

The quest for laboratory inertial fusion burn in the United States

D H Crandall

Independent

crandallhd@gmail.com

Abstract. Ignition and significant fusion yield from inertial confinement fusion (ICF) remains a grand scientific challenge with significant near-term and long-term applications. The ICF community in the U.S. is executing a coordinated effort to explore three viable approaches: laser x-ray drive, laser direct drive, and magnetic direct drive. Cooperative efforts from multiple institutions are directed at the physics basis of each of the three approaches with advancing diagnostics, precision targets, and improved simulations being the basis for the quest. X-ray drive experiments between 2010 and 2012 at the National Ignition Facility (NIF) gave yields much lower than expected because of both challenging hydrodynamics associated with high capsule convergence ($\sim 35\times$) and laser-plasma instabilities (LPI's) in the hohlraum. Recent experiments employing a variation of the laser pulse and resulting in lower convergence and lower hydrodynamic instability growth gave higher yields approaching 10^{16} neutrons (for the first time with significant fusion heating of the fuel), roughly in agreement with predictions for that approach. At the Omega Laser Facility the direct laser drive of the capsule is being developed to determine what could be expected if the NIF were reconfigured for spherical direct drive. Recent experiments on OMEGA, hydrodynamically scaled to the NIF, project to yields similar in nature to those of the best x-ray drive cases. Mitigation of cross-beam energy transfer (CBET) is required for improvement in direct-drive implosions. At the Z pulsed-power facility, a new approach of magnetically pinching a cylinder containing magnetized and laser-heated plasma shows promise for attaining significant fusion yield. Improvements in this technique are being addressed at a number of facilities. In addition to the fusion-yield experiments, a number of basic science studies use the advanced facilities to study plasma physics, materials science, and astrophysical phenomena at extreme parameters not previously available in a laboratory.

1. The U.S. ICF community seeks understanding of physics leading toward greater fusion yield

Through coordinated research, three approaches to laboratory fusion burn are being developed, following the community-developed plan for inertial confinement fusion (ICF) [1]. Highly capable facilities, including the National Ignition Facility (NIF; Livermore, CA), the Omega Laser Facility (Rochester, NY), and the Z pulsed-power facility (Albuquerque, NM) are central to this research.

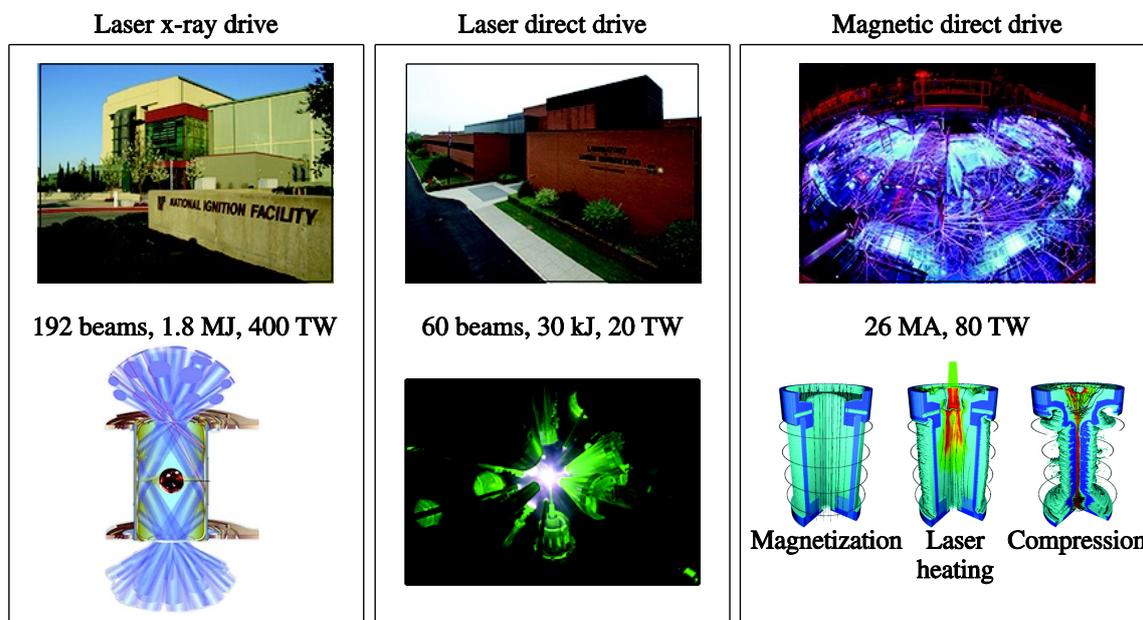
Advanced diagnostics, precision targets, and detailed simulations are critical to all three approaches. Greater resolution in time and space of the fusion capsule along with emissions from it is a particularly important objective of diagnostics development. Experiments that appropriately agree with detailed simulations are expected to serve as touch points for developing physics understanding



