Ionospheric modification and ELF/VLF wave generation by HAARP

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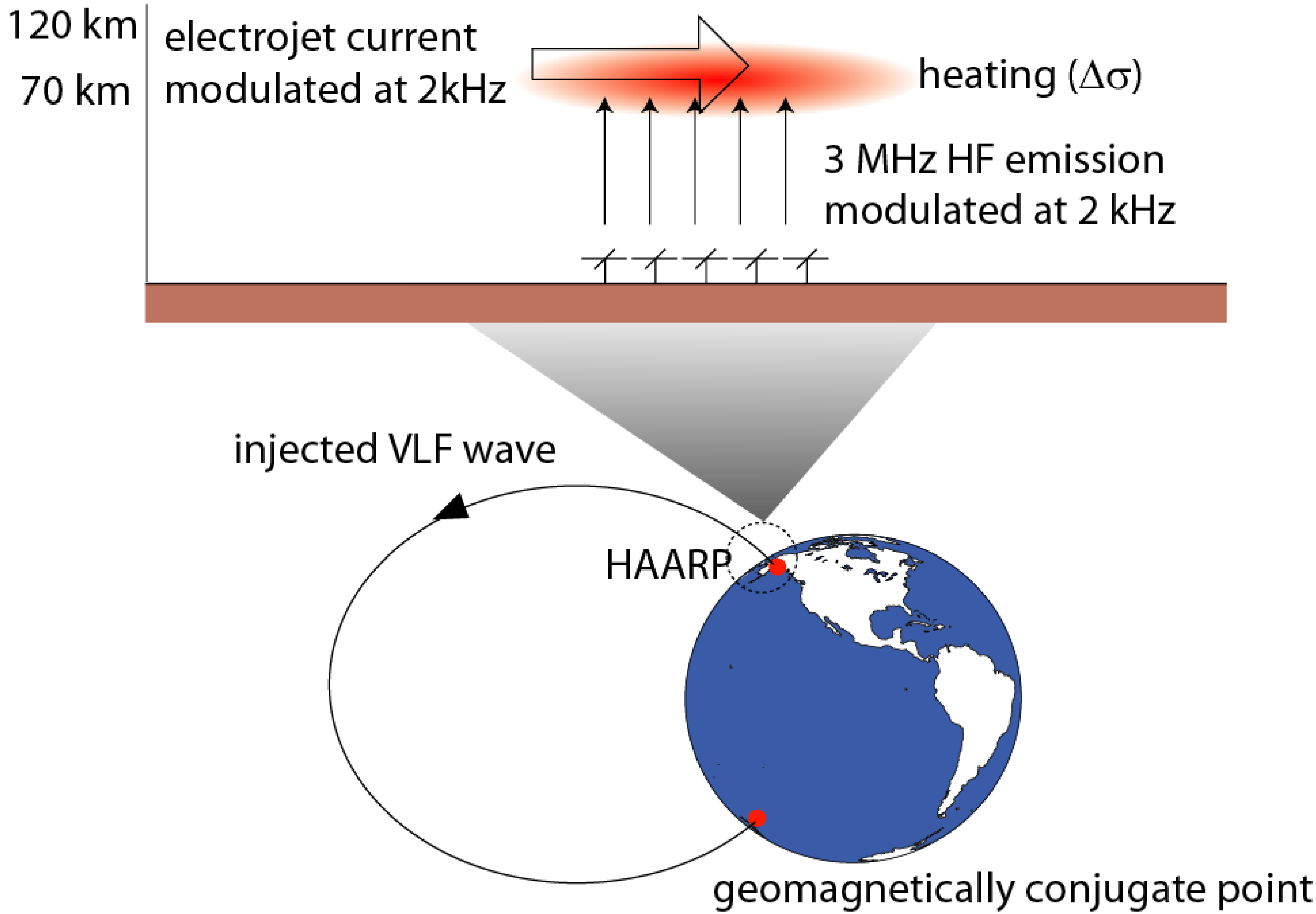
Generation of ELF/VLF waves



