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Simulation of high energy tail of electron distribution function

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Abstract: This report presents Monte Carlo simulations of the electron energy distribution for a low ionized plasma interacting with the *F*-region neutral gas. The results show a depletion in the electron distribution above 2 eV between 10 and 80%, decreasing with altitude. The depletion is mainly due to electron energy loss to N_2. This micro-physical energy transfer model gives good agreement with optical observations of enhanced emissions from $O(^1D)$ at 6300Å and EISCAT UHF measurements of electron cooling during HF radio wave heating experiments. Some implications for incoherent scatter spectra are derived. The results suggest that a weak (approximately 1000 times weaker than the ion-line) and wide (2 MHz) peak around ±1 MHz from the ion-line in the EISCAT VHF incoherent scatter spectrum should be a consequence of the electron-neutral interaction.

key words: incoherent scatter spectra, active experiments, artificial airglow

1. Introduction

The background and motivation for the work presented in this report is the theory that high frequency radio wave (HF-pump) enhanced airglow is excited by thermal electrons (Mantas and Carlson, 1996; Mantas, 1994), henceforth denoted "*thermal excitation theory*", where the electron distribution $fe(E)$ for all energies E is assumed to be Maxwellian following the local electron temperature. According to the thermal excitation theory it is the small fraction of thermal electrons with energies above the $O(^1D)$ excitation threshold of 1.96 eV that cause excitation of the $O(^1D)$ emitting the enhanced 6300 Å airglow. For T_e of 4000 K only 1.5% of the electrons have energies above 1.96 eV. This raises the question of how the electron-neutral interaction modifies the electron velocity distribution; as posed in one of the concluding comments to the paper on inelastic electron collisions at low energies by Dalgarno (1968): "The next level of sophistication in the treatment of this problem must involve examination of the actual steady state electron velocity distribution." This question has been treated by Gurevich (1978) in general terms and by Stubbe (1981) who used parameters typical of ionospheric *D*-region plasmas ($n_e \approx 10^5\,cm^{-3}$, $n_{neutrals} \approx 10^{14}\,cm^{-3}$) in solving the Boltzmann equation for a weakly ionized plasma. It was found that for high electron temperatures, T_e, the electron energy distribution had large deviations from a Maxwellian, particularly at 2–4 eV, mainly because of energy loss by excitation of vibrational states of N_2. For night time F-region conditions Mishin *et al.* (2000) showed that the same process should cause a decrease in the electron energy distribution relative to the purely thermal case also during HF-pump experiments, even in the ionospheric F-region, at around 250 km altitude. Milikh and Dimant (2002) treated the problem for the E-region with a model that also includes electron energization by a turbulent electric field. Further, the effect of electron excitation of the N_2 vibrational states has been calculated to produce significant dips in the electron spectra both during precipitation of high energy electrons (Rees, 1989) and for photoelectrons (Nilsson *et al.*, 1996), who experimentally found that the vibrational excitation of N_2 cause a minima in the enhanced plasma lines.

In this report we use Monte Carlo methods to calculate the electron-neutral interaction and the modification of the electron distribution for the F-region night time conditions (shown in Fig. 1), that is $n_e \approx 10^5\,\mathrm{cm}^{-3}$, $n_{\mathrm{neutral}} \approx 10^9\,\mathrm{cm}^{-3}$ typical for the experiment with HF-pump enhanced airglow of 16 February 1999 at Tromsø (Brändström *et al.*, 1999; Gustavsson *et al.*, 2001). For this HF-pump experiment steady state T_e of 3000–3500 K was obtained. We show that the modification of $f_e(E)$ alter the thermal excitation rates of $O(^1D)$ derived by (Mantas and Carlson, 1991) and the electron cooling rates in a way that is in agreement with observations, further, we predict a large enhancement of the "electron line" in the VHF incoherent scatter spectra.

