Final Technical Report of DE-FG02-06ER54789
Current-Driven Filament Instabilities in Relativistic Plasmas

This grant has supported a study of some fundamental problems in current- and flow-driven instabilities in plasmas and their applications in inertial confinement fusion (ICF) and astrophysics. It has also partially supported 4 PhD thesis projects in ICF, plasma astrophysics, and high performance computing. So far it has generated 20 publications [1-20], including 4 Physical Review Letters [1, 5, 9, 18]. The results have also been disseminated in a number of contributed and invited talks in international conferences (a list of selected invited talks is attached at the end of this report.)

1. The current-driven instabilities and their roles in fast ignition

Due to its importance to fast ignition (FI), the transport of an electron beam in a plasma has been recently studied intensively. The beam-plasma system is subject to various instabilities, including the Weibel/filament instability, the two-stream instability, and in general, oblique instabilities. Before our study, the evolution of the system was thought to be dominated by the Weibel/filament instability, an electromagnetic instability whose nonlinear evolution eventually caused the beam filaments merging into a single filament.

Our study uncovered a far more complex picture. We were the first to point out that the filament instability in fast ignition has an electrostatic component, induced by the temperature difference in the beam and the plasma return current, that significantly lowers the growth rate [1]. As the plasma temperature rises, the electrostatic field decreases and the filament instability growth rate can increase, a somewhat surprising result [10]. We also developed a formalism that allows us to obtain in a simple and compact form the general dispersion relation for arbitrary nonrelativistic electron distribution functions [4].

We found that the two-stream and oblique modes play an important role in the evolution of the beam-plasma system, competing with the Weibel/filament instability [6,7,20]. In low-density plasmas where collisions are unimportant, Particle-in-Cell (PIC) simulations under FI conditions showed [6] that the two-stream type of instabilities dominate the early stage of energy transfer from the beam drift energy to the beam and plasma thermal energy. The end stage of the nonlinear evolution is dominated by the Weibel/filament type of instabilities, resulting a beam with a moderately increased angular spread, reduced drift energy, and *no reduction* in the initial cross section.

As the beam propagates into denser plasmas, collisions, especially those between the background plasma electrons, become important. We found that collisions affect the Weibel/filament and the two-stream instabilities differently and thus change their relative importance in denser plasmas [7, 20]. Having developed a kinetic linear theory that employs a Krook-type collision operator, we showed that [7] collisions reduce the growth rate of or even stabilize the two-stream instability. Collisions also reduce the growth rate of the Weibel/filament instability at low densities. But at higher densities, collisions actually *increase* the growth rate of the Weibel/filament instability. These results were later extended to the more general oblique modes [20], where we found that collisions generally reduce the grow rates of the two-stream-type of modes but enhance the Weibel/filament-type of modes. This can have an important implication for fast ignition: the electron beam may be collimated in the dense core region through the nonlinear evolution of the Weibel/filament instability, a phenomenon observed in our PIC simulations [20]. This has the potential to provide a solution to the biggest obstacle faced by fast ignition: the divergence of the electron beam.

2. The flow-driven instabilities and their applications in astrophysics

In many astrophysical situations, ions moves along with electrons in a zero net current fashion and the free energy is dominated by the ions. Flow-driven instabilities are similar to the current-driven instabilities but grow at slower ion time scales. We have studied the linear theory and nonlinear evolution of flow-driven instabilities in astrophysical contexts such as gamma-ray bursts [2], low-luminosity astrophysical accretion flows [3, 11], and collisionless shocks [17, 19].

In gamma-ray bursts (GRB's), when one shell ejected from the central engine overtakes another shell, the situation is equivalent to two counter-propagating shells, viewed in the center-of-mass frame. A flow-driven filament instability can occur in the shell collision to generate magnetic fields, which are necessary to explain the observed synchrotron emissions. The electron-positron-proton plasma in each shell may share the same relativistic temperature but different shells in general have different temperatures. We analyzed the similar space charge effects [1] in the relativistic regime relevant to GRB [2]. The results showed that the space charges have similar effects on the instability as in the non-relativistic regime, reducing the growth rate and the range of unstable mode numbers. This proves the robustness and universality of the space charge effects in the filament instability.