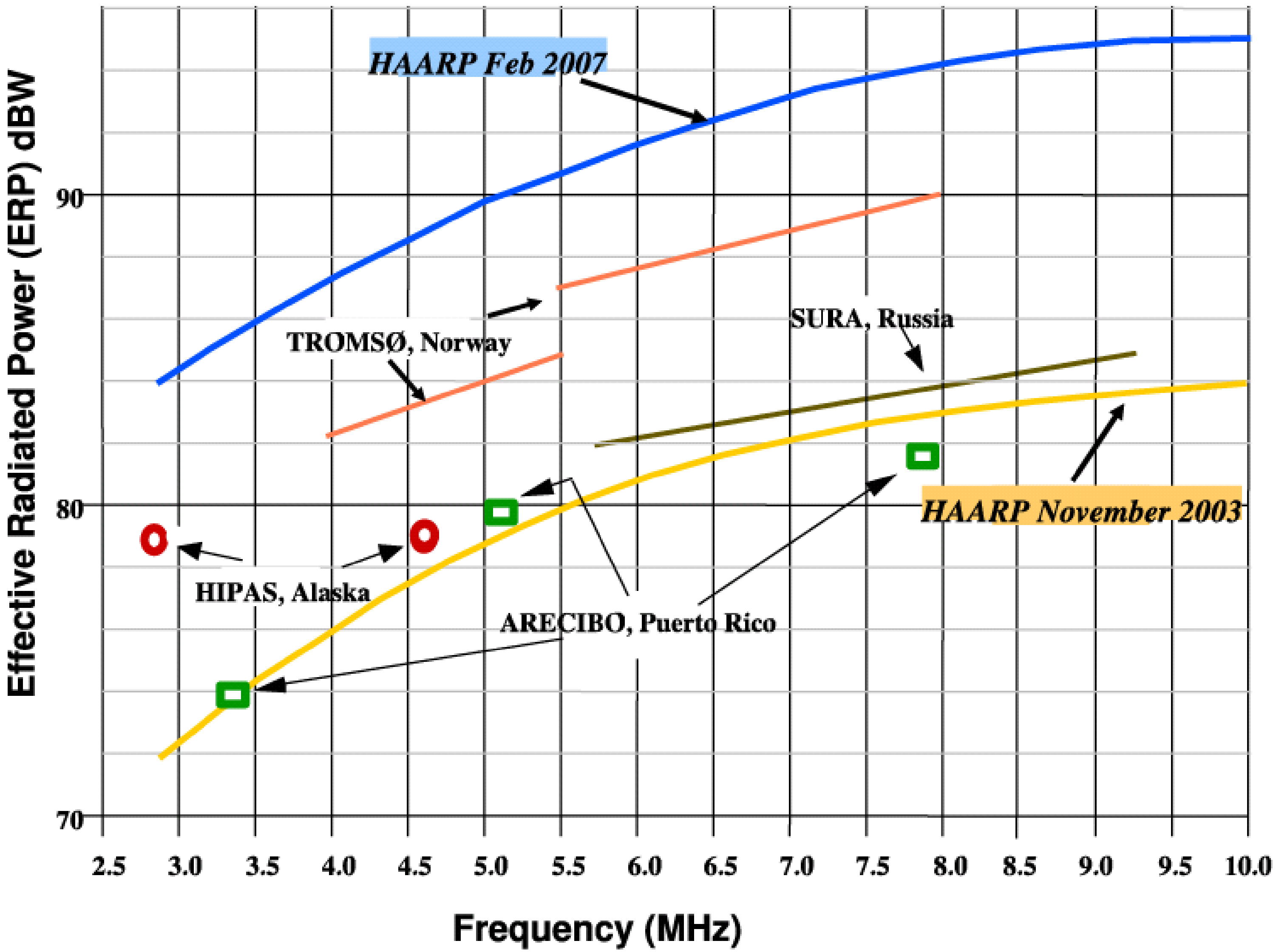
HAARP

High Frequency Active Auroral Research Program

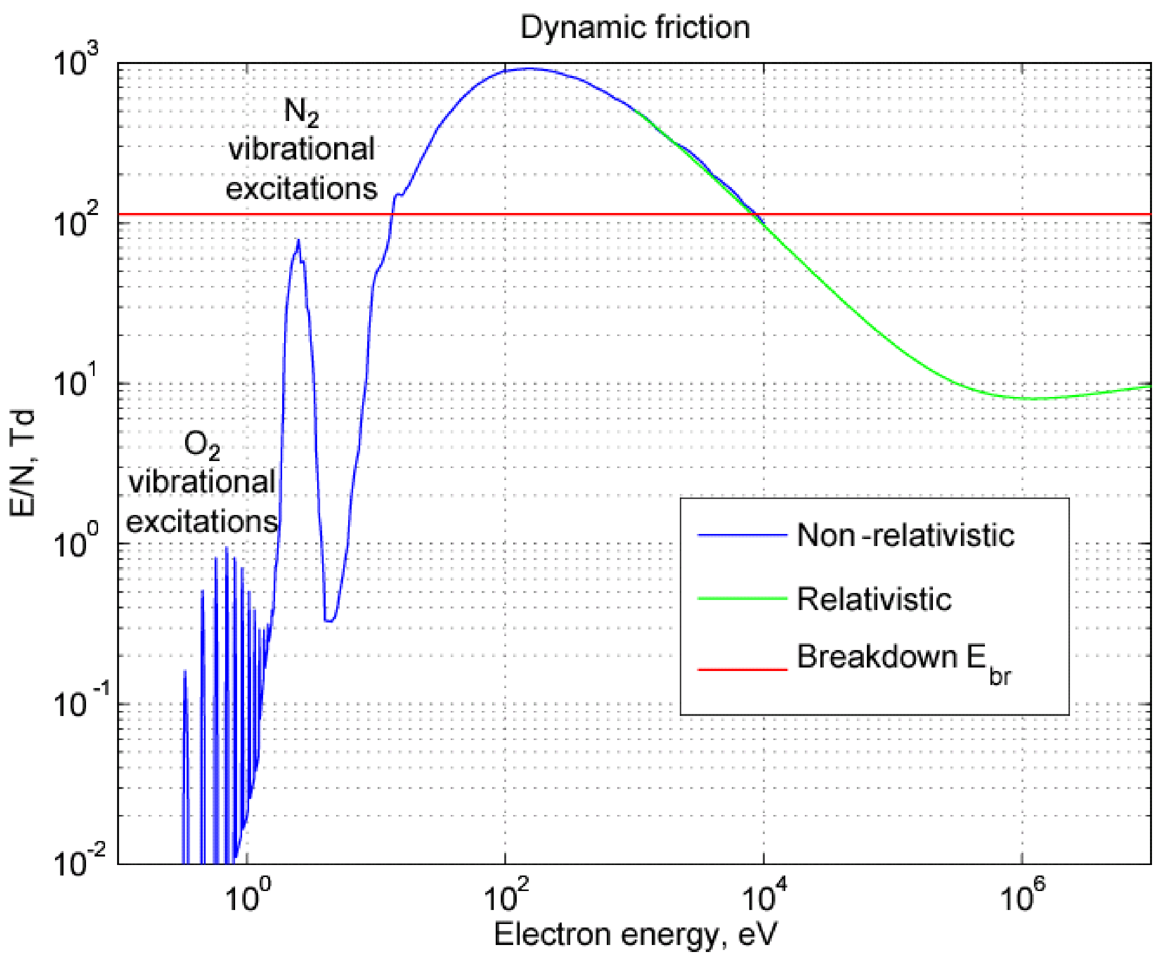
After upgrade in March 2006:

- **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



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

Inelastic processes:

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

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

Kinetic Equation Solver (modified ELENDIF)

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

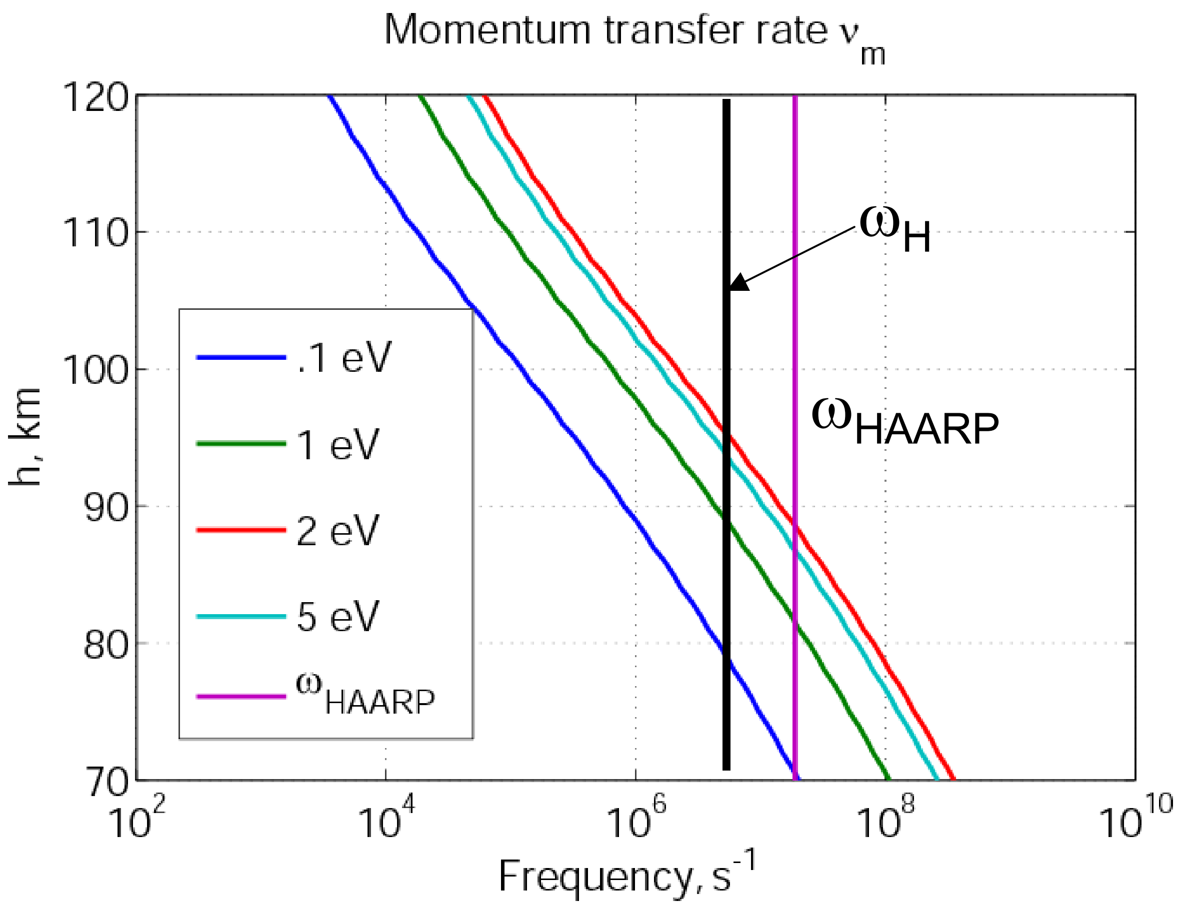
Physical processes inluded in ELENDIF:

