OVERVIEW AND STATUS OF DIRECT_DRIVE INERTIAL CONFINEMENT FUSION IN THE UNITED STATES

P. B. Radha
Laboratory for Laser Energetics
University of Rochester
Rochester, NY 14623
Email: rbah@lle.rochester.edu

Abstract

Two different approaches to direct-drive Inertial Confinement Fusion in the United States are discussed in this poster. Laser Direct Drive is being explored on the OMEGA and NIF laser with the goal of understanding implosion physics and scaling of OMEGA results on MegaJoule facilities like the NIF. Magnetic Direct Drive experiments being pursued at the Z Pulsed Power Facility and the OMEGA laser indicate that successful flux compression and measureable yields can be obtained in integrated experiments that include compression, preheat and pre-magnetization. Challenges remain for both approaches including improving laser energy coupling into the plasma, control of nonuniformity, and advanced diagnostics.

1. INTRODUCTION

Direct drive (DD) inertial confinement fusion offers a potential path for high yield and ignition. Two different approaches are being considered in the United States. In the laser direct-drive (LDD) approach [1] led by the University of Rochester, nominally identical laser beams implode a capsule with a layer of cryogenic deuterium–tritium (DT) resulting in a hot core surrounded by a cold high-density shell. LDD is of interest because nearly four times more energy from the laser is coupled into the kinetic energy of the imploding shell than in indirect drive. Alpha particles produced from the fusion reaction of the deuterium and tritium nuclei slow down primarily through collisions with the background electrons. Through electron-ion collisions, the energy is transferred to the ions increasing the ion temperature and thus the fusion reaction rate. Ignition is reached when a burn wave travels into the high-density shell producing more energy than that supplied by the laser. Simulations indicate that ignition is potentially achievable [2] at the National Ignition Facility [3].

In another approach, azimuthal magnetic fields created by an axial flow of multi-mega-amp current along a cylindrical target compress the target due to the Lorenz force. In the magnetized liner inertial fusion (MagLIF) [3] being pursued at the Sandia National Laboratories, an external axial magnetic field (> 10T) is used to pre-magnetize the deuterium fuel. A kJ, 1TW laser pulse is used to preheat the plasma just as the 16-20 MA current begins to quasi-adiabatically compress the pre-magnetized deuterium. MagLIF is the first magneto-inertial fusion concept to fully demonstrate that pre-heat, pre-magnetization, and compression can work in concert to produce measureable thermonuclear fusion. Scaled laser driven MagLIF research is also being performed at OMEGA. Ignition remains a challenge for both these approaches including improving understanding of the plasma conditions, controlling nonuniformity, improving laser coupling, and developing enhanced diagnostics.

2. LASER DIRECT DRIVE

OMEGA [4] and NIF-scale experiments are being used to improve understanding of LDD physics, validate models at the different energy scales, and provide the physics basis for ignition with LDD. On OMEGA, a combination of experiments including ignition-relevant cryogenic DT-layered implosions and experiments such as those specifically studying shocks, nonuniformity seeding and growth etc. are used to study the physics of LDD. OMEGA implosion experiments at ~25 kJ of laser energy are hydrodynamically scaled from ignition designs at ~1.8-2.1 MJ. A range of parameters including the shell implosion velocity (3×10^7 cm/s < V_{imp} < 4.3×10^7 cm/s), shell adiabat ($2.2 < \alpha < 7$, where α is defined as the ratio of the pressure to the Fermi-degenerate pressure) are systematically explored, guided by state-of-the-art radiation–hydrodynamic simulations. Observations indicate that as implosions become increasingly ignition relevant (i.e., with decreasing adiabat and increasing implosion velocity), target performance becomes increasingly compromised relative to radiation–hydrodynamic simulations. The highest hot-spot pressure obtained in OMEGA implosions is 56±7 Gbar, ~47% of the threshold value for ignition [5]. Three-dimensional simulations indicate that departures from spherically symmetric behavior resulting from nonuniformities seeded by beam-to-beam variations are likely responsible for compromised behavior for moderate-adiabat implosions (α ~ 4) [6]. (Fig. 1) For lower adiabats, simulations indicate that additional reasons may likely contribute including debris on target and short wavelength growth seeded by laser speckle. To improve target performance, several steps are being taken at the facility to improve uniformity through improved balance between the beams and smoother targets. In addition, implosions with adiabat ~7 conducted on OMEGA scale to fusion yields of ~300 kJ at NIF energies, showing the potential advantages of LDD.

