Direct-Drive Laser Fusion: Status, Plans, and Future

E. M. Campbell,[1] T. C. Sangster,[1] V. N. Goncharov,[1] J. D. Zuegel,[1] S. F. B. Morse,[1] C. Sorce,[1] G. W. Collins,[1] M. S. Wei,[1] R. Betti,[1] S. P. Regan,[1] D. H. Froula,[1] C. Dorrer,[1] D. R. Harding,[1] V. Gopalaswamy,[1] J. P. Knauer,[1] R. C. Shah,[1] O. M. Mannion,[1] J. A. Marozas,[1] P. B. Radha,[1] M. J. Rosenberg,[1] T. J. B. Collins,[1] A. R. Christopherson,[1] A. A. Solodov,[1] D. Cao,[1] J. P. Palastro,[1] R. K. Follett,[1] and M. Farrell[2]

[1]Laboratory for Laser Energetics, University of Rochester
[2]General Atomics

Laser direct drive (LDD), along with laser indirect (x-ray) drive (LID) and magnetic drive with pulsed power, is one of the three viable approaches to achieving fusion ignition and gain in inertial confinement fusion (ICF). Here we summarize the present status and future plans for laser direct drive. The program is being executed on both the OMEGA laser at LLE and the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL). LDD research on OMEGA includes cryogenic implosions, fundamental physics including material properties, hydrodynamics, and laser–plasma interaction physics. LDD research on the NIF is focused on energy coupling and laser–plasma interaction physics at ignition-scale plasmas. Limited implosions on the NIF in the "polar-drive" configuration, where the irradiation geometry is optimized for LID, are also a feature of LDD research.

LDD implosions on OMEGA, developed by a data-based statistical model that employs machine learning, have achieved record performance and when hydrodynamically scaled to NIF energies would be predicted to produce fusion yields approaching a megajoule. Systematic experiments enabled by the high shot rate of OMEGA and advanced diagnostics to explore 3-D implosion performance are routinely fielded to understand degradation mechanisms that limit the fusion performance and to develop mitigation strategies.

Figures 1 and 2 show a comparison of the predicted D–T fusion yields compared to the data-based statistical model and the hydro-scaled performance assuming spherical irradiation conditions similar to OMEGA.

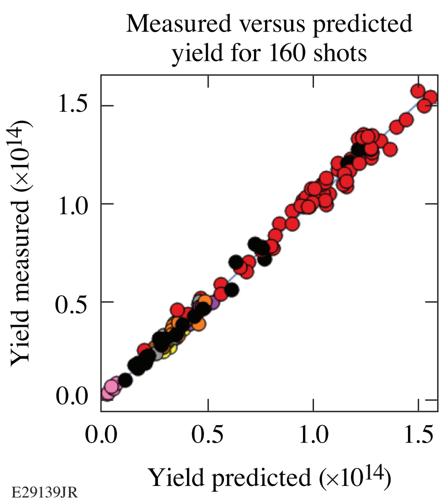

Figure 1
Comparison of a data-driven statistical model with actual experimental fusion yields. Over 160 experiments are well described by this predictive model with a wide range of parameters as described in the text.

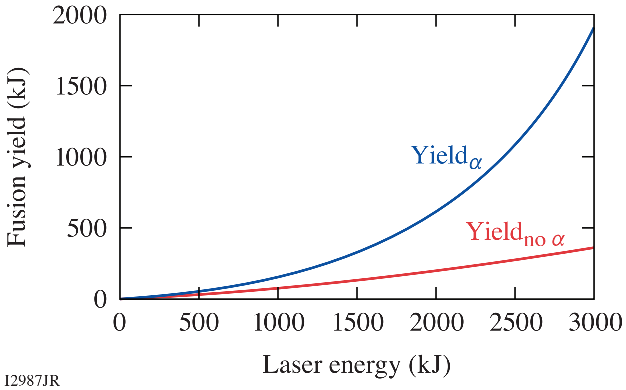

Figure 2
Fusion yield scaling with energy with and without alpha amplification.