- 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 ELENDIF requires $\nu_m >> \omega$**
- **Geomagnetic field is also important: $\omega_H \sim 2\pi$ x 1 MHz**

Analytical solution

- **Margenau distribution**

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

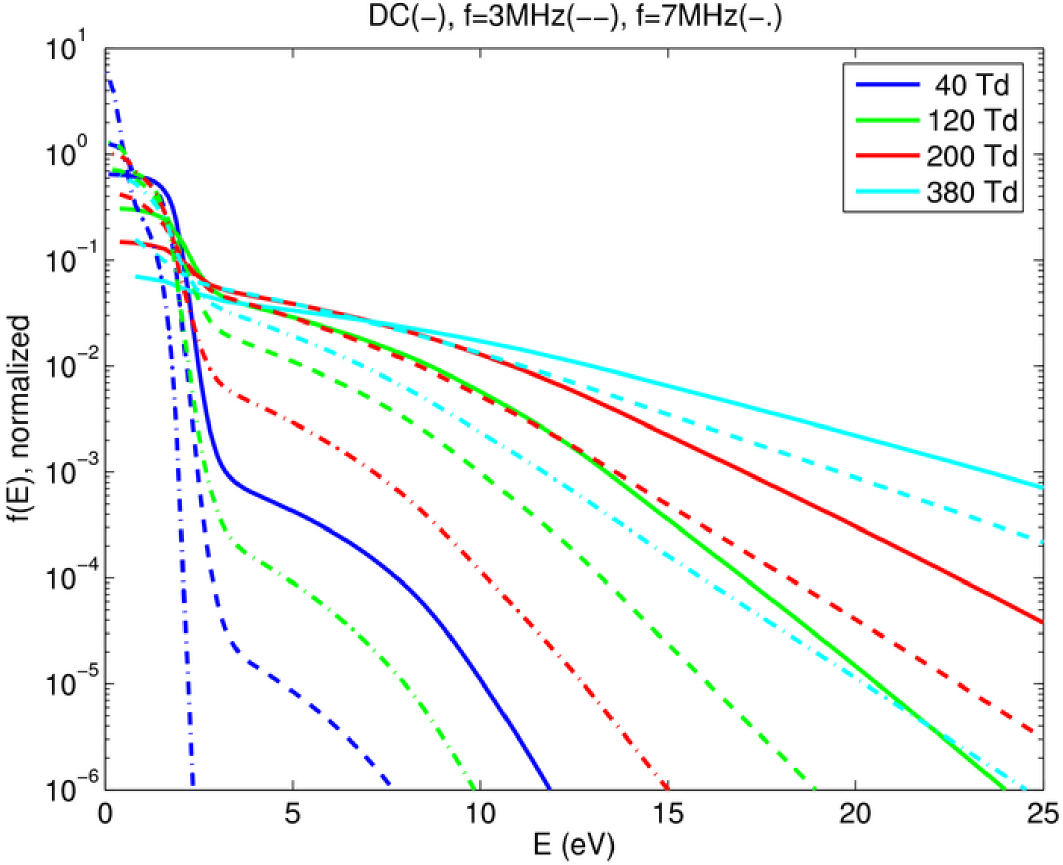
where $l = v/\nu_m = (N\sigma_m)^{-1} = const$