A two-temperature plasma with the proton temperature higher than the electron temperature are a key ingredient of models for radiatively inefficient accretion flows (RIAFs). The Weibel/current filament instabilities are also a candidate to provide faster-than-Coulomb coupling between protons and electrons in two-temperature plasmas. The existence of a faster-than-Coulomb coupling in such plasmas would cast serious doubts on their existence. We found the linear growth rate and saturation level of magnetic fields for the Weibel instabilities driven by an ion temperature anisotropy, defined as $\alpha=T_\perp/T_{||}-1$ where $T_\perp$ and $T_{||}$ are ion temperatures perpendicular and parallel to the wave vector, in the small α-limit. It was shown that the ratio of the saturated magnetic energy to the initial ion energy scales as the fourth power of the electron to ion mass ratio, m/M, for an initially unmagnetized plasma with $\alpha<M/m$. PIC simulations confirmed the mass scaling and also showed that the electron energy gain is of the same order of magnitude as the magnetic field energy. This implies that the Weibel instabilities cannot provide a faster-than-Coulomb mechanism to equilibrate the two-temperature plasmas. The results also showed that when $\alpha<M/m$, the generated magnetic field in collisionless shocks of GRBs is much smaller than previously thought [3]. We later extended the study to the flow-driven instabilities and again found that they cannot provide significant ion-electron coupling due to the electron-ion mass disparity [11].

A modified ion-driven two-stream instability also plays an important role in the formation of collisonless shocks in magnetized plasmas. The knowledge gained and numerical tools developed to solve the dispersion relations for the current- and flow-driven instabilities in unmagnetized plasmas also proved useful in analyzing this instability as a source of dissipation necessary for the shock formation [19].

3. PhD thesis projects

This grant provided partial stipend and travel support in four PhD thesis projects at University of Rochester. Two PhD students graduated in 2011 and 2012, with two more expected to graduate in 2013.

3.1 Two-plasmon Decay Instability and Energetic Electron Generation from Laser-plasma Interactions in Inertial Confinement Fusion

The two-plasmon decay (TPD) instability is a significant concern in direct-drive ICF experiments for its low threshold and high-energy electron generation. This thesis project studied the TPD instability for parameters relevant to inertial confinement fusion using a 2-D particle-in-cell (PIC) code OSIRIS and a fluid code [12] developed in the project. In the linear regime, the growth rates and thresholds predicted by the linear theories were examined in both PIC and fluid simulations. Pump depletion and convective modes' domination were observed in the well-above-threshold PIC simulations [9]. The PIC simulations showed that both the absolute and convective modes saturate due to ion density fluctuations, which can turn off TPD by raising the instability threshold through mode coupling and lead to intermittent growth [9]. A series of PIC simulations were performed on the long-term (~10 ps) nonlinear behaviors of the TPD instability [18]. When the TPD threshold is exceeded, the simulation results showed that significant laser absorption and energetic electron generation occur in the nonlinear stage. The energetic electrons are mostly forward oriented, which poses a preheating risk for targets. The hot electrons are stage-accelerated from the low-density region to the high-density region. New modes with small phase velocities develop in the low-density region after saturation. These modes can couple to background thermal electrons and form the first stage for electron acceleration [9]. Rui Yan successfully passed his thesis defense exam in 11/2011.

3.2 Laser Channeling and Hosing in Millimeter-Scale Underdense Plasmas in Fast Ignition

This thesis studied laser channeling under parameters relevant to fast ignition with two-dimensional (2D) [5] and three-dimensional (3D) [15] particle-in-cell (PIC) simulations. Laser channeling was found to be a highly nonlinear and dynamic process. Channeling in 2D and 3D simulations displayed qualitatively similar physical features, including laser self-focusing/filamentation, laser hosing, and channel bending/bifurcation/self-correction. Residual electrons in the channel are heated to relativistic temperatures, which reduce the electron quiver momentum and cause the decoupling of the plasma and the laser. The eventual formation of a straight, low density channel allows the trailing ignition pulse to transmit with a >80% transmittance. There were quantitative differences between 2D and 3D channeling simulations. Channel advancing was faster in 3D due to easier channel formation and a larger ponderomotive force from laser self-focusing.

This thesis also studied dependences of the hosing instability on plasma temperatures and dispersion. Coupled laser envelope and plasma density perturbation equations for short and long pulses were derived from the relativistic fluid theory. Hosing equations were then derived from these coupled equations using a variational method. A parameter α, which is the sum of the normalized relativistic plasma pressure and internal energy, was introduced to represent the plasma thermal effects. In a relativistically hot plasma, α is much larger than 1, and suppression of the laser ponderomotive force and laser hosing was found. Analysis of the hosing equations found that the fastest growing mode shifts to longer wavelengths as α increases. This solved a long-standing puzzle that the hosing modes observed in both experiments and simulations had much longer wavelengths than what predicted by the hosing theory for a cold plasma. Gang Li successfully passed his thesis defense exam in 4/2012

