Report: DOE Plasma Science Center Travel Fellowship

Development of a Vlasov Solver for Nonequilibrium Plasma

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My visit to CFD Research Corporation (in Huntsville, Alabama) was from June 18th to 22nd, 2012. I have set some short-term/mid-term goals for our collaboration and had fruitful discussions there with Dr. Vladimir Kolobov and other researchers.

<Overview of the research>

Low temperature plasmas that experience several types of collisions and plasma-wall interactions are known to be in a non-equilibrium state. In order to capture the non-equilibrium phenomena, the velocity distribution functions (VDFs) must be obtained accurately. As for kinetic simulations, particle methods have been well developed yet statistical noise due to the use of macroparticles is unavoidable. In comparison to particle methods, a direct Vlasov simulation that solves the Vlasov equation coupled with collision terms achieves an improved resolution of the VDFs for non-equilibrium plasmas. The project includes three phases as follows.

1. *Implementation of numerical schemes with high order of accuracy:* Currently, we have developed two types of Vlasov solvers. One is an Eulerian method that uses a finite-volume upwind scheme without dimensional splitting. This achieves 2nd order accuracy in time, space, and velocity. The other is a semi-Lagrangian method that uses a cubic spline interpolation with dimensional splitting. This achieves 2nd order in time but 3rd order in space and velocity.

2. *Application of a Vlasov solver to low temperature plasmas:* Vlasov solvers are currently applied to three cases: (1) a collisionless sheath, (2) a collisional sheath, and (3) the discharge plasma of a Hall thruster. The Hall thruster case was presented at the 48th AIAA Joint Propulsion Conference [Hara et al., AIAA-2012-4313]. Both sheath cases are currently under investigation and will be compared to the theories of plasma-wall interaction for low temperature plasmas.

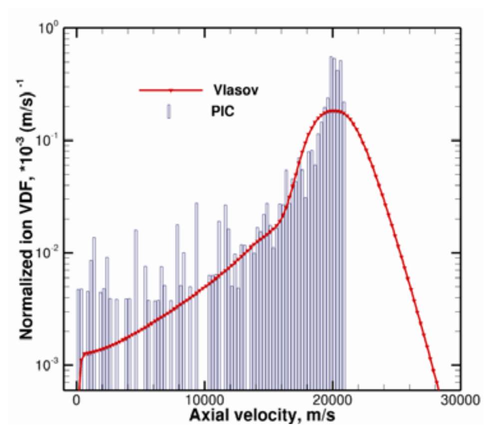

Fig. 1 Ion VDFs obtained from Vlasov and PIC simulations in the Hall thruster discharge plasma. No statistical noise observed from Vlasov solver.

3. *High performance computing:* For a three dimensional flow, the simulation goes up to six dimensions. In order to reduce the computational cost of the simulation, numerical

techniques such as parallelization and GPU computing will be implemented [Kolobov and Arslanbekov, J. Comp. Phys., **231** (2012)].

<Visit to CFDRC>

After the first two years of my doctoral degree, during which I learned about plasma/fluid simulations and the physics of low temperature plasmas, the visit to CFDRC in my second year was very fruitful.

1. *Development of Vlasov solvers:* The two methods (Eulerian and semi-Lagrangian methods) were compared for the collisionless sheath case. Through the discussions with the researchers in CFDRC, I was able to figure out the proper boundary conditions for both methods. We also discussed the plans for the collisional sheath case, which will be presented at APS Gaseous Electronics Conference in October, 2012.

2. *Testing the GPU computers at CFDRC:* A particle simulation code was used as our test case. Using two GPU computers at CFDRC (“Vlasov” computer with two NVIDIA C2075 cards and “Tesla” computer with one NVIDIA C1060 card), the speed up due to GPU computing was compared to a single CPU computation. As shown in Fig. 2, up to 300 times acceleration (!) was observed using one of the state-of-art GPU computers.

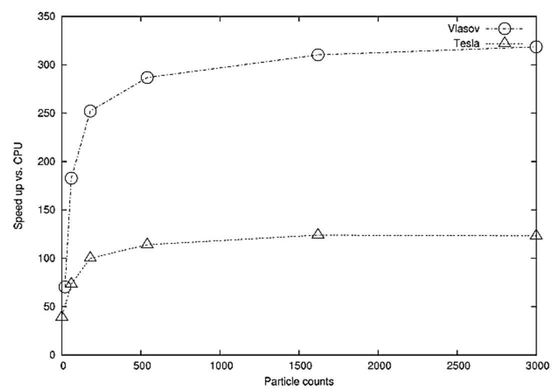

Fig. 2 Speed up comparison using a particle simulation test case. 300 times acceleration was observed using “Vlasov” computer.

3. *Application of Vlasov solvers to GPU computing:* A GPU kernel of the cubic spline interpolation was developed. Using the GPU computer in CFDRC, at least 10 times acceleration was found for a one dimensional linear advection scheme in comparison to a single CPU calculation. This indicates that semi-Lagrangian method will achieve up to 100 times acceleration in one-dimensional Vlasov solver (1D in physical space and 1D in velocity space). A more significant acceleration is expected for higher dimensional calculations. This will be further developed.