- **Druyvesteyn distribution** ω**=0**

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

Calculated electron distributions

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



- **Effective electric field is smaller than in DC case:**

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

$$\nu_{m,eff} / N = 2\times10^{-13} s^{-1} m^3$$

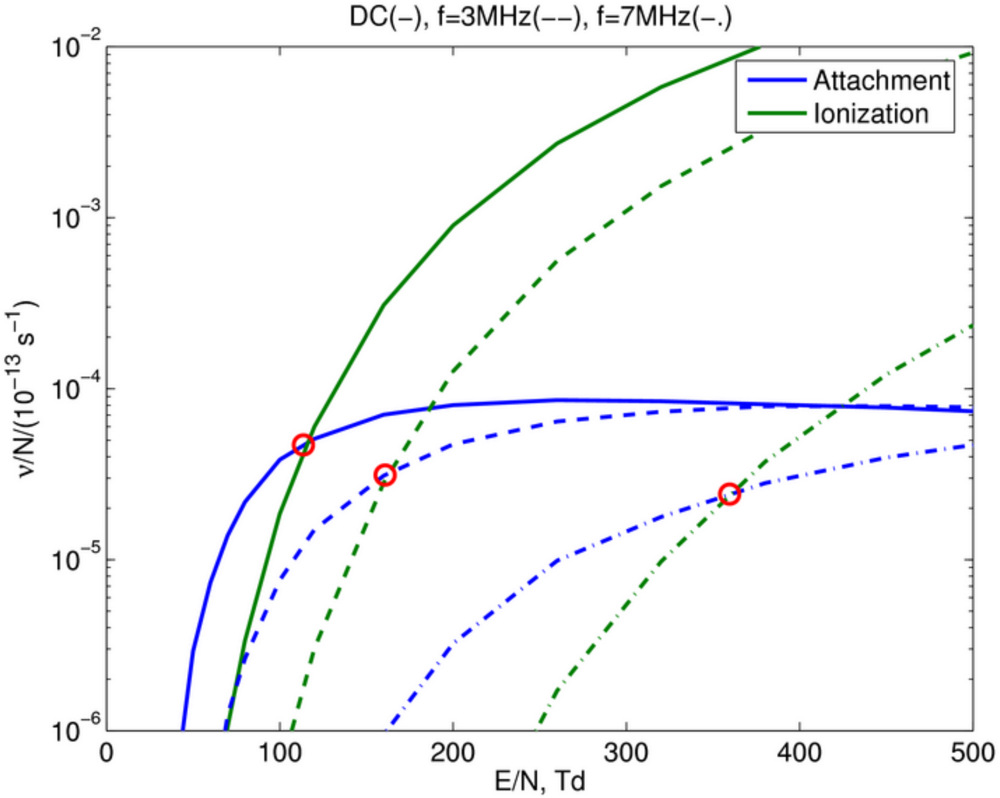
$$\omega_{eff} = \omega \pm \omega_H$$

+ ordinary

- extraordinary

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

h = 91 km, extraordinary, f_H=1 MHz



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

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

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

HF wave propagation

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

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

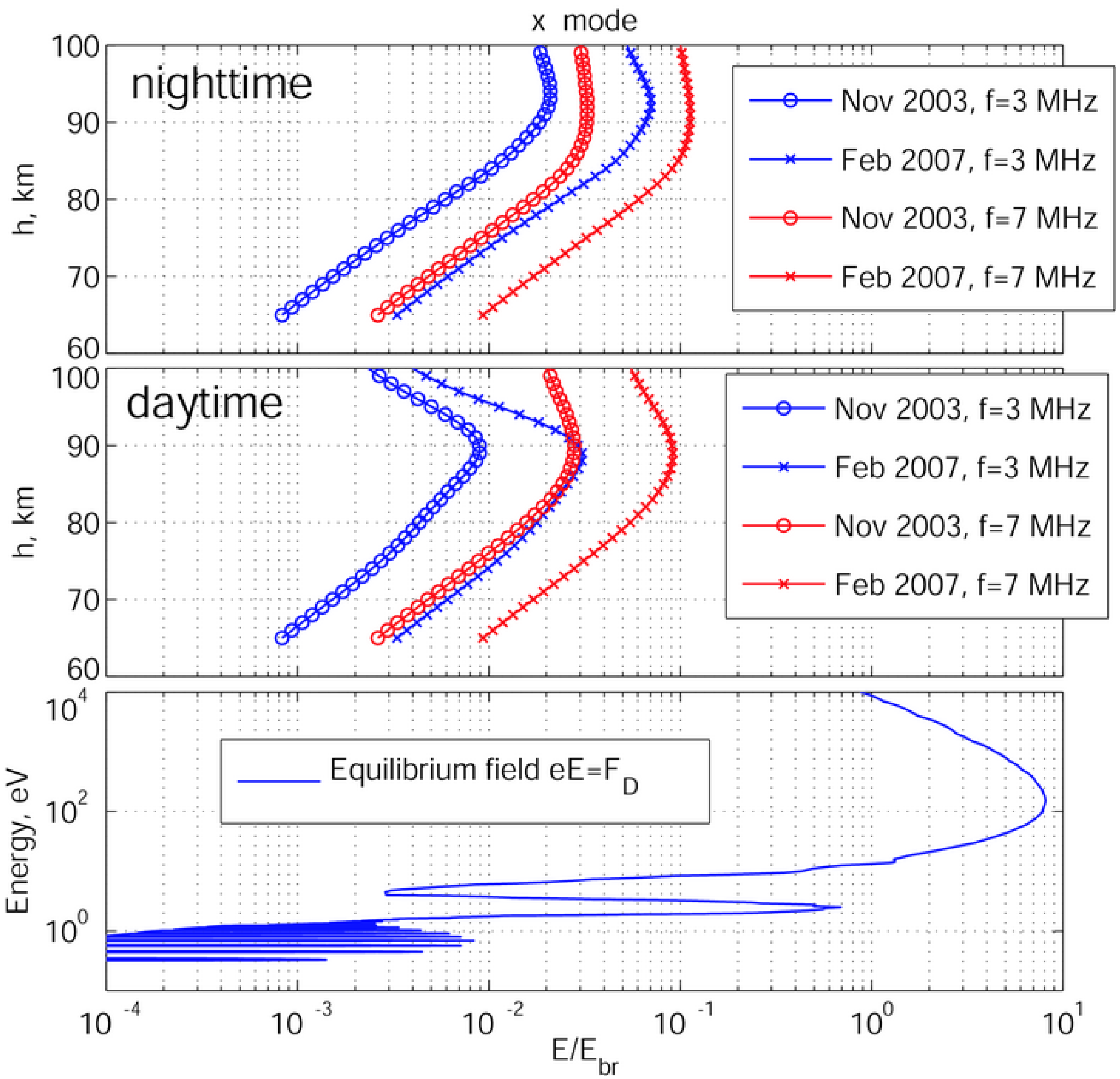
$$\alpha = 2\,\mathrm{Im}\,k + \frac{2}{R}$$

$$k = \frac{\omega}{c}\sqrt{1 + \frac{i\sigma}{\omega\varepsilon_0}}$$

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

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

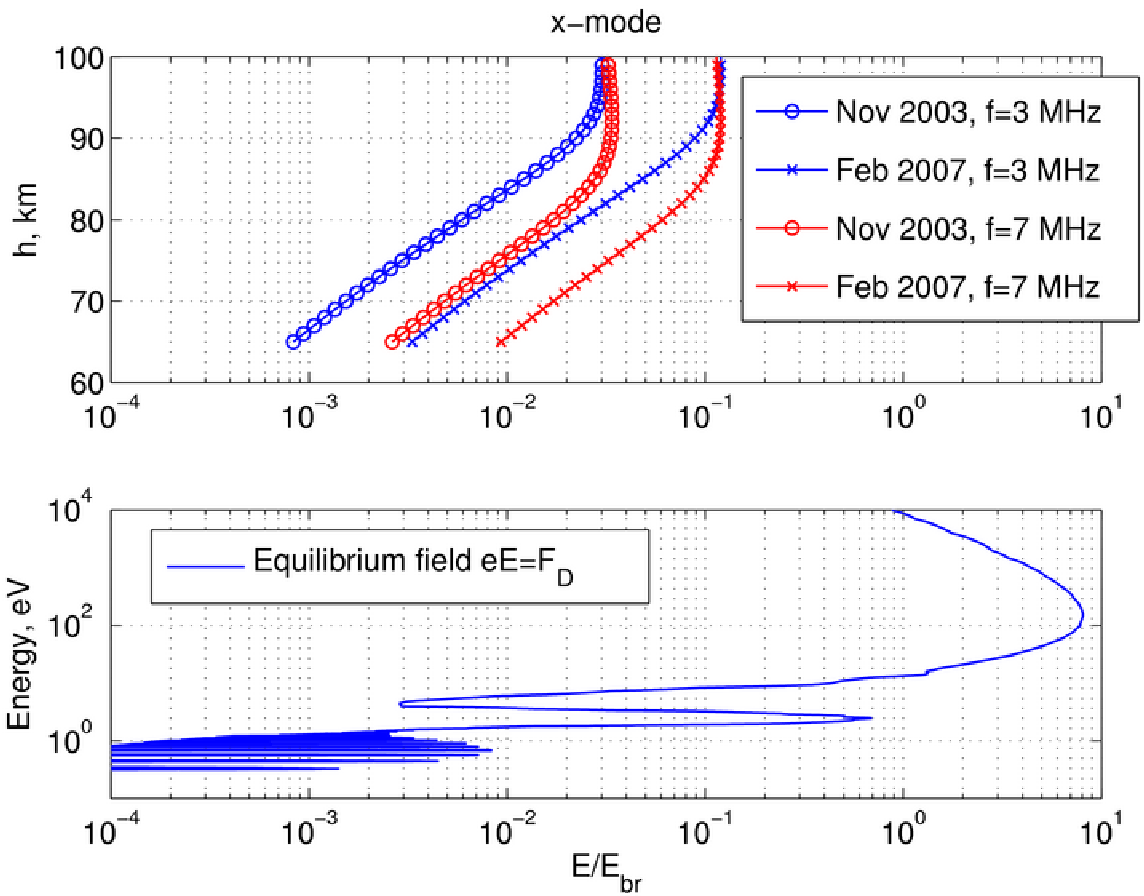
Calculated HF electric field



- **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?

