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Developing the Physics Basis of Fast Ignition Experiments at Future Large Fusion-class lasers

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FY07 LDRD Final Report

Developing the Physics Basis of Fast Ignition Experiments at Future Large Fusion-class lasers

LDRD Project Tracking Code: 05-ERI-001
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Abstract:

The Fast Ignition (FI) concept for Inertial Confinement Fusion (ICF) has the potential to provide a significant advance in the technical attractiveness of Inertial Fusion Energy (IFE) reactors. FI differs from conventional “central hot spot” (CHS) target ignition by using one driver (laser, heavy ion beam or Z-pinch) to create a dense fuel and a separate ultra-short, ultra-intense laser beam to ignite the dense core. FI targets can burn with ~ 3X lower density fuel than CHS targets, resulting in (all other things being equal) lower required compression energy, relaxed drive symmetry, relaxed target smoothness tolerances, and, importantly, higher gain. The short, intense ignition pulse that drives this process interacts with extremely high energy density plasmas; the physics that controls this interaction is only now becoming accessible in the lab, and is still not well understood.

The attraction of obtaining higher gains in smaller facilities has led to a worldwide explosion of effort in the studies of FI. In particular, two new US facilities to be completed in 2009/2010, OMEGA/OMEGA EP and NIF-ARC (as well as others overseas) will include FI investigations as part of their program. These new facilities will be able to approach FI conditions much more closely than heretofore using direct drive (dd) for OMEGA/OMEGA EP and indirect drive (id) for NIF-ARC. This LDRD has provided the physics basis for the development of the detailed design for integrated Fast ignition experiments on these facilities on the 2010/2011 timescale. A strategic initiative LDRD has now been formed to carry out integrated experiments using NIF ARC beams to heat a full scale FI assembled core by the end of 2010.

Introduction:

The Fast Ignition (FI) concept was proposed upon the emergence of ultra-high-intensity, ultra-short pulse lasers using chirped pulse amplification technique. The concept is different from conventional central hot spot (CHS) in the sense that compression and ignition phases are separate. It was immediately recognized as an attractive concept that was compatible with any fuel compression driver (*i.e.* laser, Z-pinch, and ion beams) and had the potential for higher gains and smaller energy requirements than the CHS approach. The initial concept is shown schematically in Fig. 1. In the original incarnation of the FI concept, after the fuel is compressed by an external driver, a powerful precursor laser pulse of 10^{-10} s duration is focused to a small spot on the compressed fuel. The conceptual purpose of this laser is to expel plasma radially by the ponderomotive forces creating a channel through ~1 mm of coronal plasma, at densities up to the critical, that surrounds the compressed fuel. A subsequent main ignitor pulse would be propagated through the channel to the critical surface where a stream of energetic (~1 MeV) electrons would be produced. The actual energy distribution of the laser generated electrons would be tailored to have a range matching the rR of the compressed core, which would mean that a small fraction of the core could be elevated to ignition temperatures.

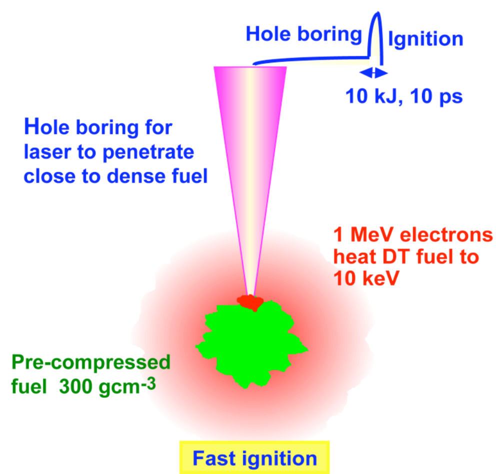

Fig. 1. Schematic of the channeling and hole-boring concept first proposed for fast ignition.

Early research on laser induced plasma channels, and propagation of powerful pulses in those channels, showed that there were too many complications, thus motivating an alternative design using a hollow Au cone inserted in the spherical shell as illustrated in Fig. 2(a). The fuel compression implosion produces dense plasma at the tip of the cone, while the hollow cone permits the short-pulse ignition laser to be transported inside it without interference, and enables the generation of hot electrons at its tip, very close to the dense plasma. A variant cone concept illustrated in Fig. 2(b) uses a thin foil to generate a proton plasma jet with multi-MeV proton energies. In this concept, the protons deliver the energy to the ignition hot spot — albeit with the loss of efficiency in the conversion of hot electrons into energetic protons.

Experimentally investigating the fast ignition concept is challenging. The fast ignition concept involves extremely high energy density physics: ultra-intense laser (intensities>10^{19} W cm^{-2}) produces >100 Mbar pressure, magnetic field in excess of 100 MGauss, and electric fields >10^{12} V/m. These laser fields generate massive currents (~ giga-Ampere in 10's μm diameter) at the critical surface. These currents are supposed to propagate through hot (keV), dense (>100 n_c) plasma. The sheer scale of the problem, e.g., generation of a large current pulse of 10's ps time duration that traverses ~100 μm requires investigations of this concept inherently require high energy and power laser facilities. Experimental access to this regime in a limited way began with operation of the LLNL Nova PW followed, after its demise, by RAL PW and now Titan at LLNL.

Planned multi-PW facilities (OMEGA EP, NIF-ARC, FIREX I) which include high-energy longer pulse beams, will be the first facilities to allow access to the physical domain that is truly relevant to fast ignition. Nevertheless, considerable progress has been made over the last few years in understanding the issues critical to the fast ignition concept and in developing an integrated understanding of how these issues play out in a realistic fast ignition target.

