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Nonlocal transport hydrodynamic model for laser heated plasmas

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The interaction of lasers with plasmas, whether pre-formed or due to ablation processes, very often takes place under nonlocal transport conditions. The nonlocality affects the transport of particles, mostly electrons, as much as it does radiation. In this study, the nonlocal transport is investigated for the plasma corona generated due to the deposition of laser energy. The nonlocal theory of the energy transport in radiative plasmas of the arbitrary ratio of the characteristic spatial scale length to the photon and electron mean free paths is applied to define closure relations of the hydrodynamic system. The corresponding transport phenomena cannot be described accurately with the usual fluid approach dealing only with local values and derivatives. Thus, the usual diffusive energy flux is instead calculated directly by solving a simplified transport equation allowing one to take into account the effect of long-range particle transport. The key feature of the proposed hydrodynamic closure is a direct solution of the simplified Bhatnagar-Gross-Krook form of the Boltzmann transport equation for electrons and the proper form of the radiation transport equation. *Published by AIP Publishing.* https://doi.org/10.1063/1.5011818

I. INTRODUCTION

The aim of this article is to use, and numerically solve, an appropriate nonlocal heat and radiation transport closure to the hydrodynamics equations in the context of laser-plasma interactions. Such a closure should be able to handle a wide range of Knudsen numbers $\mathrm{Kn} = \lambda/L$, where λ is the mean free path of either massive particles or photons and L the plasma inhomogeneity scale length. The number Kn is a fundamental quantity characterizing the type of transport regime.[1–6] A commonly used characteristic scale length is derived from the profile of the plasma electron temperature T_e (using its gradient ∇T_e) and can be defined as $L = \frac{T_e}{|\nabla T_e|}$ or as $L = \frac{1}{k}$, where k is the dominant component of the temperature profile in Fourier k-space. In principle, the characteristic scale length based on the profile of electron density n_e should also be included to address the transport regime, but since the standard hydrodynamic codes lean on the local heat flux approximation $\mathbf{q} \approx \nabla T_e$, we use the Knudsen number based on the electron temperature gradient of electrons $\mathrm{Kn}^e = \frac{\lambda^e|\nabla T_e|}{T_e} = k\lambda^e$, where λ^e is the electron mean free path. Consequently, the photon mean free path is defined as $\mathrm{Kn}^p = \frac{\lambda^p|\nabla T_e|}{T_e} = k\lambda^p$, where λ^p is the photon mean free path.

Typical transport regimes in laser heated plasmas can be divided into three domains being distinguished by the Knudsen number as follows:

- $\mathrm{Kn} > 10$: This regime of transport can be considered as free streaming. It is very common for photons in the under-critical ablative plasma, i.e., in the corona. It is very rare that the electrons enter this regime.
- $0.001 < \mathrm{Kn} < 10$: This regime of transport is called the nonlocal transport. It is typical for electrons in the corona. In the case of photons, it is rather present in the layer between critical density and ablation front (the so-called conduction zone).
- $\mathrm{Kn} < 0.001$: This regime is represented by a relatively cold and highly compressed material. It is opaque/collisional for most of the photons/electrons and this is where the Chapman-Enskog expansion method[7] applies and transport is always diffusive.

It is worth mentioning that the inhomogeneity length scale defined above is just an approximation. For example, a flat profile of temperature in the corona plasma can lead to an almost infinite length scale characteristic, and consequently, the Knudsen number would imply a diffusive regime. On the contrary, the scale length is limited by the extension of the corona and the transport of both electrons and photons is well described as ballistic. Also, the above description holds for "usual" particles; nevertheless, some extremes as fast electrons or X-ray photons can exhibit surprisingly high Knudsen numbers, which is naturally accompanied by the effect of high anisotropy of the transport.

In order to address the complex physics of nonlocality of transport, a new approach of nonlocal transport closure in hydrodynamics is presented, which leans on the idea of combining *physics* represented by the radiation transport and the linear Boltzmann transport equations and *numerics* providing their efficient and general multi-dimensional solution. Such a formulation enables the usage of arbitrary order discretization in both the space and the angle, achieving high-order accuracy and also the freedom in future extendibility of the physical model.

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