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Kinetic Simulation of Non-Equilibrium Plasmas

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Final Report

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This project is on innovative methods for kinetic simulation of non-equilibrium plasmas, which are important for applications such as directed energy, remote sensing, space propulsion and space weather. The project is focused on kinetic regimes for which current simulation methods are ineffective, and new analytic and algorithmic ideas are needed. Accomplishments include a Monte Carlo simulation of Collisional/Radiative (CR) kinetics in plasmas, a new deterministic scheme for collisional-radiative kinetics that allows for allows for non-uniform gridding of the energy axis, while maintaining exact conservation properties, a new strategy for combining a Monte Carlo particle method with computational fluid dynamics.

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plasma kinetics, Monte Carlo simulation, Collisional/Radiative kinetics

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Final Performance Report

FA9550-14-1-0283

"Kinetic Simulation of Non-Equilibrium Plasmas,"

Russel Caflisch, PI

9/1/2014 – 8/31/2018

Progress and Accomplishments.

This project is on innovative methods for kinetic simulation of non-equilibrium plasmas, which are important for applications such as directed energy, remote sensing, space propulsion and space weather. When they are required for physical fidelity and accuracy, kinetic simulations can be very demanding because of the complexity of both their formulation and their solutions. The project is focused on kinetic regimes for which current simulation methods are ineffective, and new analytic and algorithmic ideas are needed.

The research includes two projects: The first is Monte Carlo simulation of Collisional/Radiative (CR) kinetics and is in collaboration with Dr. Jean-Luc Cambier (AFRL/RQRS) . The focus is on inelastic collisions, in particular electron impact excitation/deexcitation and ionization/recombination. These are important for production of radiation and for plasma equilibration, for example after laser heating of a plasma. The second project is on development of new Monte Carlo simulation methods that have reasonable speed and accuracy for the full range of Knudsen number Kn, from the continuum regime (small Kn) to the free flow regime (large Kn) and everything in between.

A third project is identification of extreme solutions for vacuum currents, which could serve as benchmarks for critical behavior in standard simulation methods, and is potentially relevant to physical features found in extreme plasma conditions. We have developed an augmented Lagrangian approach to this optimization problem and solving a forward equation for the direct solution and a backward equation for the dual variables, that modify the boundary data so as to drive the solution to an optimum. This project is still being carried out.

In particular, we developed a new deterministic scheme for collisional-radiative kinetics, in joint work between Hai Le (UCLA) and Jean-Luc Cambier (AFOSR). This method allows for non-uniform gridding of the energy axis, while maintaining exact conservation properties.

We also developed a new strategy for combining a Monte Carlo particle method with a computational fluid dynamics method, which has the promises to achieve uniform accuracy and speed for all Kn. This has been a long time goal for computational kinetic theory. This new strategy relies on a combination of two parallel simulations: a direct Monte Carlo simulation for a full particle representation of the velocity distribution; and a deviational simulation that combines a Maxwellian with a correction terms that is represented by a collection of particles, some with positive weight and some with negative weight. In the limit of small Kn, the method produces just a Maxwellian distribution evolving according to continuum equations. In the limit of large Kn, the method is just a direct Monte Carlo simulation.

This research was be performed by the PI in collaboration with two postdoctoral scholars (Hai Le and Bokai Yan), as well as two additional our collaborator Jean-Luc Cambier. Mentoring of these junior researchers is an important part of the research effort. Hai Le finished his postdoctoral training in 2016 and took a position at Lawrence Livermore National Labs, as a Computational Physicist. Bokai Yan finished his postdoctoral training in 2017 and took a job as a Quantitative Analyst at Bank of America.

Caflisch is starting as the Director of the Courant Institute of Mathematical Sciences as of September 1, 2017. A no-cost extension was approved for this grant for the period 9/1/2017 – 8/31/2018, with a subcontract from UCLA to Courant to continue this research. A postdoc, Denis Silantyev, started working Courant in fall 2017 to work on this project. He recently received his PhD from University of New Mexico.

Publications

The following publications have been generated by the research of this grant:

B. Yan, R.E. Caflisch, F. Barekat and J.-L. Cambier ``Analysis and Simulation for a Model of Excitation/Deexcitation and Ionization/Recombination in a Plasma" J. Comp. Phys. 299 (2015) 747 - 786.

Hai P. Le, Bokai Yan, Russel E. Caflisch, and Jean-Luc Cambier. "Monte Carlo simulation of excitation and ionization collisions with complexity reduction." Journal of Computational Physics 346 (2017) 480-496.

Hai P. Le and Jean-Luc Cambier. “Conservative algorithms for non-Maxwellian plasma kinetics” Physics of Plasmas 24 (2017) 122105.