and seeking increased fusion yields. In all three cases, advances have been achieved over the past two years that provide the basis for further research and development.

2. Laser x-ray drive has achieved fusion heating for the first time

At the NIF, depicted in the first panel of figure 1, laser beams are directed to the inside walls of a hohlraum, where they generate x rays to fill the cavity and drive the ablation of the spherical capsule. The capsule has an outer ablator material (CH, Be, or high-density carbon) with an inner frozen shell of deuterium and tritium (DT) ice and central DT gas. Experiments at the NIF from 2010 through 2012 used a target and laser pulse designed to achieve ignition and modest fusion gain. The laser pulse had four steps in energy selected to drive the capsule on a low adiabat (~1.5) to a greater-than-35x convergence. The experiments achieved a fusion yield significantly lower than expected because of the growth of hydrodynamic instabilities, high convergence, and time variation of the x-ray drive. The hohlraums employed in these experiments were dominated by laser-plasma instabilities (LPI's), limiting the accuracy and quantitative understanding of the time- and space-varying radiation field needed for the demanding implosions required for ignition.



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Figure 1. The three approaches to fusion burn currently in development in the U.S. ICF program and the major facilities where research is being conducted.

To drive the capsule to lower convergence with lower hydrodynamic instability growth, a laser pulse with higher initial power (foot) and fewer energy steps was employed: the “high-foot” implosions [2]. These experiments are on a higher adiabat (~2.5) and are not predicted to result in ignition (more fusion yield than laser energy input to the target). In these experiments, yield increased by about a factor of 10 to within about a factor of 2 of prediction, and for the first time significant heating of the fuel by fusion alphas resulted in an increased fusion yield (see figure 2). These experiments are within about a factor of 2 of the hot-spot density, temperature, and pressure required for ignition. Under these conditions the yield is slightly more than doubled as a result of alpha heating [2,3].

Understanding and improving the hohlraum energetics and x-ray drive at the NIF are critical to achieving the ignition goal. Hohlraums with different shapes and different gas fills are being investigated [4] along with different ablators for the capsule that have either improved hydrodynamic

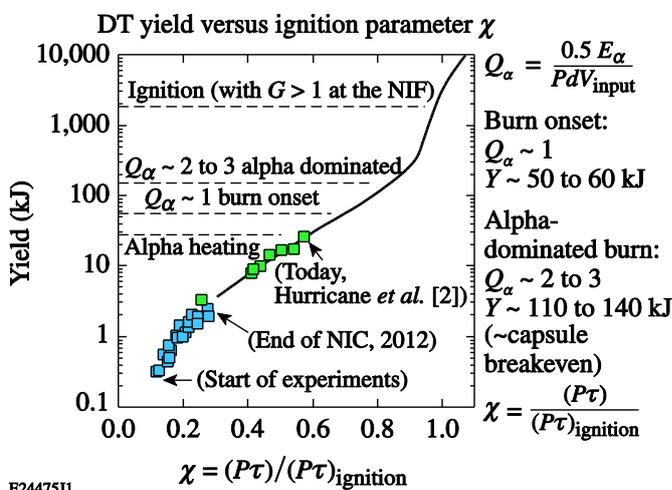
behavior or are better matched to a specific hohlraum and radiation pulse. A number of papers within this volume discuss these investigations; in particular see Hurricane *et al.* [2].