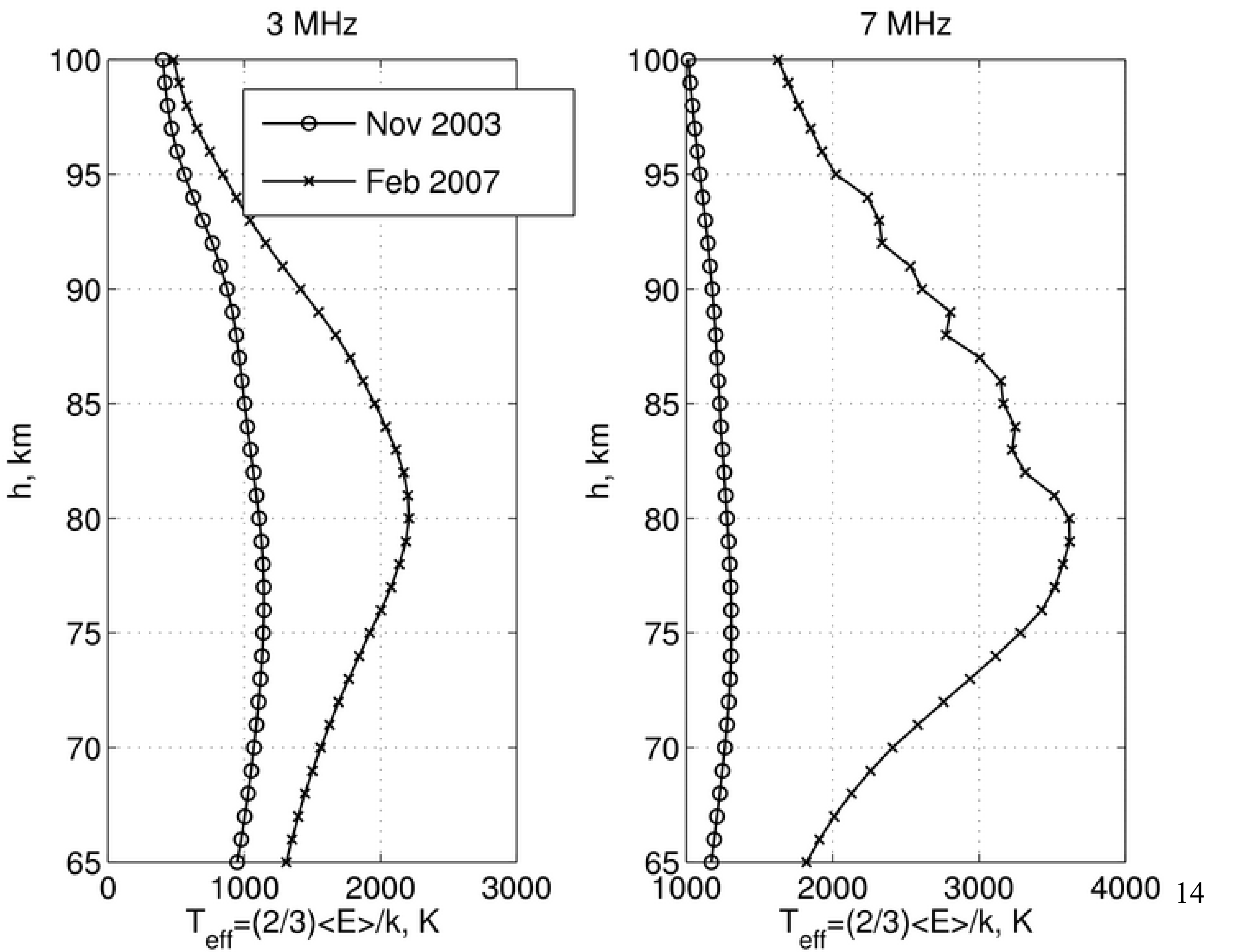
Propagation with no absorption



- **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.**

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

Temperature modification (daytime, x mode)



