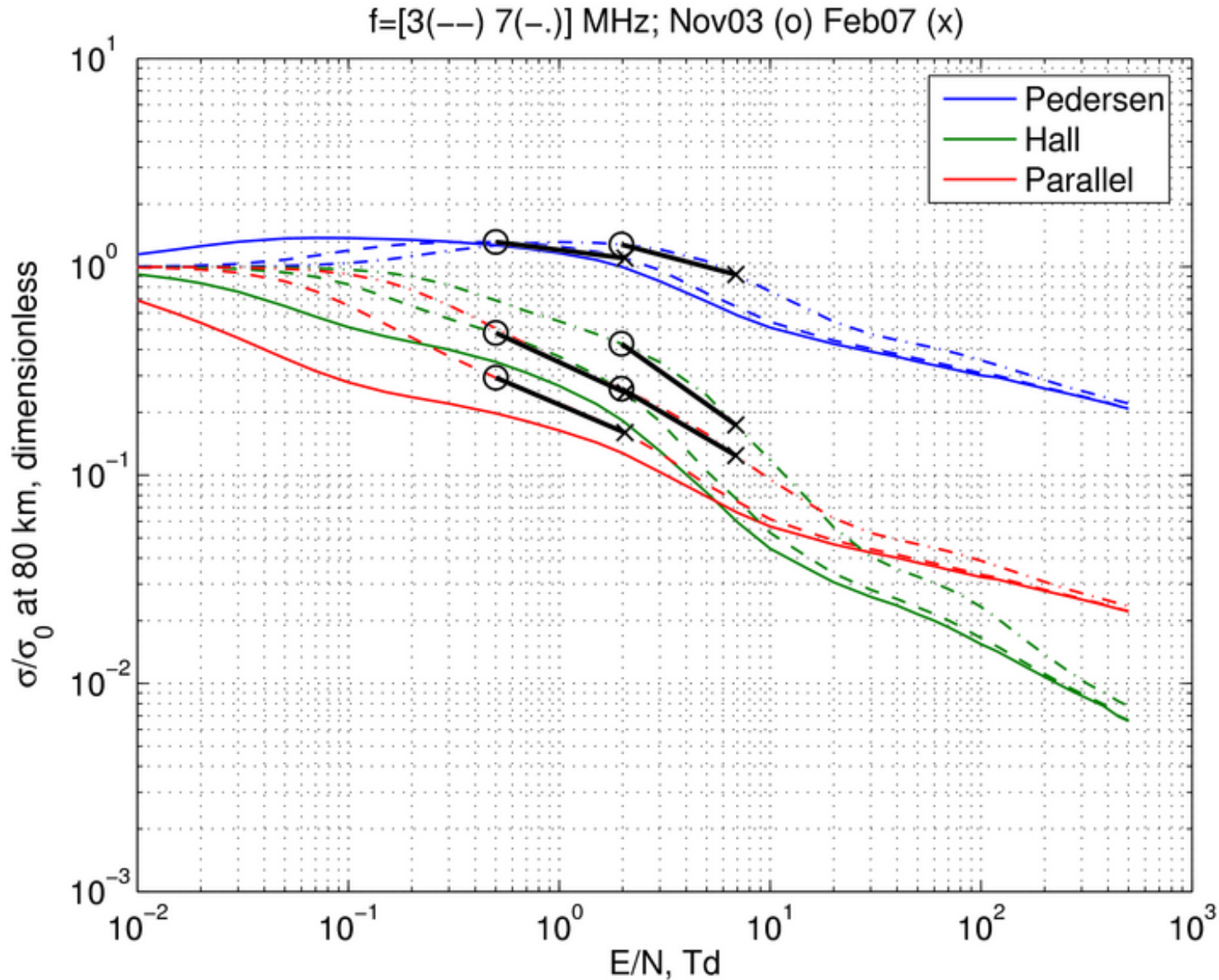
Conductivity as a function of E/N (x-mode, h=80 km, f=0,3,7 MHz)



- Solid line shows conductivity modifications by DC field
- Black intervals connect the conductivities modified by maximum HAARP heating before and after upgrade



Relative change of conductivity

$$\sigma(E)/\sigma(E=0)$$




Electric current calculations

- In most previous works, it is assumed that the electrojet field $E_{ej} = \text{const} \Rightarrow$ inaccurate at low frequencies (no account for the accumulation of charge)
- We assume static current, i.e.