3. Laser direct-drive experiments seek an understanding of what might be achieved by reconfiguration of the NIF for spherical direct drive

Most experiments on laser direct drive are conducted at the Omega Laser Facility, depicted on the center panel of figure 1. Experiments are also conducted at the Nike KrF laser at the Naval Research Laboratory and at the NIF [with polar direct drive (PDD) [5], which approximates symmetric drive without spherical laser beam input]; these experiments address specific direct-drive physics issues. Experiments on OMEGA investigate spherical drive of layered DT-filled capsules with an extensive suite of diagnostics. Hydrodynamic scaling of parameters used on OMEGA to NIF laser energies allows one to infer what may be accomplished with spherical drive at the NIF. The NIF can be reconfigured for spherical direct drive but the time and cost of reconfiguration lead to a requirement for high confidence as to the fusion yield that might be obtained. The physics of spherical direct drive presents a compelling opportunity for laser-driven fusion. Relative to x-ray laser drive, the direct coupling requires smoother laser beams but, for a given laser energy, will allow ~7x more fuel to be compressed at the same implosion velocity, in turn requiring 3x- to 4x-lower stagnation pressure (~120 Gbar versus ~350 Gbar for NIF indirect drive designs) and lower convergence as a result.

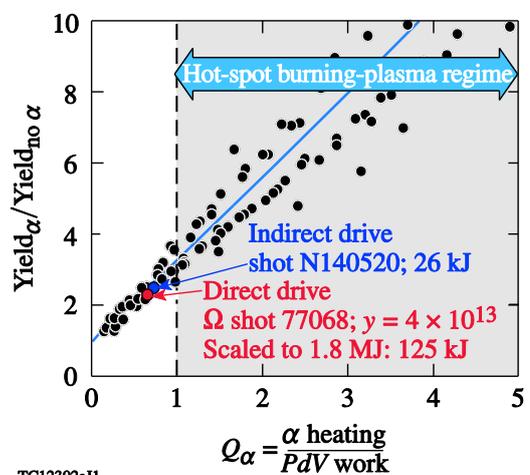
Current DT implosions on OMEGA, scaled to NIF conditions, would give alpha heating with about the same results as x-ray drive (see figure 3), with somewhat greater yield (~100 kJ) because of the increased amount of fuel compressed. These results are presented by Goncharov *et al.* [6] in this volume. The best OMEGA direct-drive result to date produced 56 Gbar in the hot spot of the converging capsule. A pressure of about 120 Gbar is required for ignition at the NIF with spherical direct drive.

Observations on OMEGA provide evidence that laser-plasma interactions in the plasma ablating from the capsule surface limit laser coupling to the capsule through cross-beam energy transfer (CBET). Some of the incident laser energy is coupled to the outgoing portion of laser beams missing the converging target, reducing ablation pressure by up to 50%. Techniques to mitigate CBET by zooming [7] the laser beams to a smaller spot size as the capsule implodes, together with other improvements, are being implemented on OMEGA with the goal of demonstrating $P_{fuel} > 100$ Gbar by the end of the decade. Realizing this goal would provide reasonable confidence that ignition might be achieved at the NIF through reconfiguration for spherical direct drive.



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Figure 2. Fusion yield with laser x-ray drive at the NIF as a function of the Lawson scaling parameter [2,3].

