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NONLOCAL DESCRIPTION OF ELECTRON HEAT TRANSPORT IN PLASMAS HEATED BY INVERSE BREMSSTRAHLUNG

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The problem of electron energy transport is of great interest in plasma physics in general and particularly for controlled thermonuclear fusion, magnetic as well as inertial. To investigate such problems there are different approaches. The most accurate is the kinetic approach, which consist of solving numerically the Fokker-Planck equation. However, the computational cost for such simulation is very high, especially for multidimensional problems and large scale plasmas such as those in Tokamaks or if various physical processes, i.e. ionization, recombination and excitation, are taken into account. The hydrodynamic approach is widely used, but then several physical mechanisms of kinetic character such as nonlocal transport and non-Maxwellian plasma behavior cannot be accurately included. The aim of this work is to develop formulas that will allow us to take into account nonlocal electron transport as well as non-Maxwellian effects on the macroscopic plasma characteristics, in the framework of a hydrodynamic model. The first formula which will be treated here concerns the nonlocal heat flux [1], the second one will describe the electron velocity distribution function (EVDF) as a convolution over local Maxwellians.

The first nonlocal heat flux model was developed by Luciani and Mora [2], assuming a Maxwellian electron distribution function. The nonlocal heat flux was assumed equal to a convolution over the local Spitzer-Härm [3] heat fluxes and a kernel that takes into account the contribution of supra-thermal electrons that can make nonlocal contributions to the macroscopic plasma characteristics, i.e.,

$$q(x) = \int_{-\infty}^{+\infty} w(\xi(x,x'))q_{SH}(x')dx' \tag{1}$$

where $\xi(x,x',Z) = \frac{1}{\lambda_e(x',Z)}\left|\int_{x'}^{x} \frac{N_e(x'')}{N_e(x')}dx''\right|$, $\lambda_e(x,Z) = v_{th}/\nu_{ei}$

λ_e is the electron mean free path, while ν_{ei} is the mean electron-ion collision frequency at velocity v_{th}. q_{SH} is the Spitzer-Härm flux, w is the nonlocal propagator or kernel.

Our goal then, is to extend the nonlocal kernel w to the case when the electron velocity distribution function is not Maxwellian. To do so, let us consider an initially uniform infinite plasma. All problems in this work are treated in one dimension. Our plasma is heated by modulated laser field (~ 1% intensity modulation) up to a certain temperature. As our model was first developed for problems relevant to the ICF, the maximal temperature was considered equal to 2 keV and the initial conditions of the plasma where assumed as follow: electron density n_e=10^{21} cm^{-3} and electron temperature T_e= 100 eV. However the formulas obtained are also applicable for Tokamak divertor plasmas as will be shown in [4], i.e. for temperature T_e ~ 25 to 1 eV and densities around 10^{14} cm^{-3}.

In the case of laser heated plasma for example, under strong laser collisional heating, i.e. inverse bremsstrahlung, the electron velocity distribution function (EVDF) [5], is strongly deformed and takes the following form:

$$f_m(x,v,t) = C_m\ (x,t)\exp\left[-\left(\frac{v}{v_m(x,t)}\right)^m\right] \qquad (2)$$

where 2<*m*<=5, *m*=2 corresponds to the Maxwellian case, and *m* is an increasing function of the intensity and atomic number.

By taking the ratio of the Fourier transform of the heat flux calculated by our Fokker-Planck code FPI [6] ($q_e \sim \int f_1 v^5 dv$) to the Fourier transform of the Spitzer-Härm heat flux (see Eq.3) we obtain a function commonly called flux propagator or corrected thermal conductivity. We have obtained this ratio as function of $k\lambda_e$, Z, and α, where *k* is the wave vector of the perturbation and λ_e is the free path length of electron-ion collisions, Z the ionization state, and α which characterize the deformation of the EVDF due to the collisional heating mechanism, α is also called Langdon parameter [5]. In the case of Maxwellian EVDF, α tends to zero and *m* to two. This latter dependency was not considered in the existing nonlocal models.

$$\tilde{w}(k\lambda_e,\alpha,Z) = \frac{\tilde{q}(k\lambda_e,\alpha,Z)}{\tilde{q}_{SH}(k\lambda_e,Z)} \qquad (3)$$

an example of the resulting heat flux propagator is presented in Fig.1 for Beryllium for different degrees of EVDF deformation, i.e. at different α. The nonlocal heat flux is then calculated using Eq. 1 with the inverse Fourier transform of our new propagator (Eq.3).