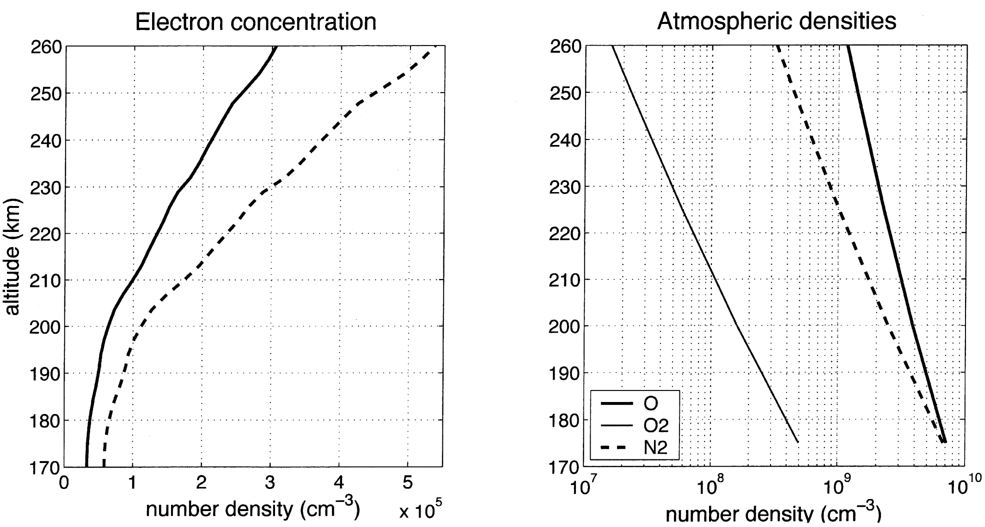

Fig. 1. Left panel show the "low electron concentration" profile (solid) typical for EISCAT UHF radar measurements from 19990216 and the "high electron concentration" profile (dashed). In the right panel the MSIS model Hedin (1991) for the major neutral species are displayed.

2. Monte Carlo simulation of electron distribution function

To address the question above we make a local time dependent Monte Carlo simulation of the electron-neutral and electron-electron interaction by tracing the velocities for 10^5

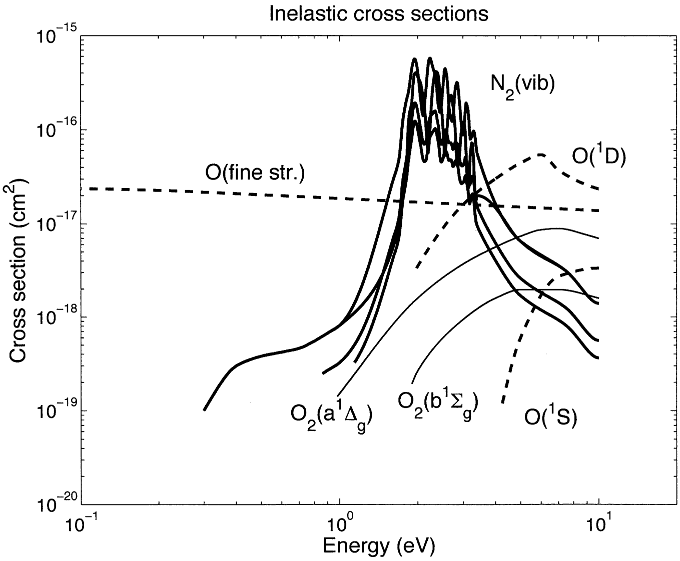

Fig. 2. Inelastic cross sections for important F-region electron-neutral interactions.

electrons with a 10 ms time-step, taking the inelastic interactions into account. Individual electrons randomly lose energy by excitation of $O(^1D)$, $O(^1S)$ and the fine structure of oxygen; the (1, 2, 3, 4) vibrational states of N_2 from the ground state; the molecular oxygen states $O_2(a^1\Delta_g^+)$ and $O_2(b^1\Sigma_g^+)$, as presented in Fig. 2. In particular the cross sections for excitation of the vibrational states of N_2 are large, up to $6 \cdot 10^{-16}$cm^2 at 2 eV (Itikawa *et al.*, 1986), with an energy loss of 0.2888 eV per vibrational level.

Here we neglect vibrational and rotational transitions in O_2 since the O_2 concentration at above 170 km of altitude is less than 10% of the atomic oxygen concentration. At lower altitudes, however, these have to be taken into account as Stubbe (1981) did for modeling of the *D*-region plasma. Further, we also neglect the excitation of the rotational states in N_2 since the N_2 concentration is less than half of the oxygen concentration at 170 km of altitude and also decreases faster with altitude. In addition to the lower number density the excitation cross section of the N_2 rotaional states is smaller than the excitation of the fine structure of atomic oxygen. There are a large number of electronic states in O, O_2 and N_2 with excitation energies slightly higher than 4.17 eV. Unfortunately, by modeling all individual electrons of an electron distribution the number of electrons above 6 eV is so low that the result dissolves into uncertainties of the counting statistics. When studying altitudes below 150 km the excitations of the molecular states have to be taken into account.