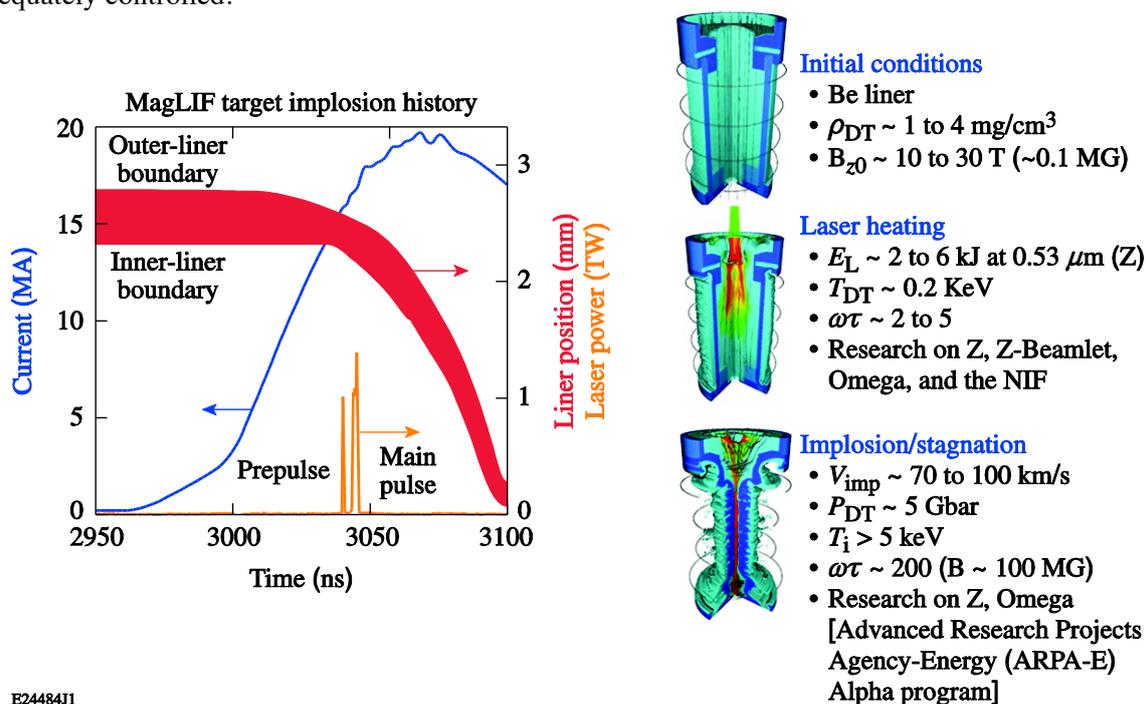


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Figure 3. Fusion yield showing the best result with laser direct drive on OMEGA, scaled to NIF energy [3,6].

4. Magnetic direct drive of a magnetized and laser-heated plasma can provide fusion yield

At the Z pulsed-power facility, a new approach is being developed for fusion yield as depicted in the third panel of figure 1 and in figure 4. A cylindrical beryllium liner, 1 cm in length and containing a magnetized plasma heated by a laser to ~ 200 eV, is pinched by a strong, fast electrical pulse directly driving the plasma to fusion conditions [8]. The Z operates at a current of up to 26 MA and power up to 77 TW. Recent experiments [8] obtained 2×10^{12} DD fusion neutrons but, as expected, increases in both the applied magnetic field (B_{z0}) and laser heating are required to obtain more-significant yield. Evidence has been developed that the Z Beamlet laser (ZBL) with an unconditioned beam and a thick laser entrance window ($\sim 3 \mu\text{m}$) coupled only several hundred joules rather than the ~ 1 kJ of expected energy into preheating the plasma, so this is an area for further research. Experiments on OMEGA and the NIF that can help address this issue are currently underway. The use of multiple facilities and research teams can rapidly advance this concept. A D–D fusion yield equivalent to 100 kJ of D–T yield is predicted for experiments at Z if 6 to 8 kJ of preheat, and ~ 30 -T B field, and ~ 25 MA of current can be successfully applied to the target, provided that instability and mix can be adequately controlled.