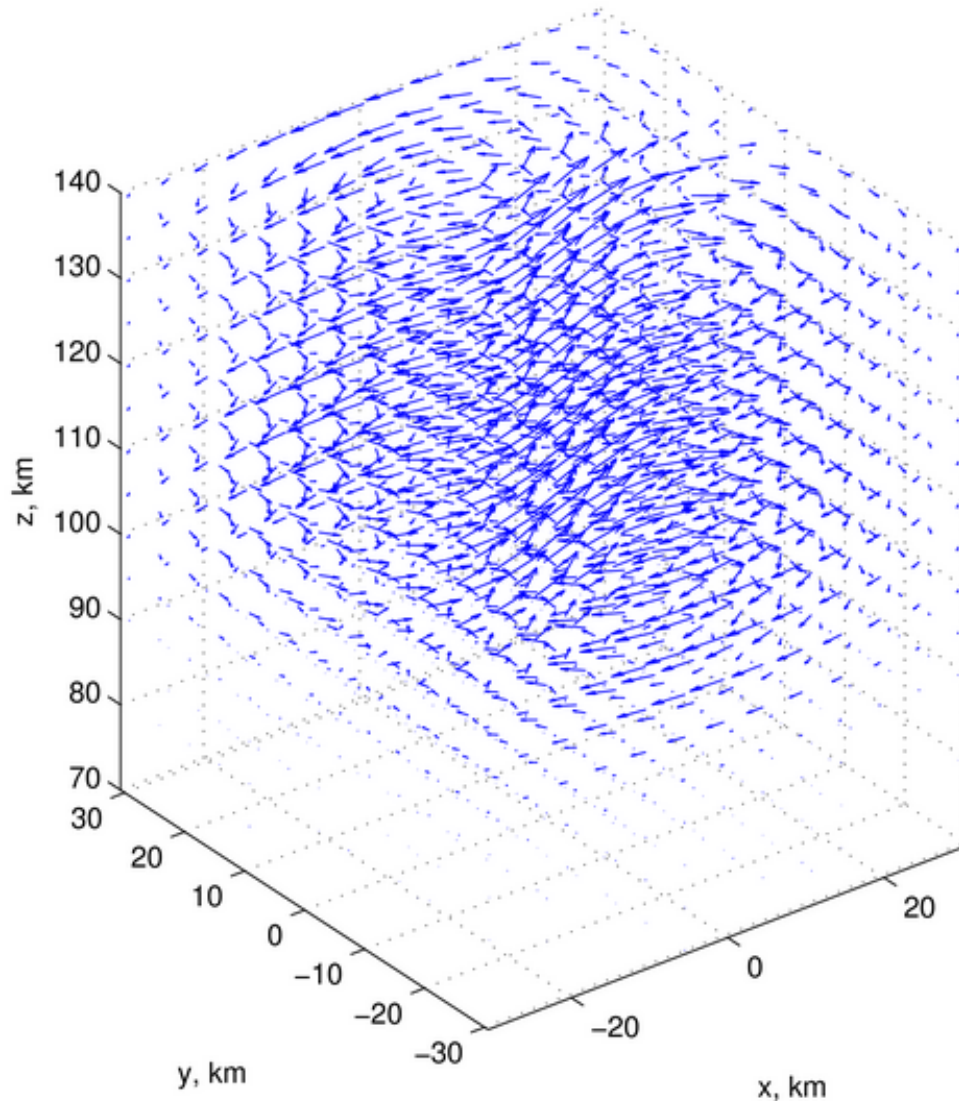
$$\vec{J} = -\vec{\sigma} \nabla \varphi$$