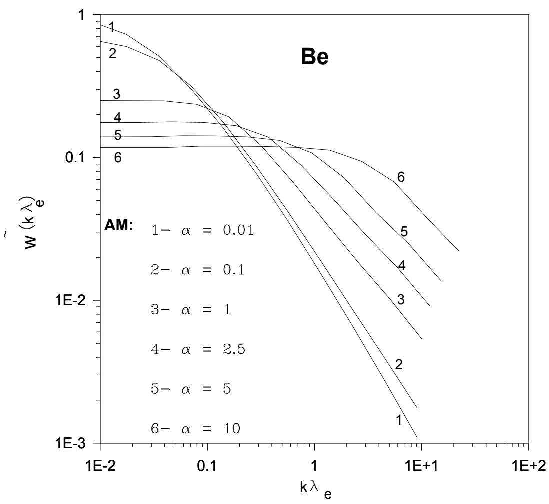
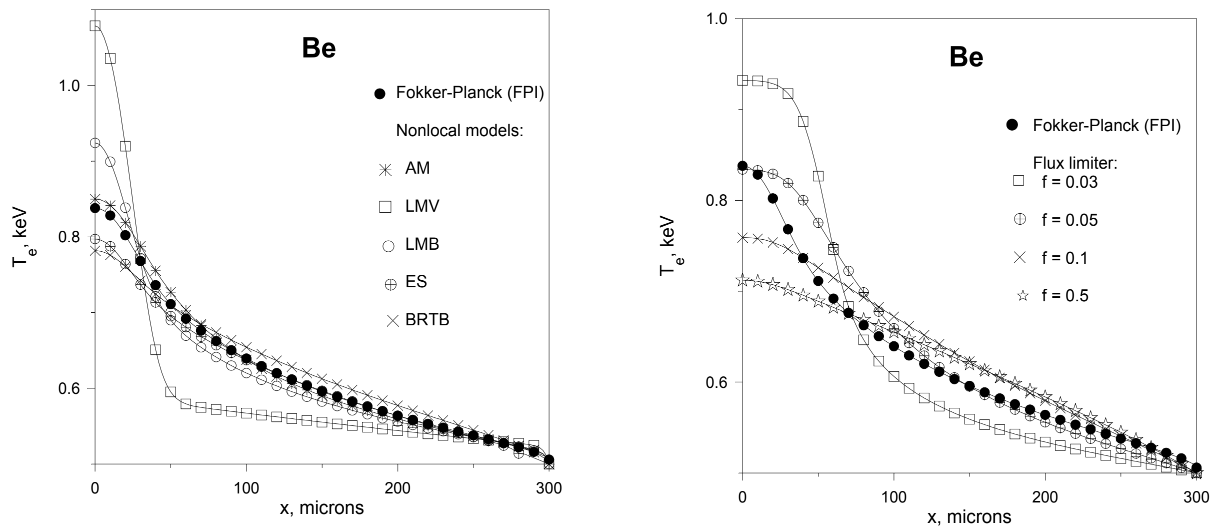


Figure 1: Heat flux propagators.

In Figures 2a and 2b we present the electron temperature profiles obtained at the peak of the laser heating pulse, (I_0=10^{15} W/cm^2, FWHM = 200 ps, spatial FWHM = 38 μm and Z=4), with the kinetic simulation (FPI) taken as the reference. In Fig. 2a ,one can see that our new formula (AM) reproduces the Fokker-Planck results very well especially near the center of the hot spot (X=0) , where the EVDF is the most severely deformed. To increase to relevance of this comparison, we have added in Fig. 2a the results obtained using the best known nonlocal models (LMV [2], LMB [7], ES [8], BRTB [9]), and we see that there are differences between those models and the Fokker-Planck results due to the deformation of the EVDF and under the combination of collisional heating and nonlocal transport. We have also compared our Fokker-Planck results to the traditional flux limiter method, with limiters f = 0.03, 0.05, 0.1, 0.5, (Fig.2b). It is seen that the temperature profiles in these conditions cannot be described by this method for any value of the flux limiter.



a **b**

Figure 2: Temperature profiles, I_0=10^{15} W/cm^2, duration of 200 ps, spatial FWHM equal to38 μm and Z=4.

This approach has also showed a good agreement with the kinetic data in the case of plasma with conditions typical for the Tokamak borders [4], i.e. Z=1, T_{Max} = 25 eV and T_{min} = 1eV and plasma scale length about 10 m, taking the limit $\alpha \to 0$.

An approach analogous to that used for the heat flux was applied for the isotropic component $f_0(x,v,t)$ of the EVDF, i.e. we again consider the model situation of an initially homogeneous plasma heated by an intensity modulated laser field. The hypothesis made here is that the solution of Fokker-Planck equation can be written as a convolution of local Maxwellians with a kernel that includes the nonlocal effects and the deformation of the EVDF in each spatial point in the plasma. This kernel is obtained by taking the ratio of the Fourier transforms of the numerical solution of the Fokker-Planck equation (FPI) and the local Maxwellian at different electron velocities and wave vectors:

$$\tilde{g}(k,\alpha,v) = \tilde{f}_0(k,\alpha,v) / \tilde{f}_M(k,v) \tag{4}$$

The inverse Fourier transform of Eq. 4 is then: $f_0(x,v) = \int_{-\infty}^{+\infty} g(\xi(x,x'),\alpha(x'),v)\, f_M(x',v)\, dx'$ (5)

We have applied this formula to the following case: plasma heated by a laser pulse of intensity I_0=10^{15} W/cm^2, duration of 200 ps, spatial FWHM equal to 38 μm and Z=11. the choice of this situation is arbitrary and this method have showed a good result independently of the laser or plasma characteristics. A good agreement was obtained between our model for the EVDF and the numerical solution of Fokker-Planck equation at low electron velocities comparing the a Maxwellian EVDF or even to the Langdon function [5], which is of particular interest for absorption calculations.

In conclusion we can note that our newly developed model of the heat flux is of particular interest to describe nonlocal electron transport in Maxwellian plasma but even more so when there is a departure from the Maxwellian equilibrium, due to the heating mechanism and allows us to describe the main plasma macroscopic characteristics with kinetic like precision and with time of computation comparable to a simple hydrodynamic calculations. Even when describing well, the plasma characteristics, the knowledge of the EVDF still required to describe series of kinetic effects that hydrodynamic model cannot describe, such as rates of atomic physics processes [10], and wave propagation and parametric instabilities [11] in plasmas. In this context, our formula for the EVDF is very promising as it allows reproducing the Fokker-Planck solution simply by using convolutions over local Maxwellians.

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