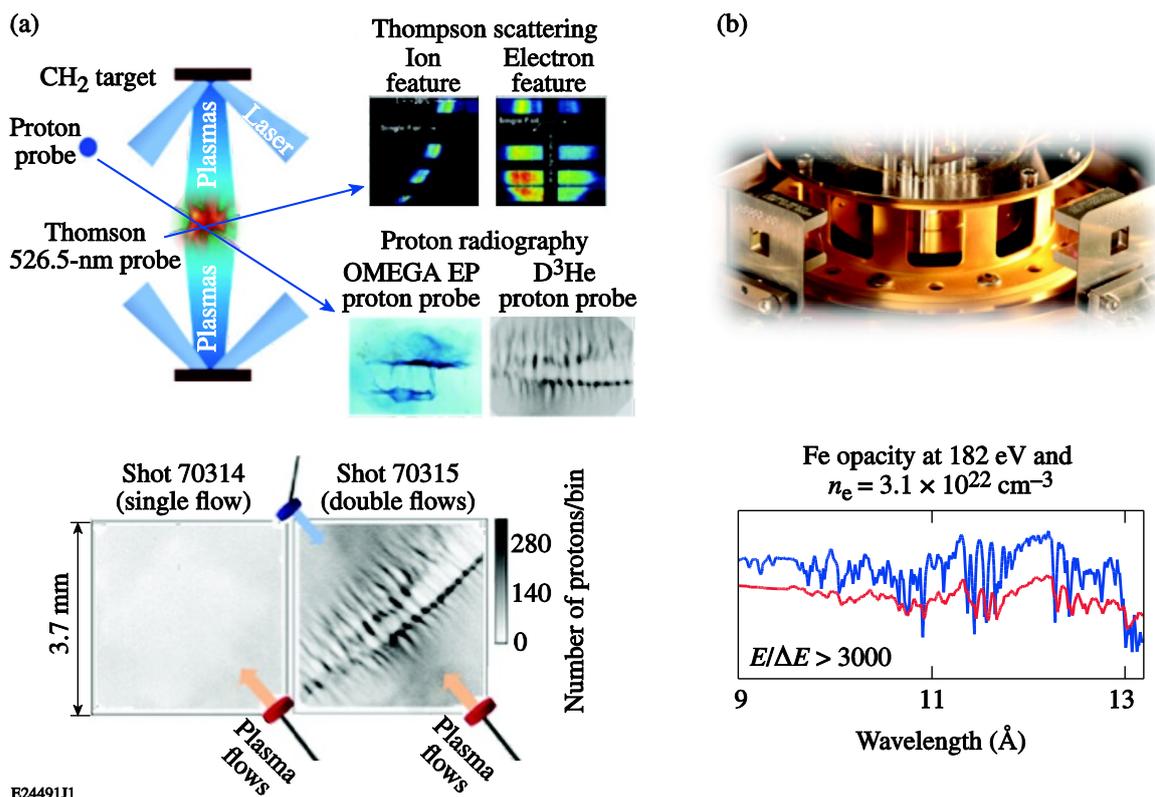


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Figure 4. Magnetic liner implosion fusion (MagLIF) with a beryllium cylinder filled with a magnetized deuterium plasma and preheated by the Z Beamlet Laser (ZBL) directly pinched in the Z.

5. The ICF facilities provide extreme conditions that can advance other physics areas

The NIF, OMEGA, and Z all provide an opportunity to study plasma physics, atomic and nuclear physics, material behavior, and astrophysical phenomena at conditions of temperature and pressure not previously available in the laboratory. As an example, material properties at pressures relevant to planet formation are being studied on the NIF [9], Z, and OMEGA. Experiments on OMEGA and Z show distinct plasma-flow-generated instabilities [10] and important opacity of iron [11], respectively (see figure 5 for configuration and data examples). Significant contributions in the future are expected in a wide range of high-energy physics topics using these state-of-the-art facilities. Contributions to planetary science, material science, fundamental plasma physics, stellar, and astrophysics are expected over the next decade.



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Figure 5. (a) Experiments on OMEGA [10] and (b) Z [11] provide advanced physics results.

6. Conclusion

The U.S. Inertial Confinement Fusion (ICF) Program continues the quest for fusion yield in the laboratory through the cooperation of multiple institutions and research teams addressing the physics constraints. The three approaches may provide different advantages in the various application of ICF. Over the next few years, research will focus on the science and understanding needed for ignition and either achieving it or determining what is needed and in advancing high-energy-density physics.

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