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A Comparison of Kinetic and Multifluid Simulations of Laser-Produced Colliding Plasmas

P. W. Rambo and R. J. Procassini
University of California, Lawrence Livermore National Laboratory
P.O. Box 808, Livermore, CA 94551

I. Introduction

The collision and subsequent interaction of counter-streaming plasmas occurs in several areas of laser-plasma research including double foil targets for x-ray lasers and the plasma blow-off inside ICF hohlraums. Because a single fluid model allows for only one value of the flow velocity at any one spatial location, interpenetration of the plasmas is not allowed resulting in immediate stagnation with complete conversion of the ion-streaming kinetic energy to thermal energy. Multifluid models have been developed which employ multiple ion fluid species that interact through the self-consistent electrostatic field and collisional coupling [1,2]. Because they are approximations to a kinetic situation, the form of these coupling coefficients is not unique, with various workers using differing approximations. More recently, Larroche [3] has implemented a finite difference approach to the ion Fokker-Planck equation while Jones and co-workers have performed two-dimensional simulations of colliding plasmas using a particle-in-cell code with a new collisional model [4].

Our kinetic modeling also makes use of particle in cell (PIC) techniques with Monte Carlo (MC) particle-particle collisions. This work differs from that of Ref. 4 in our use of a binary particle-particle collision algorithm that is equivalent to the Fokker-Planck collision operator. We have made direct comparison of this MC-PIC model to multifluid simulations on both simple slowing-down and equilibration problems as well as problems characteristic of laser generated colliding plasmas. These comparisons have established the validity of the multifluid model as well as aided in the development of the kinetic capability for more challenging geometries.

II. The MC-PIC Kinetic Model

Both the multifluid and kinetic models treat electrons and multiple ion species, coupled through the electric field E and collisional interaction. Here we briefly describe the MC-PIC kinetic model; the equations for the multifluid model and their implementation are detailed in Ref. [1]. We confine ourselves to one spatial dimension in planar geometry with all variation assumed to be in the x direction. In both models, the electrons are assumed to be a massless fluid with density n_e, fluid velocity in the x direction u_e, and temperature T_e. The electron density and velocity are given by quasi-neutrality and current-free conditions respectively. The electric field is found from the electron momentum equation neglecting inertial effects and magnetic fields

$$E = \frac{-1}{en_e}\frac{\partial p_e}{\partial x} - \frac{m_e}{e}\sum_i \nu_{ei}(u_e - u_i); \quad \nu_{ei} \equiv \frac{4\sqrt{2\pi}Z_i^2 e^4 \lambda_{ei} n_i}{3m_e^{1/2}T_e^{3/2}}$$

where $p_e=n_eT_e$ is the electron pressure, Z_i is the ion charge, and λ_{ei} is the Coulomb logarithm. The electron-ion momentum transfer collision frequency, ν_{ei}, is evaluated for the usual case of ion velocities much smaller than the electron thermal velocity, $v_i << (T_e/m_e)^{1/2}$.

The kinetic model makes use of a particle-in-cell representation of the ions augmented by Coulomb collisions. The collisions include interaction with the electron fluid and between all the ion particle species. Ion-ion collisions between particles are handled using a binary particle scattering algorithm [5], equivalent to the Fokker-Planck description of cumulative small angle Coulomb scattering. Particles sharing the same spatial cell are randomly paired up, and then undergo a collision irrespective of their positions in the cell. Each collision is kinematically correct, thus ensuring microscopic energy and momentum conservation. Species 1, 2, 3... are collided against each other sequentially, i.e. 1–1, 1–2, 1–3..., 2–2, 2–3... where species may be different physically or the same physically but with different simulation labels (e.g. for diagnostic purposes). For scattering between species α and β, the collision is performed in the center of mass frame for each particle pair with a polar scattering angle for the particle from species α picked from a Gaussian distribution with width

$$\theta^2 \equiv \frac{8\pi Z_\alpha^2 Z_\beta^2 e^4 \lambda_{\alpha\beta} n_\beta}{m_{\alpha\beta}^2 |\delta v|^3} \delta t$$

