Ionospheric modification and ELF/VLF wave generation by HAARP

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Generation of ELF/VLF waves

120 km  70 km

electrojet current modulated at 2kHz

heating (Δσ)

3 MHz HF emission modulated at 2 kHz

injected VLF wave

HAARP

geomagnetically conjugate point
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

Inelastic processes:
- Rotational, vibrational, electronic level excitations
- Dissociative losses
- Ionization

\[ F = \sum N\sigma_i(v)\Delta\varepsilon_i \]

\[(E/N)_{br} = 130 \text{ Td} \quad \text{where} \quad 1 \text{ Td} = 10^{-21} \text{ V-m}^2\]
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 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 ELENDIF requires \( \nu_m >> \omega \)
- Geomagnetic field is also important: \( \omega_H \sim 2\pi \times 1 \text{ MHz} \)
Analytical solution

- Margenau distribution

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

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

- 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)

- Effective electric field is smaller than in DC case:

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

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

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

+ ordinary
- extraordinary
Breakdown field (used for the estimate of $\nu_{m,\text{eff}}$)

$h = 91 \text{ km, extraordinary, } f_H = 1 \text{ MHz}$

- Breakdown occurs when $\nu_{\text{ion}} > \nu_{\text{att}}$
- 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:

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

\[
\alpha = 2\text{Im}k + \frac{2}{R}
\]

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

- 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?

- 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)

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

- Hall (off-diagonal)

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

- Parallel

\[
\sigma_z = -\frac{2e^2}{3m} \int \frac{\varepsilon^{3/2}}{\nu_m} \frac{\partial}{\partial \varepsilon} \frac{n}{\varepsilon^{1/2}} d\varepsilon \approx \frac{N_e e^2}{m} \left\langle \frac{1}{\nu_m} \right\rangle
\]
Conductivity modification

- Pedersen conductivity is increased
- Parallel conductivity is decreased

![Graph showing conductivity modification](image)
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
\( \sigma(E)/\sigma(E=0) \)

\( f = [3(--), 7(--)\] MHz; Nov03 (o) Feb07 (x) \)
Electric current calculations

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

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

$$\nabla \cdot \mathbf{J} = 0$$
3D stationary $\Delta J$

- Vertical B
- Ambient E is along $x$
- Ambient current is mostly along $y$
- Models with $\Delta E=0$ do not consider closing side currents
- $\max \frac{\Delta J}{J_0} \approx 0.3$ for this case
Calculated $\Delta J/J_0$ for various frequencies

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

- Our model includes both:
  - Non-Maxwellian electron distribution
  - Self-absorption
- Maxwellian electron distribution models, which calculate $\Delta T_e$, 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.
- Electrojet current modulation in non-static case
- ELF/VLF emission
- ELF/VLF wave propagation along the geomagnetic field line