Comparison of Maxwellian and non-Maxwellian approaches

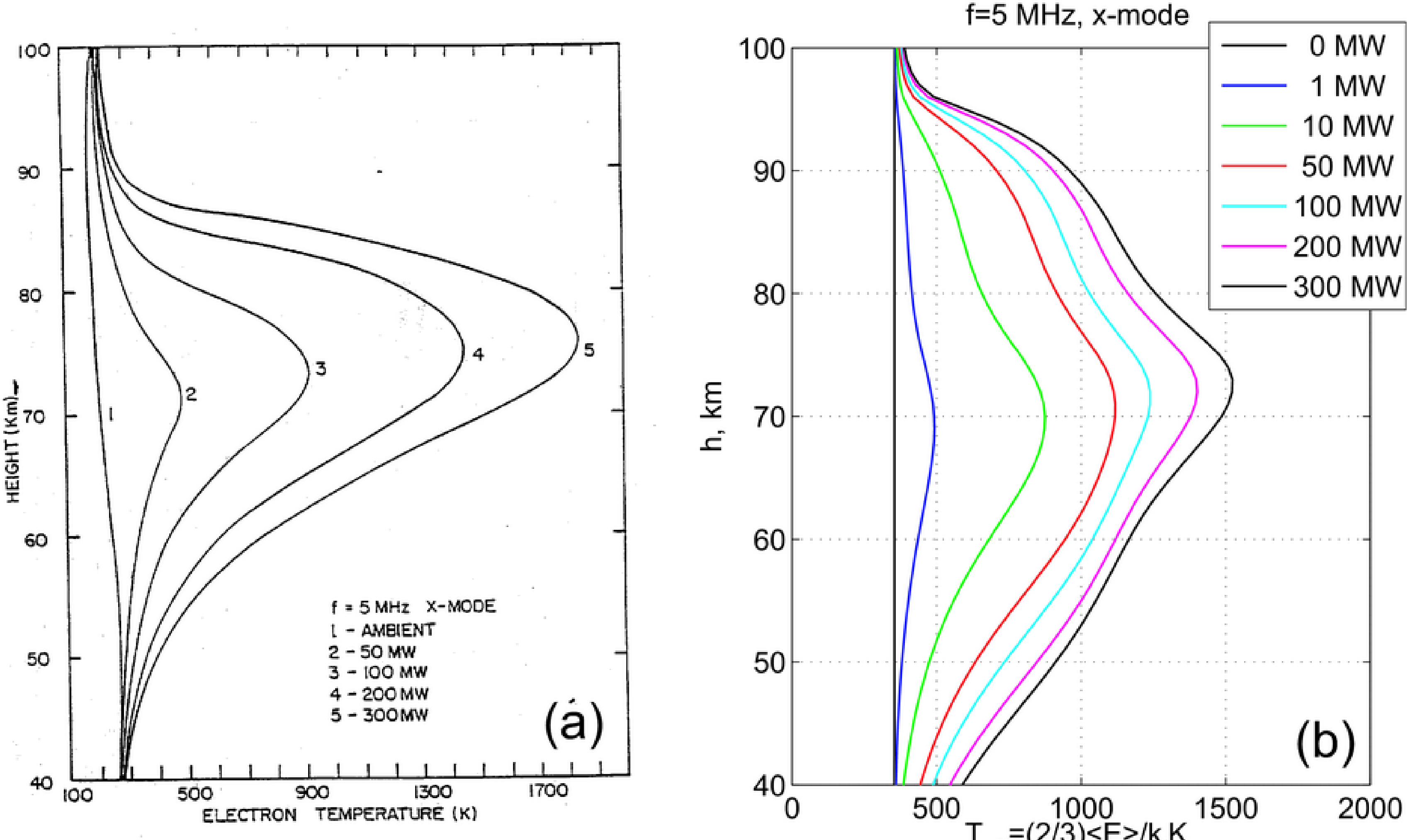


Figure 3.5 - Steady state electron temperature profiles for various heating powers.

DC conductivity changes (for electrojet current)

Conductivity tensor (DC)