Laser–plasma interaction (LPI) physics continues to be a major focus of LDD research. Innovative diagnostics, for example, that measure electron distribution functions (EDF's) on a single shot and increased laser/facility capabilities that enable a quantitative understanding of LPI over a range of plasma conditions created on both OMEGA and the NIF have advanced our understanding of LPI. The present state of research and future plans to eventually determine acceptable operating parameters and laser requirements for LDD ignition are summarized. Figure 3 shows an advanced optical Thomson-scattering diagnostic that enables one to determine the electron distribution function and the distortions in the EDF that occur with increasing laser intensity.

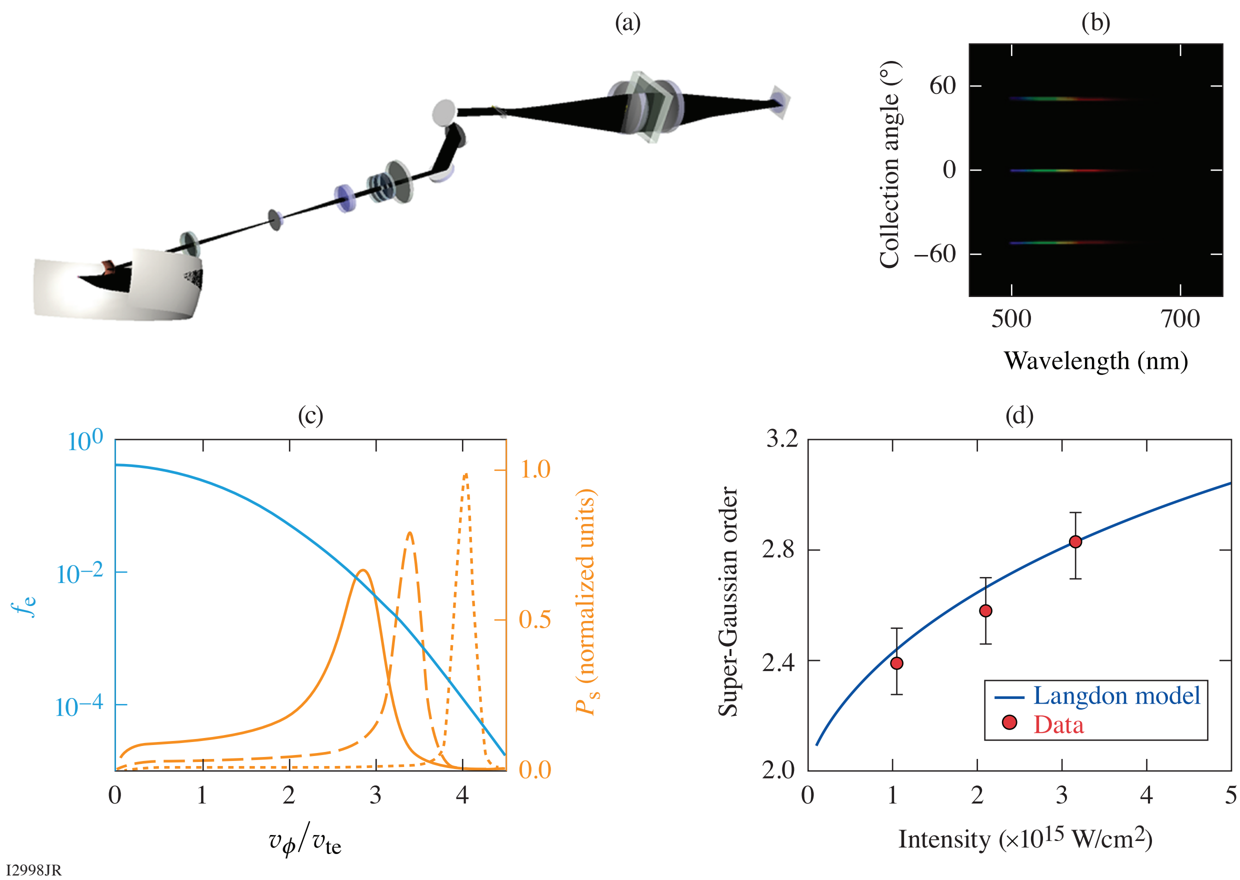

Figure 3
(a) Schematic and (b) Thomson-scattered light measured over 120°. (c) Scattered light from different angle select different regions of the electron distribution function. (d) Gaussian order of the electron distribution function's dependence on laser intensity compared to the simulations.

