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The Development of Scaled Astrophysical Experiments for Current and Future Lasers

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FY07 LDRD Final Report

Project Title: "The Development of Scaled Astrophysical Experiments for Current and Future Lasers"

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Abstract

This research proposes to design and field scaled astrophysical experiments for the Laboratory's intense-short-pulse Titan laser in the collisionless plasma regime to investigate plasma-scaling properties with regard to powerful astrophysical phenomena such as gamma-ray bursts and supernovae. In addition, we propose to design an experiment using high-gain thermonuclear ignition coupled with petawatt lasers to produce conditions relevant to a magnetized, radiation-dominated accretion disk surrounding stellar black holes. This work will enable development of a high-energy-density (HED) platform for scaled astrophysical science on fusion-class lasers. We will implement proton deflectometry to characterize magnetic fields associated with the interaction of short-pulse, high-energy lasers with solids

Introduction/Background

The purpose of this 3 year LDRD is to design and to field a set of staged scaled astrophysical experiments on the Titan laser to build toward a High Energy Density (HED) platform for astrophysical science on NIF. The LDRD research to accomplish this involves 3 objectives. (1) Demonstrate comprehensive scaling experiments on Titan in the collisionless plasma regime. This will lead to an astrophysics relevant scaling in the collisionless regime. (2) Establish relevance to energetic astrophysical phenomena such as Gamma Ray bursts (GRBs), Supernova remnants and AGN jets. (3) develop a full NIF + high gain +ARC astrophysics design for radiation dominated accretion disks around black holes. This will permit both the collisionless and the collisional regimes of astrophysical environments to be studied on NIF.

Unique regimes of collisionless astrophysics may be accessible on the Titan laser. Experiments concerned with the Weibel instability relevant to gamma-ray burst shocks may be possible on Titan. This instability is a 2-stream magnetic instability that leads of current filamentation. It is thought to be relevant to the source of the strong magnetic fields in GRB shocks. Relevant conditions thought to be present in the internal shocks due to shell collisions inside the GRB fireballs may be accessible on Titan. These regimes may be reached on Titan by driving the forward beam of hot electrons into a preformed plasma. The ensuing electron current filamentation due the Weibel instability may be diagnosed by using stacks of radiochromic film and particle track detector film.

This research has significant value for long term laboratory goals. It develops scaled collisionless plasma experiments on Titan and an integral use of ignition on NIF. This will provide confidence in astrophysical High Energy Density (HED) scaling and design of the first earth based experiment to probe scaled radiation dominated accretion disks which are an important component of many astrophysical phenomena. This research pushes the boundaries of exciting new science in HED physics leading to high visibility and collaboration led by LLNL. It uses and validates state-of-the-art 3D Hybrid plasma simulation codes (LSP). It uses and validates the technique pf Proton Deflectometry for probing ultra-strong magnetic fields. It develops the groundwork for eventual experiments on a NIF and Omega-EP petawatt laser. Finally, it explores new HEDP regimes and develops experimental test beds of high temperature (T > keV) and high density experimental science of relevance to laboratory programs.

Expected Results

We expected to experimentally demonstrate scaling in collisionless plasmas on the Titan laser for possible astrophysics experiments. We planned to design and field a set of scaled experiments to study the Weibel instability relevant to gamma-ray burst shocks, and also design a scaled experiment using the concept of high-gain thermonuclear ignition to develop astrophysics experiments for fusion-class lasers. The success of this project will give us the ability to successfully scale Laboratory experiments to astrophysical phenomena, and test scaling methodology relevant to the science-based Stockpile Stewardship Program at LLNL.

Research Activities

Our research activities for this 3 year LDRD were unexpectedly cut short without explanation after one year which severely curtailed our research plan for the LDRD. We were notified of this cut after only 7 months into FY07 (our first year) for this 3 year LDRD. As such, many of our goals were not possible. This was particularly unfortunate as most of our experiments to demonstrate scaling for collionless plasmas that we were designing in the first year of the LDRD, were not scheduled to be accomplished until years 2 and 3 and as a result of the cut to this proposal could not be attempted. We were, however, able to carry out initial experiments demonstrating proton deflectometry as a means of measuring superstrong magnetic fields generated in laser solid interactions.

FY07 Accomplishments and Results

We participated in laser experiments to determine the range of plasma parameters and observables accessible on Titan (e.g., laser intensities, density-scale lengths, electron temperatures, magnetic fields, electric fields, harmonics, and pressures). This required experimental scans and simulations with both radiation-hydrodynamics codes and LSP/PIC codes. We conducted an experiment on Titan to study the B fields generated in the interaction of an ultra-intense laser with a thin metallic foil. We investigated B fields as a function of target thickness and energy in the laser pulse. Simulations using LSP code were started to discriminate the respective influence of B and E fields on the protons trajectories. Laser generated protons were used to probe the temporal and spatial evolution of megagauss magnetic fields. Grid deflectometry techniques were applied to proton radiography to obtain precise measurements of proton beam angles caused by magnetic fields in laser produced plasmas. We obtained data in two different regimes of interactions at ultra high intensity (10^{20} W/cm2) where hot electrons are supposed to be responsible of the B field, and at lower intensity (10^{17} W/cm2) and later time where the gradients of temperature and density are responsible of the B field.

We used laser driven proton beams to probe high magnitude B fields created by a short laser pulse. With a laser driven proton beam, high magnitude electric and magnetic fields can be probed near critical density with a temporal resolution of a picosecond. The first experiment presented data on self-generated B fields during the proton acceleration processes. The preliminary results show the presence of large B fields at the back of the target. LSP simulations confirm that a large B field (10 MG) on a really small distance (less than a micron) has a strong influence on the radial velocity of the protons. From the mesh distortions, the B field amplitude is estimated at 500 MG. Further experiments changing the intensity on target or the target material should be conducted to confirm the first measurement. Our second experiment obtained data from a two beams setup. In this experiment the B fields are generated on a second target and are thus decoupled from those generated during the proton generation processes. Data are recorded at late time, i.e. when the B fields are induced by temperature and density gradients. The first results estimate B fields in the order of 0.01 MG. Further experiments will be carried out to measure the B fields at shorter time, i.e. when the B fields are generated by the hot electrons current. This work resulted in a paper published in Astrophysics and Space Science.
"Proton radiography of megagauss electromagnetic fields generated by the irradiation of a solid target by an ultraintense laser pulse" (Le pape, S., Hey, D., Patel, P., Mackinnon. A., Klein, R.I., Remington, B., Wilks, S., Ryutov, D., Moon, S., Foord. M.), 2007, Astrophysics and Space Science, Vol. 307, issue 1, 341.

To summarize, in this first and only year of our LDRD we:

- Reviewed Titan experiments to date and determined the range of plasma parameters which can be reached by scaled collionless experiments
- We made initial designs of experiments to test the scaling theory in the collisionless regime
- We made an initial study of achievable conditions on NIF with high-gain ignition
- We obtained data on Titan with proton deflection for initial measurement of B-field