The electron-neutral interaction is modeled as a random process with the probability p_i^j of an excitation event for an electron with velocity v_e during the time period from t to $t + dt$, (Birdsall, 1991):

$$p_i^j(v_e) = 1 - \exp(-\sigma_i^j(v) \cdot n_i \cdot v_e \cdot dt). \qquad (1)$$

Here n_i is the concentration of specie i and σ_i^j is the velocity dependent cross section for excitation of its j'th state. For a time-step of 10 ms the probability of inelastic collisions is small, $< 2\%$, and thus multiple inelastic collisions during one time-step can be neglected.

The inelastic electron-neutral collisions cause the electron velocity distribution to fall of more rapidly than a Maxwellian distribution in the energy range where the inelastic cross sections are large. In this situation, one effect of electron-electron collisions is to give some electrons higher velocities. During one time-step of 10 ms an electron undergoes several electron-electron collisions each causing a small random velocity change. The total velocity change during dt is then according to the central limit theorem approximately normal distributed. Taking this into consideration it is possible to model the electron-electron collisions by a Wiener process:

$$v'_e(t+dt) = v_e(t) + dv\,(t, \Sigma). \tag{2}$$

Here the random velocity change dv is a normal distributed random variable with a width Σ. This random walk of the electrons in velocity corresponds to a diffusion in velocity space in the same way as normal spatial diffusion is caused by spatial random walk of particles.

The total energy of the electron gas is conserved during the electron-electron collisions and thus the velocity distribution must be normalized:

$$v_e(t+dt) = v'_e(t+dt)\frac{<\tilde{v}_e^2(t)>^{1/2}}{<v'^2_e(t+dt)>^{1/2}}. \tag{3}$$

To model steady state conditions, with constant electron temperature, we take $\tilde{v}_e$ as the velocities at the beginning of the time step, thereby keeping the total energy of the electron gas constant. When we model electron cooling, we take $\tilde{v}_e$ as the velocities after the energy losses to the neutrals. Since all electrons have the same random distribution of the velocity increment, the scaling of the velocities in eq. (3) is an implicit cooling of supra-thermal electrons. This we use to determine the appropriate value of Σ by looking at the energy loss of 2 eV electrons and compare that with the electron energy loss function in *e.g.* Fig. 1 of Stamnes and Rees (*e.g.* 1983). The best fit is obtained with $\Sigma = 94\sqrt{n_e}$, with n_e in cm^{-3}. Here it should be noted that we do not claim that this method of modeling electron-electron collisions is good for the general case, with for example beams of precipitating energetic electrons, but it is working for the case here, where there is small deviations from a Maxwellian distribution.

3. Model results and agreement with data

In this work we calculate the modification of the electron energy distribution for different electron and neutral concentrations corresponding to altitudes from 175 to 275 km. As can be seen in Fig. 3 the ratio, C_{bg}, between the modeled $f_e^{\mathrm{atm}}(E)$ and a purely thermal $f_e^{\mathrm{th}}(E)$ electron distribution is small at 2 eV and above for the lower altitudes. Since this "bite-out" is caused by the electron neutral collisions it is natural that it increases with increasing neutral concentration at lower altitudes. It is also natural that the bite-out is smaller for the high electron profile, since it is counteracted by the electron-electron collisions. Further, the agreement with Mishin *et al*. (2000) is striking, the small differences can be attributed to either the use of slightly different inelastic cross sections or the different methods and their implicit assumptions. Here it should be noted that the modification small to vanishing in the