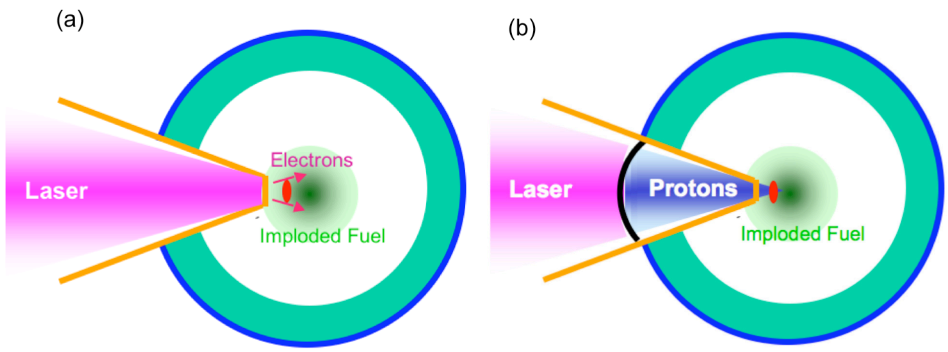

Fig. 2. The cone-guided implosion concepts in which (a) electrons or (b) protons ignite the compressed fuel.

Research Activities

In order to provide the physics basis for integrated experiments on large multi-kj laser systems such as Omega EP and NIF-ARC this LDRD has carried out research in the following areas:

1) Simulations that describe indirect drive of a capsule in a hohlraum with a re-entrant cone.
2) Experiments on RAL PW and Titan lasers to investigate the outstanding issues of electron source generation by intense laser pulses and the subsequent transport of these electrons through solid density materials.
3) Simulations to investigate optimum conditions for proton production
4) Proton focusing of PW laser pulses to heat solid density materials

This work has been disseminated widely in international conferences and published in a series of refereed publications that are described in detail in the Results and technical outcomes section.

Results/Technical Outcome

A summary article describing the technical progress in fast ignition by summer of 2007 was published in Phys of Plasmas in July 2007 by M. Key [UCRL-TR-226302]. This publication places our LLNL work in context with research from other US and international institutions. A summary article that describes technical progress in the field of proton fast ignition and proton source characterization was published by M.Key et al., in a special issue of Fusion Science and Technology (2006) [UCRL-JRNL-209599]. This paper describes proton fast ignition work undertaken at LLNL in context with work from US and international institutions. The following articles describe our results in electron transport, target heating by high-energy electrons and protons and uses of protons for probing plasmas:

1. An article describing our work on the simulation of Fast Ignition hydro assemblies was published by S. Hatchett et al., in Fusion Science and Technology volume 49 issue 3 (2006).
2. Surface heating of wire plasmas laser irradiated cone geometry was described by J. Greene et al., in Nature Physics (2007).
3. Energy transport in solid density plasmas was presented by K. Lancaster et al., Physical Review Letters (2007).
4. Fast electron transport and heating of solid targets using Ka fluorescence diagnostics was published by E. Martinolli et al., in Physical Review E (2006).
5. Initial studies of Electron transport and target heating in cone wire targets was published in Nature by R. Kodama et al., Volume 432, (2005).
6. The most recent work on target heating of solid matter by light pressure driven shocks at ultra-relativistic intensities has been submitted to Physical Review Letters (2007).
7. Heating of solid targets to temperatures of 1 million degrees by MeV protons was published in Physics of Plasmas by B. Zhang et al., (2007).
8. The use of mono-energetic protons for diagnosing magnetic fields was described in Review of Scientific Instruments, (2006).

Exit Plan:

In FY08 we started work on a strategic initiative LDRD to prepare and carry out integrated Fast Ignition experiments on the NIF laser using NIF ARC to heat a capsule imploded by the conventional NIF laser. This project involves the creation of a closely coupled team to complete an experimental design for Fast Ignition experiments on the NIF by the end of 2010. The team will carry out hydrodynamic target design and experiments, high-energy particle production and transport simulations and experiments and diagnostic evaluation and development with the goal of creating a point design for integrated short and long pulse experiments on NIF. Execution of the experimental campaign will then become integrated into the NIF plan in time for the experiments in 2010. It is expected that NNSA will take over funding of fast ignition science once viability of the technique has been established through the NIF integrated experiments

Summary

This LDRD has provided the physics basis for Fast ignition experiments on large-scale lasers. A new strategic initiative has been now been launched that will provide the framework for Fast ignition experiment on NIF ARC in 2010. Work undertaken with this LDRD has been widely disseminated and published in the highest quality science journals (e.g. Physical Review Letters, Nature, Physics of Plasmas).

Articles attached to this report:

1. M. Key, Physics of Plasmas, 14, 5 p 055502 (2007); [UCRL-TR-226302]
2. M. H. Key et al., Fusion Science and Technology, 49, p440; [UCRL-JRNL-209599]
3. S. Hatchett et al., Fusion Science and Technology, 49, p200. (2006); [UCRL-JRNL-215884]
4. J. Green et al., Nature Physics, 3, p853, (2007); [LLNL-JRNL-401083]
5. K. Lancaster et al., Physical Review Letters, 98, p125002, (2007); [LLNL-JRNL-401081]
6. E. Martinolli et al., Physical Review E, 73, p056309, (2006); [LLNL-JRNL-401080]
7. Nature Volume 432, Iss:7020 p1005-1008, (2005); [LLNL-JRNL-401085]
8. K. Akli et al., submitted to Physical Review Letters (2007); [UCRL-JRNL-233806]
9. B. Zhang et al., Physics of Plasmas , 14, p092703 (2007). [UCRL-JRNL-211106]
10. C.K. Li et al., Review of Scientific Instruments, 77, p10E725 (2006); [LLNL-JRNL-401084]