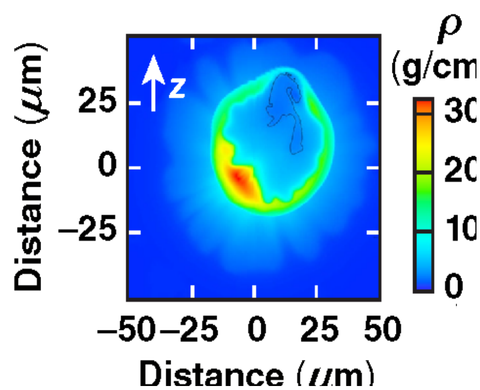

Fig. 1: A slice of the mass density profile from a three-dimensional hydrodynamic simulation at peak compression showing the bubble formed in the shell due to long wavelength nonuniformities seeded by beam-to-beam imbalances. Fuel and heat escapes the hot spot through the low-density bubble, compromising performance in these high-adiabat implosions.

For MegaJoule-class machines such as the NIF, the coronal density scale length is ~4× larger than that on OMEGA. Therefore, interactions of the laser with the plasma such as cross-beam energy transfer and preheat caused by electrons accelerated by plasma waves induced by the laser are expected to influence performance. Experiments on the NIF [7] are supplementing OMEGA experiments with the goal of validating models that predict high yield and ignition. Improved laser-energy coupling has been demonstrated by the mitigation of cross-beam energy transfer using the wavelength detuning capability of the NIF beams [8]. Mitigation of electron preheat and improved implosion symmetry will be the focus of future experiments on the NIF.

3. MAGNETIC DIRECT DRIVE

Promising ion temperatures (~ 3KeV) and neutron yields ($5x10^{12}$ DD neutrons and secondary DT yields of ~5×10^{10}) have been obtained with MagLIF experiments at relatively low implosion speeds of ~7×10^6 cm/s. [9] These high temperatures are consistent with the time-integrated images of the hot emitting plasma in the 6-9 keV photon energy range (Fig. 2). At the same time, magnetic field-radius products of 0.4-0.5 MG-cm [10] have been inferred which not only indicates successful magnetic flux compression but confinement of thermonuclear tritons and sufficiently high magnetic fields to inhibit thermal conductivity losses required for ignition.

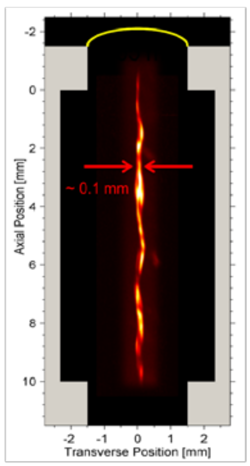

Fig. 2: Time integrated self-emission image of the hottest region of the fuel at stagnation.

Recent work in MagLIF has been focused on two areas. The first is centered on improving the physical understanding of plasma conditions from the initial magnetization and laser heating of the fuel to stagnation and burn. This has led to more than doubling of fusion yields from initial experiments, which are now within ~50% of pre-shot simulation predictions. The other focus area is the development of more capable platforms on Sandia's Z with increased levels of pre-magnetization, drive current, and fuel pre-heating. Simulations indicate 100kJ DT fusion yields with gain ~1 could be obtained with relatively modest upgrades to the MagLIF platform (30T magnetic fields, laser energies of 3-4kJ, currents ~25MA).

4. SUMMARY

Direct-drive inertial confinement fusion is a promising approach to obtain high fusion yields. The focus of Laser Direct Drive is to improve cryogenic implosions performance on the OMEGA laser and understand issues relating to laser-plasma instabilities such as laser-energy coupling and fast-electron preheat relating to MJ-scales on the NIF laser. Plausible mechanisms for the degradation of implosion performance include the formation of bubbles due to long wavelength nonuniformity, through which heat and fuel escape the hotspot. While OMEGA implosions can be hydrodynamically scaled to the NIF, Laser-Plasma instabilities cannot. In parallel, experiments on the NIF laser use to study the effects of these instabilities on energy coupling and preheat indicate that coupling can be improved using by detuning the wavelength of overlapping beams. The Magnetized-Liner Inertial Fusion experiments indicate that preheat, pre-magnetization, and compression can produce measureable yields. Challenges remain for both approaches including improving laser energy coupling, preheat, and control of nonuniformity.

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