$$\nabla \cdot \vec{J} = 0$$



3D stationary ΔJ

x-mode; f=3 MHz; Feb 2007

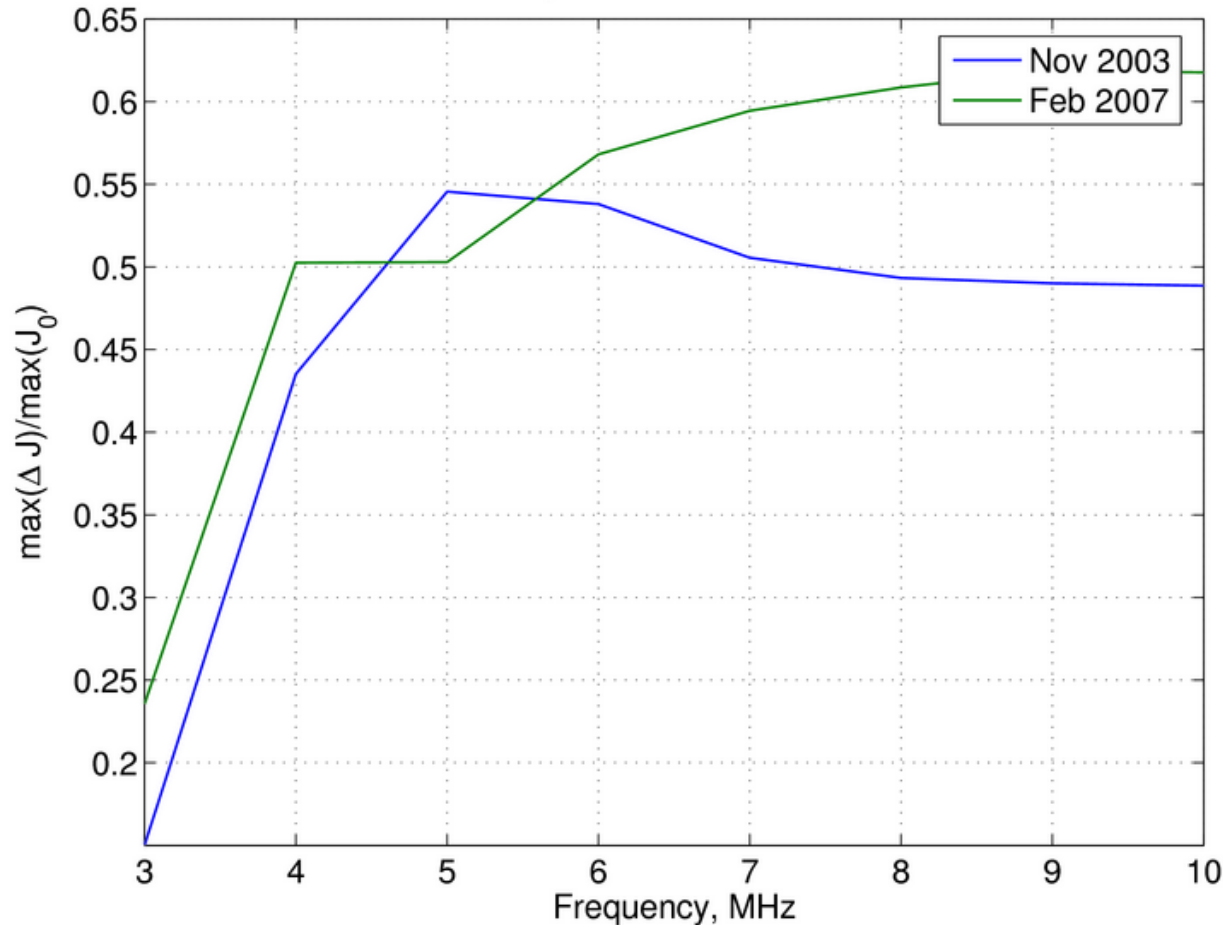


- **Vertical B**
- **Ambient E is along x**
- **Ambient current is mostly along y**
- **Models with $\Delta E=0$ do not consider closing side currents**
- **$\max \Delta J/J_0 \sim 0.3$ for this case**



Calculated $\Delta J/J_0$ for various frequencies

x-mode, max occurs at $h=109$ km



- Range 70-130 km
- Modified region radius ~ 10 km before upgrade and ~ 5 km after upgrade
- Calculated maximum current and its modification occur at ~ 109 km



Conclusions

- **Our model includes both:**
 - **Non-Maxwellian electron distribution**
 - **Self-absorption**
- **Maxwellian electron distribution models, which calculate ΔT_e , cannot account for the nonlinear T_e saturation.**
- **The non-Maxwellian model allows to calculate processes for which high-energy tail of the electron distribution is important, such as:**
 - **optical emissions**
 - **breakdown processes.**



Work in progress

- **Electrojet current modulation in non-static case**
- **ELF/VLF emission**
- **ELF/VLF wave propagation along the geomagnetic field line**