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

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

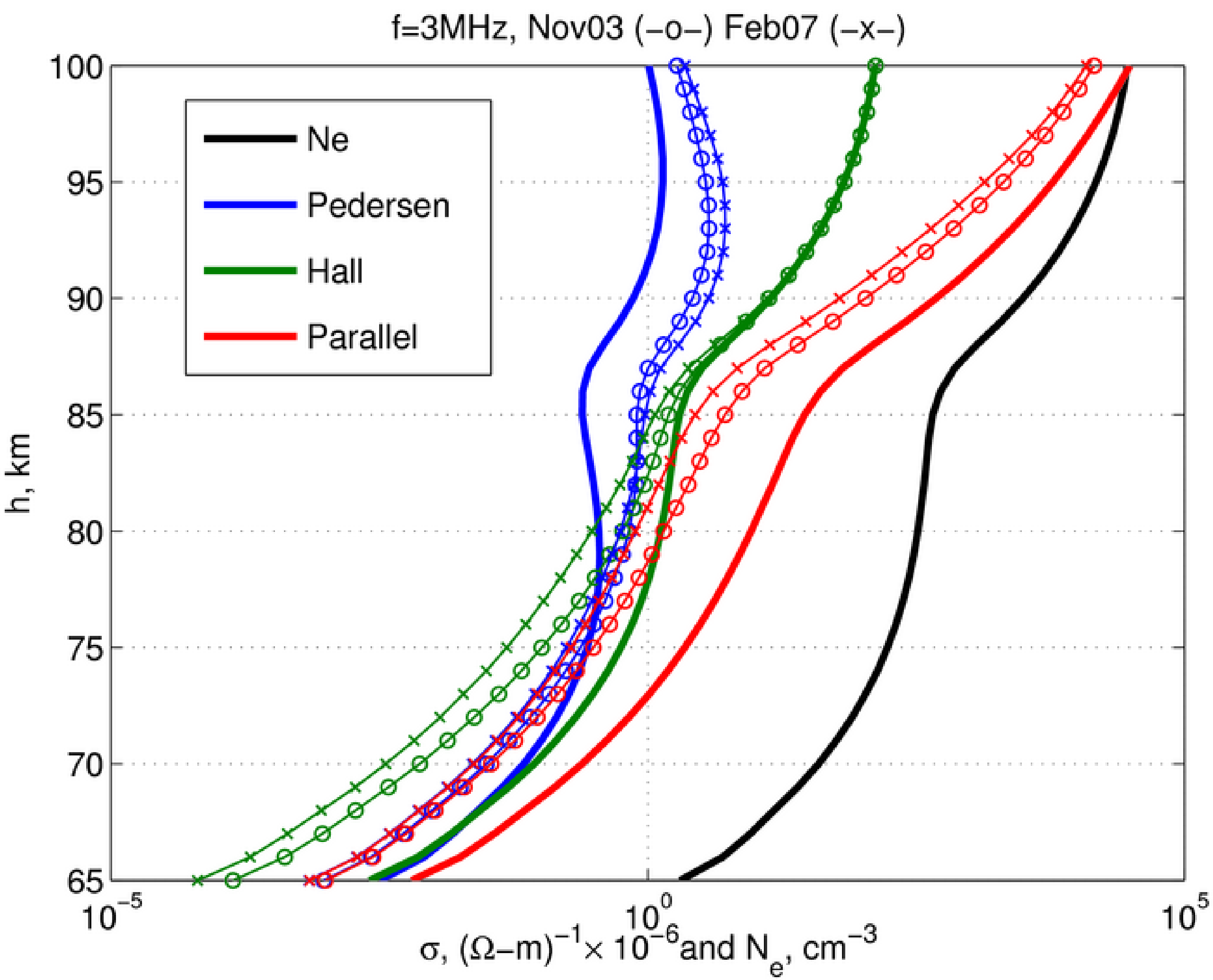
- **Hall (off-diagonal)**

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

- **Parallel**

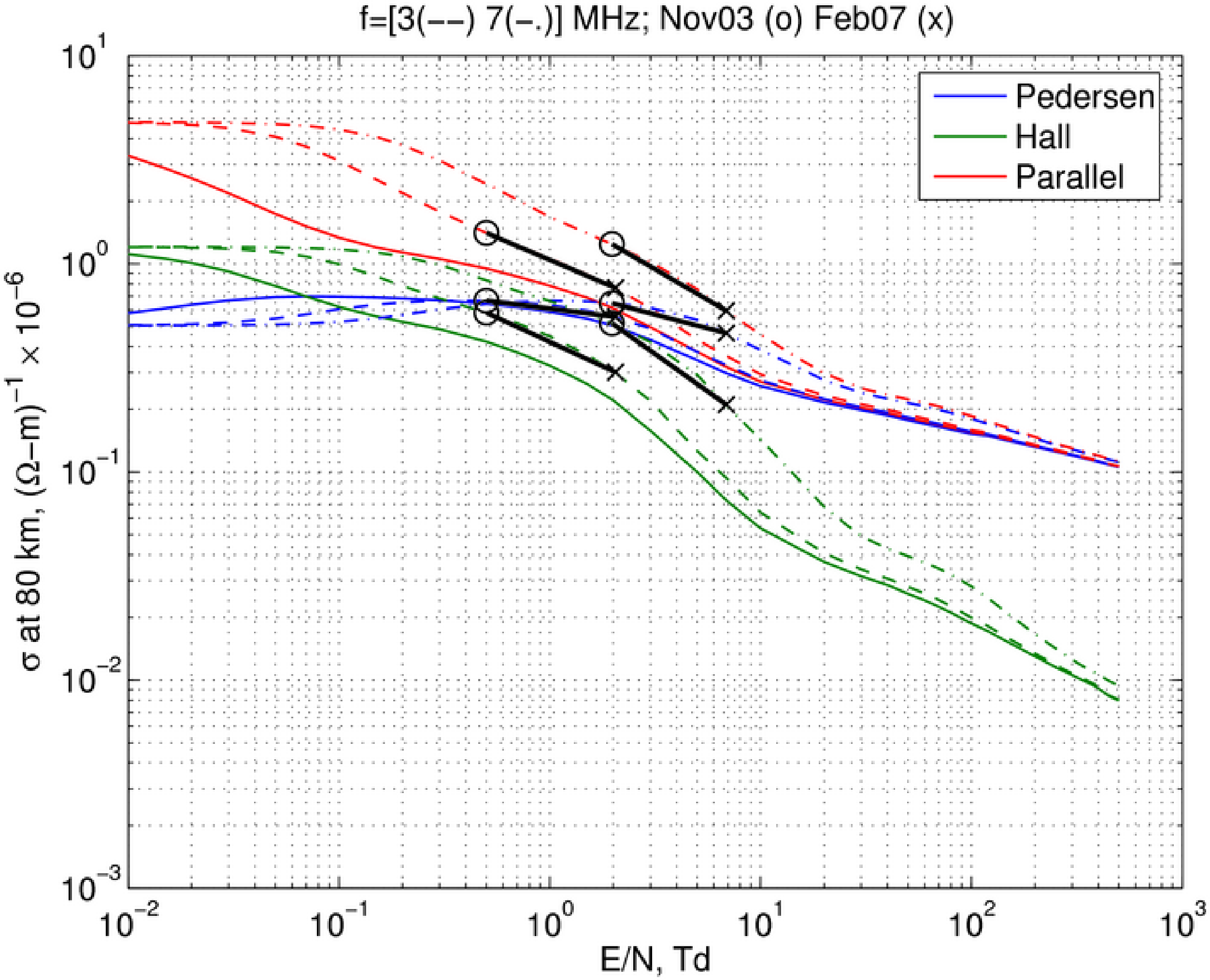
$$\sigma_z = -\frac{2e^2}{3m}\int \frac{\varepsilon^{3/2}}{\nu_m}\frac{\partial}{\partial\varepsilon}\frac{n}{\varepsilon^{1/2}}d\varepsilon \simeq \frac{N_e e^2}{m}\left\langle \frac{1}{\nu_m}\right\rangle$$

Conductivity modification



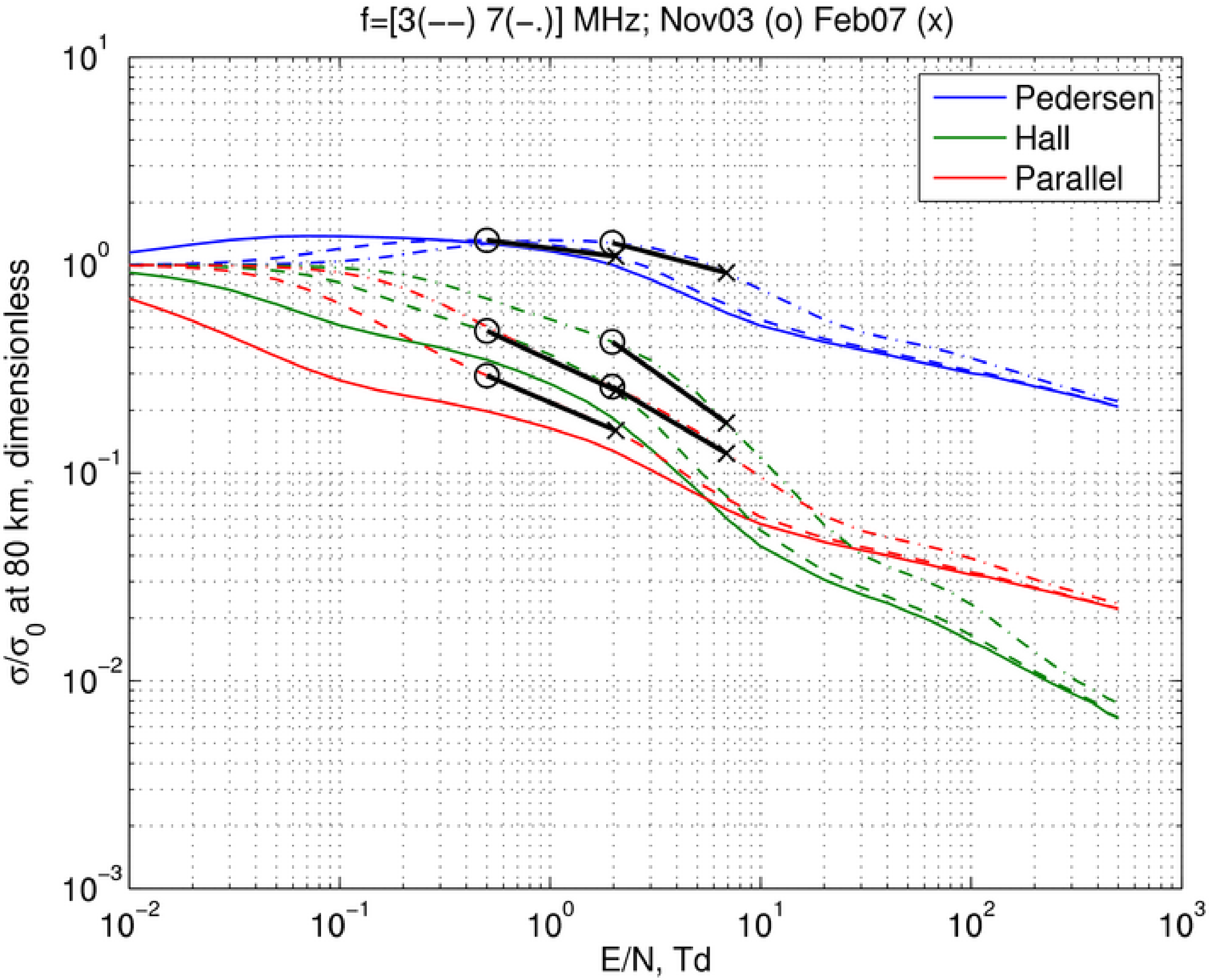
- **Pedersen conductivity is increased**
- **Parallel conductivity is decreased**

