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Reply to comment by M. Rapp and F.-J. Lübken on "The response time of PMSE to ionospheric heating"

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1. Introduction

[1] The comment by *Rapp and Lübken* [2003b] (hereinafter referred to as R&L) on our paper [*Belova et al.*, 2003] (hereinafter referred to as BCKR) contains two major points. The first pertains to an extension to their own work [*Rapp and Lübken*, 2000] reducing the relevant time constant. The second relates to the correctness of using the electron Debye length in formula (1) of BCKR for plasma where the electron temperature T_e is much more than the ion temperature T_i. We reply first to the second point, which is the most important one, and then consider the first.

2. Discussion

2.1. Quasi-Neutrality in a Plasma

[2] In BCKR we used equation (1) in the form

$$n_e(k,t) = \frac{\sum_{\beta \neq e} S_\beta n_\beta(k,t)}{1 + (k\lambda_{De})^2} \quad (1)$$

where S_β is the ratio of the charge of species β (other than electrons) to electron charge, k is the spatial Fourier component. This was derived by *Hill* [1978] and expresses the departure of a plasma from quasi-neutrality. Equation (1) allows the temperatures of electrons and ions to be different, and λ_{De} here is the electron Debye length in a multi-component plasma given as follows:

$$\lambda_{De} = \sqrt{\frac{\varepsilon_0 k_B T_e}{e^2 N_e}} \quad (2)$$

R&L propose that we should have used the plasma Debye length as given by, e.g., *Frank-Kamenetzkii* [1967]:

$$\lambda_D = \sqrt{\frac{\varepsilon_0 k_B}{e^2 N_e}} \cdot \sqrt{\frac{T_e T_i}{T_e(1+2\Lambda) + T_i}}. \quad (3)$$

[3] They argue that this is the appropriate length scale relevant to shielding and hence to charge quasi-neutrality in a plasma.

[4] We believe that this is not correct since the length scale for shielding is, in general, not necessarily the same as that for quasi-neutrality. By following *Landau and Lifshitz* [1979] we will show that the equation for quasi-neutrality $N_e \approx Z \cdot N_i$, where Z is the ion charge number, results from the Poisson equation for an electric potential when considering scale length much longer than the electron Debye length. For simplicity we assume Z = 1; that is, ions have a single positive charge. If there is an uncompensated electric charge in the plasma, then the electric potential is given by Poisson's equation:

$$\varepsilon \cdot \nabla^2 \Phi = e(N_e - N_i), \quad (4)$$

where $N_{e,i} = N_0 + n_{e,i}$. Here N_0 is the plasma density at a large distance where $\Phi = 0$ and $n_{e,i}$ are electron and ion density perturbations, respectively. By replacing $\nabla^2\Phi$ with Φ/L^2, where L is spatial scale and $n_{e,i}$ with $e\Phi N_0/k_B T_{e,i}$ according to the Boltzmann distribution and by transforming equation (4), one arrives at

$$\left|\frac{n_e - n_i}{n_e}\right| \approx \frac{\lambda_{De}^2}{L^2} \equiv \alpha_e$$
$$\left|\frac{n_e - n_i}{n_i}\right| \approx \frac{\lambda_{Di}^2}{L^2} = \alpha_e \frac{T_i}{T_e} \equiv \alpha_i \quad (5)$$

Here λ_{Di} is the ion Debye length.

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[5] By taking into account equation (5), one can derive the following:

$$|N_e - N_i| = |n_e - n_i| \approx \alpha_e \cdot n_e \approx \alpha_i \cdot n_I \tag{6}$$

If $\alpha_e \ll 1$, then for $T_e \gg T_i$, parameter α_i is even smaller, i.e., the condition $\alpha_i \ll 1$ is certainly fulfilled and then

$$\begin{aligned} N_e - N_i &\ll n_e \\ N_e - N_i &\ll n_i \end{aligned} \tag{7}$$

that is, the difference between electron and ion densities is much smaller than both electron and ion density perturbations. Then one can say that the quasi-neutrality equation $N_e \approx N_I$ is valid on a scale length much longer than the electron Debye length. In contrast, plasma can deviate from quasi-neutrality on a scale length shorter than the electron Debye length as equation (1) states.

[6] At the same time, according to equations (2) and (5) of R&L, the electric potential in a plasma shows an exponential decrease on the scale length determined by the "cold" ion component. Thus, at the scale lengths longer than the ion Debye length electrical shielding takes place but quasi-neutrality can be violated unless the scale length becomes longer than the electron Debye length.

2.2. Multipolar Diffusion

[7] Now we discuss whether multipolar diffusion as described by *Rapp and Lübken* [2000] and in more detail by R&L can account for a decrease of PMSE power during heating.

[8] At the time of preparation of our paper (BCKR) the only calculations on diffusion under quasi-equilibrium conditions were those available from *Rapp and Lübken* [2000]. Thus we drew our conclusion on the response time for diffusion based on Figure 2 of that paper, where the time of decay of a perturbation to 10% of its initial value is shown. This time constant was around 100 ms.

[9] R&L state, quite correctly, that radar backscatter is determined by the power spectral density of the electron fluctuations at the radar Bragg scale. In R&L's Figure 1, top panel, the decay due to diffusion of the power spectral density is shown. R&L obtained the result that diffusion can reduce the power-spectral density at one particular scale size by 10 dB from its initial value in only 1 ms. However, it seems that this result does not need to apply in general. Different relations between the initial perturbations of the electron and the ion/aerosol densities used by *Rapp and Lübken* [2000] and by *Rapp and Lübken* [2003a] (and probably by R&L) lead to different temporal development of the diffusion. One can see this when comparing Figure 3 of *Rapp and Lübken* [2000] and Figure 1, top panel, of R&L.

[10] The main problem we see with multipolar diffusion applied for heating experiment is that the equations and hence the solutions were obtained by *Rapp and Lübken* [2000] and R&L under assumption of plasma quasi-neutrality. We showed in the previous section that this assumption may be not valid on the scale length shorter than the electron Debye length. BCKR showed that for powerful heating and low enough electron density the EISCAT VHF radar Bragg length and hence length scale of plasma fluctuations detected with this radar are comparable with the electron Debye length enhanced because of heating. For such a situation multipolar diffusion should be reconsidered under nonneutrality conditions.

3. Summary

[11] In conclusion, we should say that we do not reject in general a role for multipolar diffusion in the heating effect on PMSE. When the electron temperature enhancement due to heating is not so strong as to increase the electron Debye length substantially, intensified quasi-neutral multipolar diffusion will indeed smooth out electron density fluctuations initially controlled by aerosols. However, if the electron Debye length has grown enough that quasi-neutrality breaks down on the spatial scale of the radar Bragg wavelength, then electrons can diffuse freely (and hence very fast) to reach a new balance with ions/aerosols according to equation (1). Then again, multipolar diffusion will take place but under nonneutral conditions. Thus what we likely see with the radar with a time resolution of several ms is some combined effect of free and multipolar diffusion.

[12] However, we realize the importance of the problem brought up by R&L regarding length scales in a plasma for quasi-neutrality and for the transition between individual and collective electron behavior. We acknowledge that BCKR's approach is simplified and that the problem should be reconsidered on a more comprehensive level.

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