3.3 Energy Transfer and Particle Energization in Collisionless Astrophysical Plasmas

In addition to the electron-ion coupling in the two-temperature plasma [3, 11] mentioned in Section 2, this thesis project also studied weakly compressive fast shocks that can occur in magnetic reconnection outflows and are considered to be a site of particle energization in solar flares [17, 19]. The project studied the microphysics of perpendicular [19] and quasi-perpendicular [Park et al., in press], low Mach number collisionless shocks using two-dimensional particle-in-cell (PIC) simulations with a reduced ion/electron mass ratio and a moving wall boundary method for initial generation of the shock. The results revealed the prevalence of shock drift acceleration (SDA) of both electron and ions in a shock with Alfven Mach number of $M_A =6.8$ and ratio of thermal to magnetic pressure $\beta=8$. The transition energy between the thermal and non-thermal spectrum and the spectral index from the simulations are consistent with some of the X-ray spectra from *RHESSI* in the energy regime of $E< 40\text{-}100$ keV. Plasma instabilities associated with the shock structure such as the modified-two-stream and the electron whistler instabilities were identified using numerical solutions of the kinetic dispersion relations. It was also shown that the results from PIC simulations with reduced ion/electron mass ratio can be scaled to those with the realistic mass ratio. Jaehong Park is expected to have his thesis defense exam in 4/2013.

3.4 Particle-in-Cell Simulations with Charge-Conserving Current Deposition on Graphic Processing Units

This thesis project developed an implementation of 2D [14] and 3D fully relativistic, electromagnetic particle-in-cell code, with charge-conserving current deposition, on parallel graphics processors (GPU) with CUDA. A particle-based computation thread assignment was used in the current deposition scheme and a parallel particle sorting scheme was also developed and used. The implementation took advantage of fast on-chip shared memory. With the few-branch current deposition scheme and efficient use of the shared memory, our current GPU PIC code can achieve a one-particle-step process time of 1.2-3.2 ns in 2D and 2.3-7.2 ns in 3D using linear interpolation, depending on plasma temperatures, on a Tesla M2050 (Fermi) card, corresponding to speed ups of ~40 from the SSE version and ~80 from the non SSE version of the OSIRIS code on the fastest i7 processor. We have also integrated our GPU computation kernels into the production code OSIRIS. This allows us to ship the computation-intense kernels, such as current deposition and smoothing, field solver, particle pusher and sorting, and collision calculations to the GPU and to retain the original code's MPI infrastructure to handle communications between CPU's. The computation-intense kernels can constitute 90% of a computation cycle but only 10% of the source code. Various well-tested particle and field boundary conditions, constituting more than 90% of the source code, can be retained without modification. This approach can help speedily develop a production code for the heterogeneous GPU/CPU clusters at leadership class facilities such as Blue Waters, Titan and TACC. Xianglong Kong is expected to have his thesis defense exam in 5/2013.

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Selected Invited Presentations

2011	Invited talk, "Particle-in-cell simulations with charge-conserving current deposition on graphic processing units," the 22nd International Conference of Numerical Simulation of Plasmas, *September 7-9, 2011, Long Branch, New Jersey*
2011	Seminar, "Particle-in-Cell Simulations Using Graphic Cards," January 13, Princeton Plasma Physics Lab
2010	Seminar, "Laser Channeling and Hosing in Fast Ignition," July 14, Department of Physics, Shanghai Jiaotong University, Shanghai, China
2009	Seminar, "*Nonlinear Evolution and Energy Transfer in Plasmas with Counter-Streaming Particles,"* July 2, Department of Physics, Shanghai Jiaotong University, Shanghai, China
2009	Invited talk, "*Particle-in-Cell Simulations for Fast Ignition*," Forum on Frontiers in Science, Jan. 9, Shanghai Jiaotong University, Shanghai, China
2008	Overview talk, "*High Intensity Laser and Energetic Particle – Matter Interactions,"* Workshop on Scientific Opportunities in HEDLP, Aug. 25-27, Washington DC

2008	Invited poster, "*Particle-in-Cell Simulations for Fast Ignition,*" The 2008 SciDAC (Scientific Discovery through Advance Computing) Conference, Jul. 13-17, Seattle, Washington
2007	Invited talk, "*Laser channeling in mm-scale underdense plasmas of fast ignition targets,*" The 20th International Conference on Numerical Simulation of Plasmas, Oct. 10-12, Austin, TX
2007	Review talk, *"Progress in Fast Ignition Research,"* The 37th Anomalous Absorption Conference, Aug. 27-31, Maui, HI
2007	Invited talk, *"Recent Particle-in-Cell Simulation Results on Fast Ignition,"* West Lake International Workshop on Fusion Theory and Simulations, Mar. 18-22, Hangzhou, China
2006	Invited talk, *"Recent Particle-in-Cell Simulation Results on Fast Ignition,"* International Conference on Physics Education and Frontier Physics, Jun. 27-30, Taipei, Taiwan