All present major ICF facilities are based on laser science and technology developed decades ago. To increase the operating space for target designs, LLE has developed a concept for producing a broadband (bandwidth >10-THz) UV laser with a flexible pulse format. This concept, which leverages the science of optical parametric amplifiers and nonlinear frequency, has a goal of producing broadband (>10-THz) 350-nm light. The concept and early experiments that demonstrate the feasibility of the laser design are shown in Fig. 4. Demonstrating the laser at scale (100 J) and conducting experiments on both LPI suppression and laser imprint will be a major focus of LLE research in the years ahead.

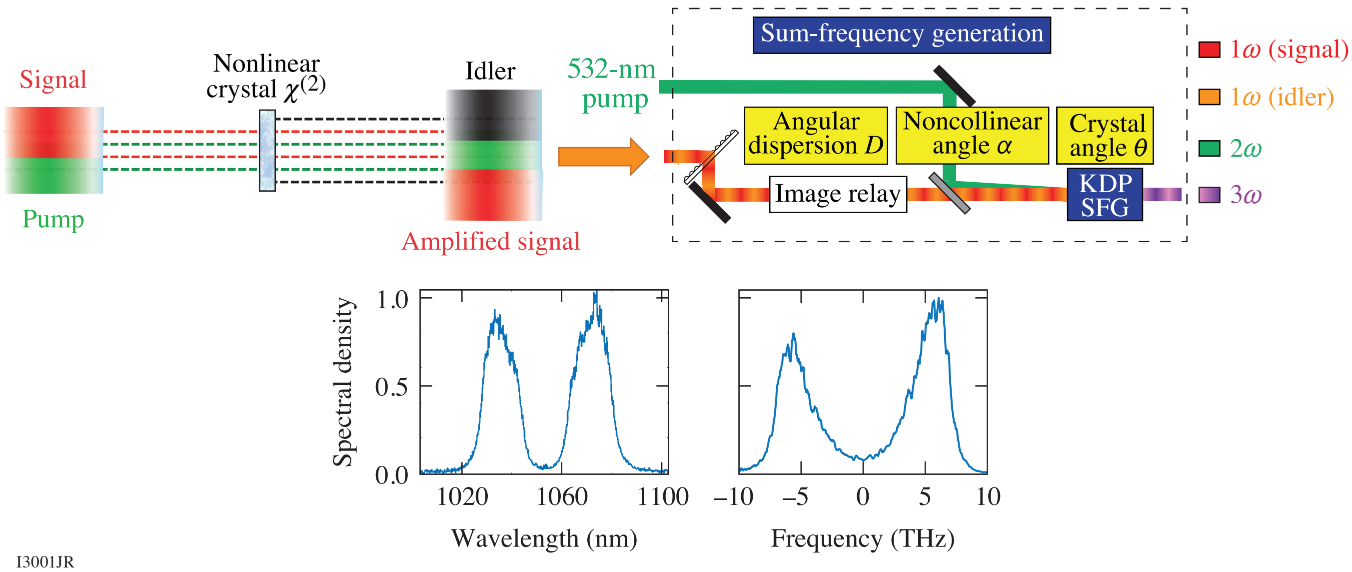

Figure 4
Schematic of an advanced laser approach (sum-frequency generation) that exploits optical parametric amplifier technology to generate broadband (>1% bandwidth) UV light (the FLUX laser).

This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0003856, the University of Rochester, and the New York State Energy Research and Development Authority.