where $m_{\alpha\beta}=m_\alpha m_\beta/(m_\alpha+m_\beta)$ is the reduced mass and δv is the relative velocity between each scattering pair. The collisional time period δt may be picked equal to the particle advance time step Δt or the collisions may be subcycled M times, $\delta t=\Delta t/M$, with M picked in each cell according to an average collisionality. The azimuthal angle is picked uniformly over the interval $[0, 2\pi]$. The post-collision velocity of the particle from species β is given by the kinematic relations. For unlike species collisions ($\alpha\neq\beta$), the species in each grid cell with the most simulation particles is the field species β and all particles from species α are collided, N_α in number. This means that momentum and energy transferred from species α to β is given to only a fraction N_α/N_β of the particles of species β; subsequent collisional time steps as well as β–β collisions share this exchange with the entire distribution of β particles. For $\alpha=\beta$ collisions, $N_\alpha/2$ collisions are performed. Validity of the method depends on the mean square scattering angle being a small quantity, $\theta^2<<1$. To avoid overly restrictive time steps in highly collisional regimes, however, the method has been implemented so that if $\theta^2>\Theta^2$ (typically $\Theta^2\equiv 1$), the scattering angle is picked isotropically in solid angle. This comparison is done for each colliding pair, so that for instance a high energy beam will still have the proper velocity dependence while collisional bulk particles "gracefully" become collisional to the limit of the simulation resolution. Tests have shown that in the very collisional regime, $\theta^2>\Theta^2$ for all particle pairs, adiabatic fluid behavior is recovered.

We have implemented two different methods for colliding particle ions with the fluid electrons. The first method is also a Monte Carlo method with the particle velocity changes picked so as to be consistent with the Fokker-Planck equation[6]. An alternative method for handling the ion-electron collisional interaction based on the technique of Jones et al. [4] has also been implemented. Essentially, this latter method involves accumulating particle moments to the grid before the collisions, advancing these moments according to the collisional interaction, and finally adjusting the particle velocities to conform to the new moments through a drag and dilation relative to the mean velocity. The collisional advance of the moments may be performed implicitly as is done for the multifluid implementation described in Ref. [1]. This allows stable large time step, relaxing the time step limitation noted in Ref.[4] which utilized an explicit application of the collisional force. This extension to large time step is also relevant when this method is applied to inter-particle collisions which has,

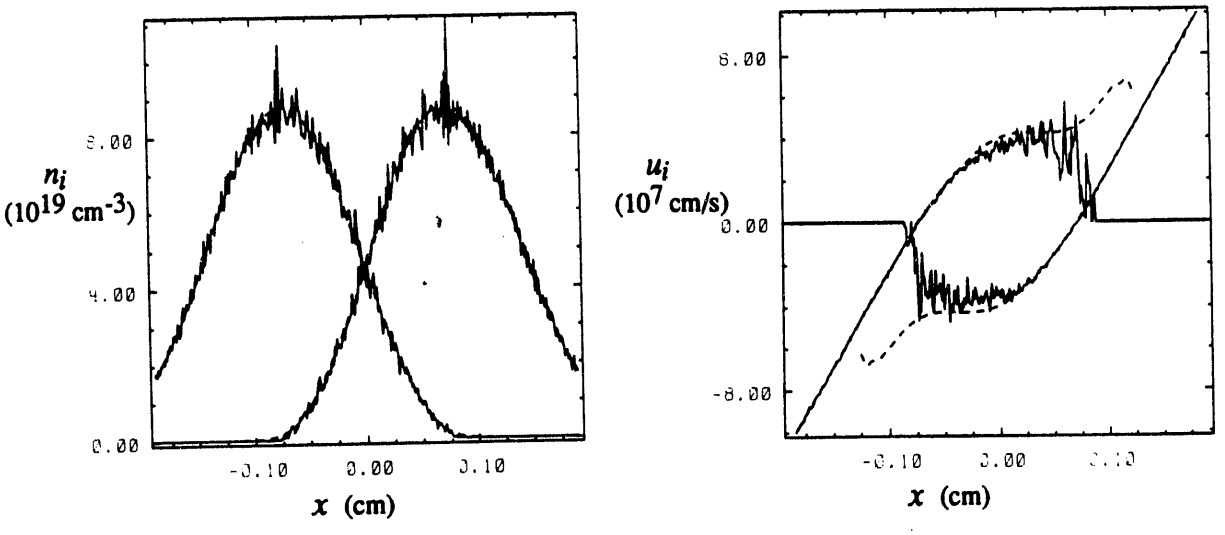

Fig. 1 Ion density and velocity profiles at t =800 ps, comparing MC-PIC (solid line) and multifluid (dashed line) simulations of two colliding foils.

also been implemented. This method of taking into account e-i collisions has other advantages over the former Monte Carlo method. When advancing the particle moments, the electron temperature is updated as well making inclusion of particle sources in the electron energy equation simple. Additionally, the method facilitates coupling to other algorithms of the code such as the current-free constraint adopted here, or more generally an implicit field equation. In either model for the collisional e-i interaction, changes in the ion particle momentum are accumulated to the grid for use in the electric field equation, in a manner consistent with momentum conservation.