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



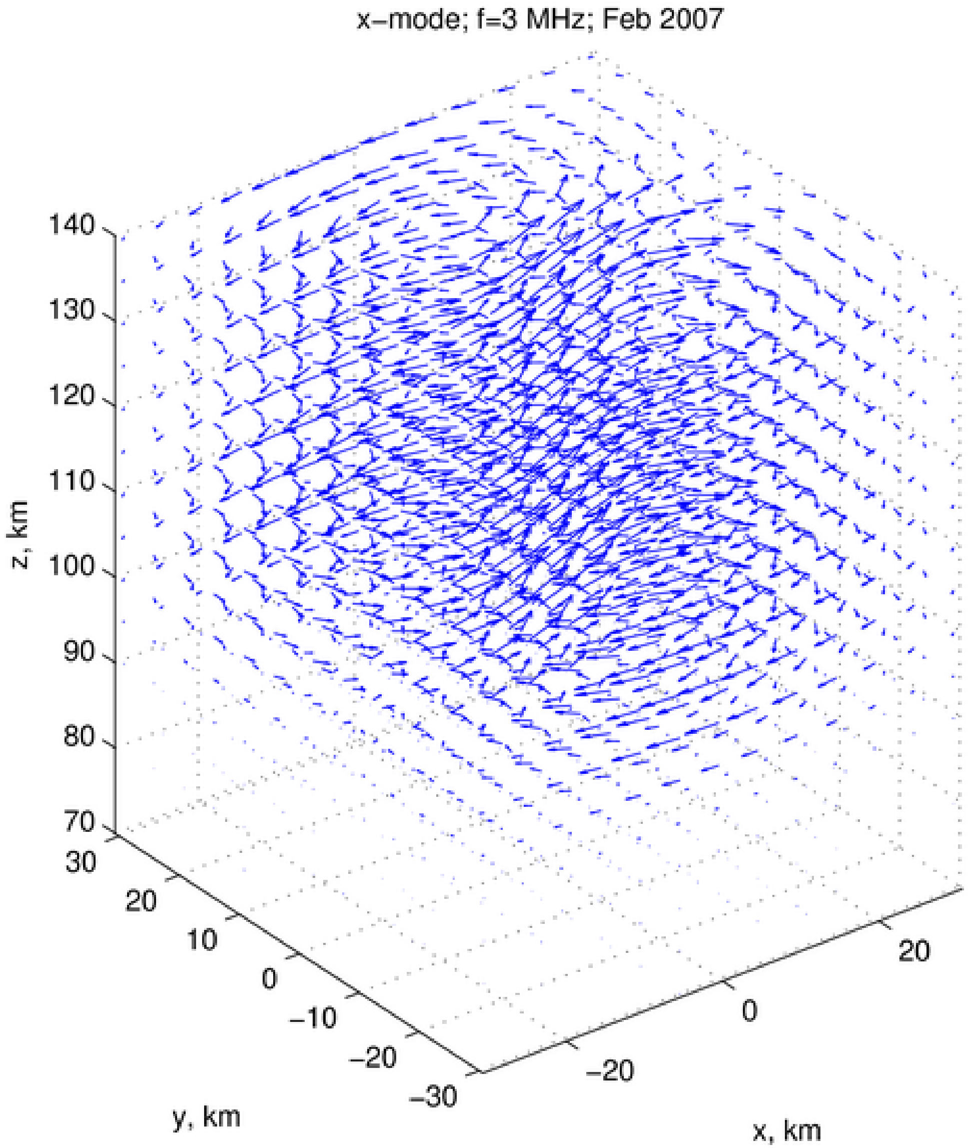
Electric current calculations

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

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

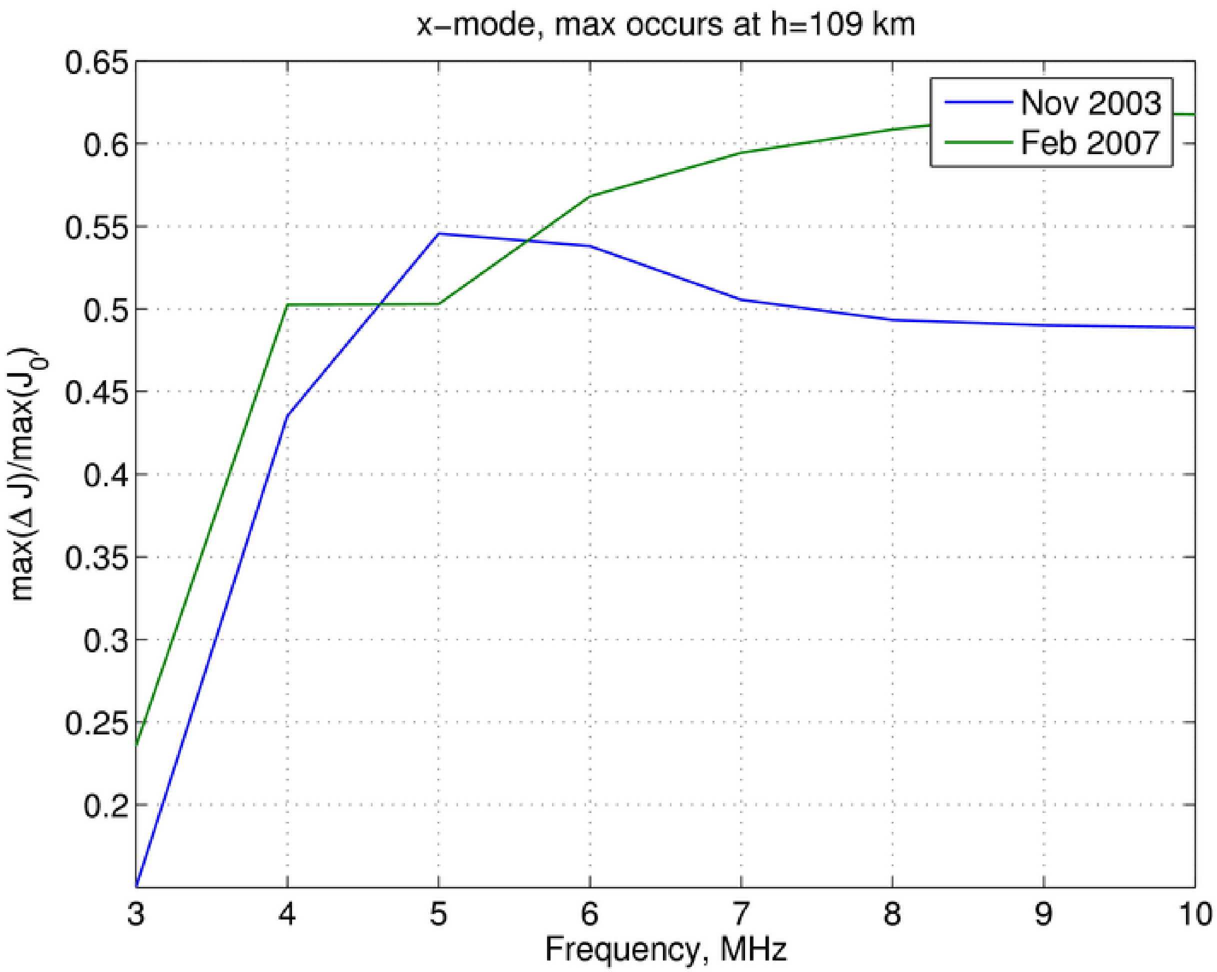
$$\nabla \cdot \vec{J} = 0$$

3D stationary ΔJ



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

Calculated $\Delta J/J_0$ for various frequencies



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

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