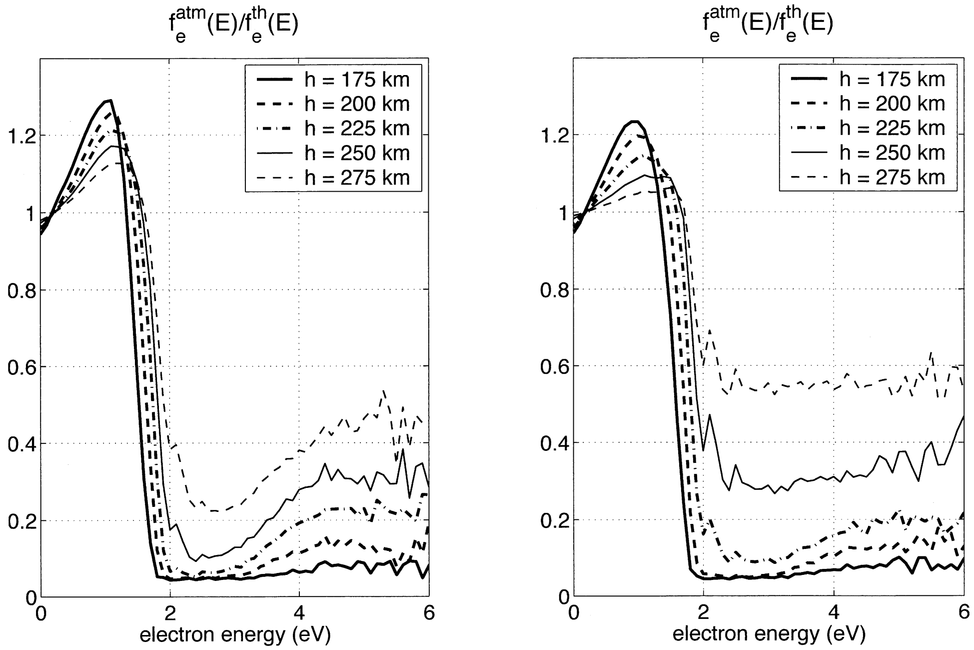

Fig. 3. The left panel shows C_{bg}— the ratio between the electron distribution modified by electron-neutral collisions and a pure thermal electron distribution for the low electron concentration profile. The right panel shows the ratio between the electron distribution modified by electron-neutral collisions and a pure thermal electron distribution for the high electron concentration profile.

F-region, at lower altitudes, however, the modification increases at successively lower altitudes (*E*-region Milikh and Dimant, 2002; Stubbe, 1981, *D*-region). The effect of the electron-neutral interaction is thus that the electron distribution is falling off steeper than a Maxwellian distribution at 2 eV and thus is “sub-thermal”.

3.1. *Effects on $O(^1D)$ excitation and 6300 Å emission*

To calculate the excitation of $O(^1D)$ we take a typical smoothed electron temperature profiles for the HF-pump experiment on 16 February 1999 and obtain the altitude distribution of the $O(^1D)$ excitation rate from a thermal electron distribution:

$$O(^1D)(T_e, z) = n_O(z) \int_0^\infty f_e\,(E, T(z), z)\,\sigma(E)\,v(E)\,dE, \tag{4}$$

and the modified electron distribution:

$$O'(^1D)(T_e, z) = n_O(z) \int_0^\infty C_{bg}\,(E, z)\, f_e\,(E, T(z), z)\,\sigma(E)\,v(E)\,dE, \tag{5}$$

for the two electron profiles with a peak electron temperature of 3400 K, as is seen in Fig. 4. The modified electron distribution creates significantly less excitation at altitudes below 250 km than the thermal electron distribution because of the increasing modification, that is due to lower electron concentration and higher neutral density.