III. Comparison of Kinetic and Multifluid Simulations

A comparison of multifluid (dashed lines) and MC-PIC simulations (solid lines) is shown in Figs. 1 and 2 for the case of two exploding foils, which expand and then collide. The 3.2 μm thick carbon (Z=6) foils are initialized as isothermal (T_e=1.5 keV, T_i=500 eV) self-similar Gaussian expansions separated by 1500 μm. The time step for both simulations is Δt=1.0 ps. Figure 1 shows snapshots at t=800 ps after the start of the simulation, clearly showing interpenetration of the foils and slowing down due to collisional interaction; quantities for both left and right foil are shown. Time histories at the center of the system for electron temperature and ion temperature of the left foil are shown in Fig. 2; again agreement is quite good. Calculations of CH foils with separate species for the carbon and protons have also been performed, with similar agreement between kinetic and multifluid simulations. The multifluid calculation shown here uses one particular functional form for the collisional coupling coefficients [1], but this choice is not unique. This choice and an alternative formulation [2] give similar levels of agreement when compared to the kinetic model on simple homogeneous slowing down and equilibration problems, with the multiple fluid approach (either set of coefficients) missing the slow equilibration of high energy particles accounted for by the kinetic model.

This work has given us confidence that the MC-PIC model is applicable to the study of

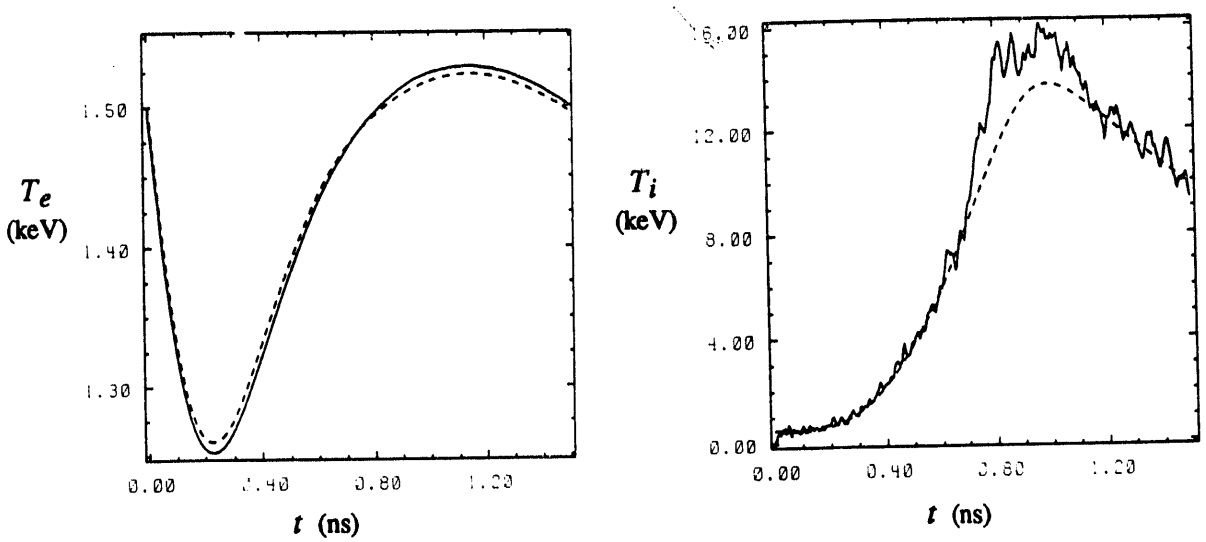

Fig. 2 Time histories of electron temperature and left-foil ion temperature at center of system, comparing MC-PIC (solid line) and multifluid (dashed line) simulations of two colliding foils.

plasma interpenetration problems. The use of Langrangian particles in phase space has the advantage of naturally resolving the large streaming velocities found in plasma expansions without the difficulty of meshing a large region of velocity space necessary in a finite difference code. The MC-PIC method is also easily extendable to non-Cartesian geometry or multiple dimensions [4], and simulations of axial stagnation in cylindrical geometry have recently been performed.

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