Abstract

HAARP is a high power transmitter facility operating in the HF frequency range. After an upgrade to 3.6 MW power scheduled in 2006 it will have an effective radiated power (ERP) of the order of 2 GW in 2.8-10 MHZ range, only a factor of ten less than lightning. The emission at 3 MHZ, modulated at 2 kHz, will cause a modification of electron distribution at altitudes of 70-120 km. The resulting change in conductivity will modulate the polar electrojet current and lead to emission of ELF/VLF waves into the magnetosphere. The wave then propagates to a point geomagnetically conjugate to HAARP. We use a time-dependent solver of the kinetic equation, similar to ELENDIF to calculate the electron distribution function. Since the modification of ionosphere affects the propagation of the HAARP radio wave, the power flux is found self-consistently with the solution of the kinetic equation at each altitude. The problem bears significant scientific interest because of highly nonlinear dependence of elecrojet modulation on the applied HF power, and the geomagnetic field effects.
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
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

\[(E/N)_{br} = 130 \text{ Td where } 1 \text{ Td} = 10^{-21} \text{ V-m}^2\]
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
Solution of kinetic equation

- Effective electric field is smaller than in DC case:

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

\[
\nu_{m,\text{eff}} / N = 2 \times 10^{-13} \text{ s}^{-1} \text{ m}^3
\]

\[
\omega_{\text{eff}} = \omega \pm \omega_H
\]

+ ordinary
- extraordinary

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(-.)
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

For comparison, we show the dynamic friction function.

Current and upgraded HAARP power are both shown.
Temperature modification
(daytime, x mode)

3MHz

7MHz

Nov 2003
Feb 2007
Comparison of Maxwellian and non-Maxwellian approaches

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

- Conductivity changes due to modification of electron distribution
- Previous models: \( \Delta E = 0 \) (inaccurate at low frequencies)
- This model: static fields, \( \text{div} \ J = 0 \)
Conductivity tensor (DC)

- Approximate formulas were used before
- 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
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
- $\max \Delta J/J_0 \sim 0.7$ for this case

\[
\vec{J} = -\vec{\sigma}\nabla \phi
\]

\[
\nabla \cdot \vec{J} = 0
\]
Conclusions

- Maxwellian electron distribution models, which calculate $\Delta T_e$, cannot account for the nonlinear $T_e$ saturation.
- The non-Maxwellian model allows to calculate optical emissions and breakdown processes.
- We are working on a creation of a universal modelling tool for ionosphere heating, which will calculate ELF/VLF emission on ground level and in space.
Work in progress

- Current changes in non-static case
- ELF/VLF emission
- ELF/VLF wave propagation along the geomagnetic field line