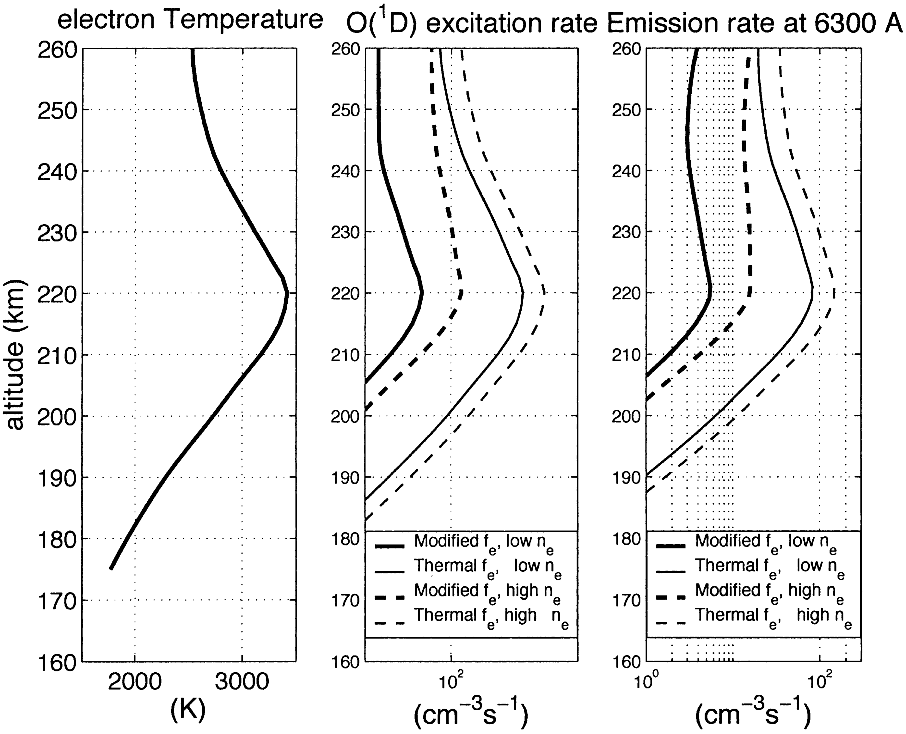

Fig. 4. Left panel shows the electron temperature typical for night time HF-pump experiments at EISCAT. Middle panel shows excitation of $O(^1D)$ from thermal and modified electron distributions with temperatures corresponding to the temperature profiles in the left panel. In the right panel are the corresponding volume emission rates at 6300 Å.

The effect of the modification on the 6300 Å column emission rate is a decrease to approximately 15% for the high electron concentration profile and 10% for the low electron concentration profile—here exact figures of course depend on the altitude of interaction and the neutral densities.

3.2. *Effects on electron cooling*

Reduction in the electron energy loss to the neutrals and thus a reduction in the electron cooling rates should be a direct consequence of the modification of $f_e(E)$. This is because the "bite-out" at 2 eV leads to reduced rates of excitation for both $O(^1D)$ and the vibrational states of N_2.

Maxwellian and modified electron distributions. To make comparisons with EISCAT UHF measurements we calculate the electron energy loss for an altitude of 225 km for both Maxwellian and modified electron distributions. From the Monte Carlo model results we calculate the temperature from the gradient $\frac{\partial f_e}{\partial E}$ at $E = 0$ eV, which is what is obtained from the incoherent scatter spectrum. As can be seen in Fig. 5 the main difference is that electron cooling is less rapid initially for the modified electron distribution when the electron temperatures are above 2000 K. For lower temperatures there is no major difference because

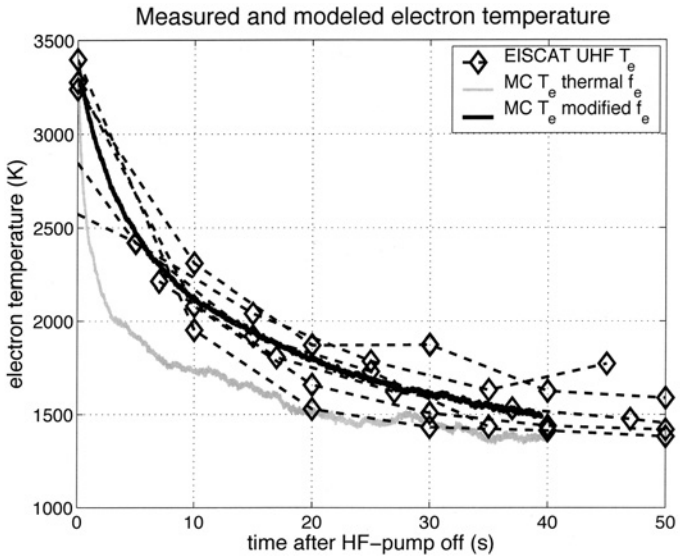

Fig. 5. Measured and modeled electron temperature decay. To compensate for the varying observed electron temperatures at the end of the HF-pump pulses the individual cooling curves are shifted in time so that their spread is minimized. Apparently the thermal electron distribution, plotted in gray, has a too fast initial cooling while the cooling of the modified electron agrees better with the observations.

then the electron energy loss is dominated by the low energy ($E < 2$) eV electron excitation of the fine structure states of atomic oxygen. Previous work on thermal response to ionospheric heating Mantas *et al*. (1981); Mantas and Carlson (1982) studied cases where the electron temperature not exceeded 1200 K, at these temperatures the energy loss to $O(^1D)$ and $N_2(vib)$ is negligible and thus the modified electron distribution should give the same characteristics as a Maxwellian.

To compare the model results with data we take the electron cooling characteristics from the six HF-pump pulses where the measured T_e peaked at 217±20 km (for the original data see Gustavsson *et al*., 2001). To adjust for the fact that each pulse reach different max T_e we adjust cooling curves by shifting them in time to obtain as small a spread as possible, which should be the appropriate procedure since we are interested in $\frac{\partial T_e}{\partial t}(T_e)$.

As can be seen in Fig. 5 the cooling of the modified electron distribution seems to agree better with what is observed. Here it should be noted that the model calculation only takes local energy loss into account and the observational data was taken at the peak in electron temperature, for which the electron cooling is a sum of local energy loss and thermal outflow which gives a faster cooling than only local energy losses would. The reduction in the electron cooling rate should be even more signifficant at lower altitudes due to the larger modification of the electron distribution function.

4. Effects on incoherent scatter radar spectrum

The recent extension to the incoherent scatter theory by Häggström *et al*. (2000), allowing multiple Maxwellian distributions of electrons, makes it possible to predict the effects of the modified electron distribution on the EISCAT spectra. Fitting the simulated electron distribution in Fig. 3 ($h = 225$ km) to a number of Maxwellians with different width and peak, and model values for other parameters, the predicted EISCAT VHF (224 MHz) spectrum is shown in Fig. 6. An enhancement at 0–2 MHz offset for the modified electron distribution is the most evident feature, but it is about 1000 times weaker than the ion line. This means that the signal is at around 0.5% SNR. Signal levels of 1% SNR are not unusual at EISCAT and good measurements are often made with integration times of a few minutes. So, by integrating 15–30 min, and measuring at offsets of up to 2 MHz it should be possible to confirm the predictions of the high energy tail. In the UHF (927 MHz) spectrum, not shown, the peaks are moved further out in frequency reaching the plasma lines, making any possible detection difficult.

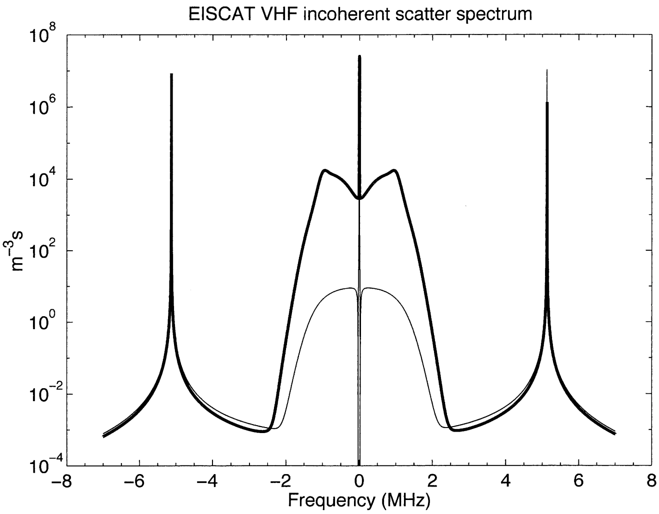

Fig. 6. *Theoretical EISCAT VHF spectra from 220 km altitude with an electron temperature of 3500 K (thin line) and the modified electron distribution (thick line). The central strong peak is the ion line and the peaks at 5 MHz offset the plasma lines.*

5. Summary and conclusion

In this report we address the question whether the electron gas can remain thermal/Maxwellian for HF-pump experiments. It is found that the electron-neutral interaction causes significant modification of the electron distribution. This is done with a Monte Carlo method that takes into account the inelastic scattering processes that are relevant for the night time *F*-region ionosphere. The conservative estimate of the electron distribution modification causes the total excitation rate from thermal electrons to decrease by 30–50%. This also leads to a reduction in the electron cooling rates at temperatures above approximately 2000 K. The Monte Carlo method is able to reproduce the EISCAT UHF measurements of the electron temperature decay after HF-pump turn-off. Finally we predict that the modification of the electron distribution should produce wide peaks (≈2 MHz) ±1 MHz from the ion-line in the spectra of EISCAT VHF radar.

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