Progress towards polar-drive ignition for the NIF

2013 Nucl. Fusion 53 113021

(http://iopscience.iop.org/0029-5515/53/11/113021)

IOP Publishing and International Atomic Energy Agency Nuclear Fusion
Nucl. Fusion **53** (2013) 113021 (5pp) doi:10.1088/0029-5515/53/11/113021

Progress towards polar-drive ignition for the NIF

R.L. McCrory[1,a], R. Betti[1,a], T.R. Boehly[1], D.T. Casey[2], T.J.B. Collins[1], R.S. Craxton[1], J.A. Delettrez[1], D.H. Edgell[1], R. Epstein[1], J.A. Frenje[2], D.H. Froula[1], M. Gatu-Johnson[2], V.Yu. Glebov[1], V.N. Goncharov[1], D.R. Harding[1], M. Hohenberger[1], S.X. Hu[1], I.V. Igumenshchev[1], T.J. Kessler[1], J.P. Knauer[1], C.K. Li[2], J.A. Marozas[1], F.J. Marshall[1], P.W. McKenty[1], D.D. Meyerhofer[1,a], D.T. Michel[1], J.F. Myatt[1], P.M. Nilson[1], S.J. Padalino[3], R.D. Petrasso[2], P.B. Radha[1], S.P. Regan[1], T.C. Sangster[1], F.H. Séguin[2], W. Seka[1], R.W. Short[1], A. Shvydky[1], S. Skupsky[1], J.M. Soures[1], C. Stoeckl[1], W. Theobald[1], B. Yaakobi[1] and J.D. Zuegel[1]

[1] Laboratory for Laser Energetics, University of Rochester, 250 East River Road, Rochester, NY 14623-1299, USA
[2] Plasma Science Fusion Center, 173 Albany Street, Massachusetts Institute of Technology, Cambridge MA 02139, USA
[3] Department of Physics, State University of New York at Geneseo, 1 College Circle, Geneseo NY 14454, USA

E-mail: rmcc@lle.rochester.edu

Received 31 December 2012, accepted for publication 4 September 2013
Published 27 September 2013
Online at stacks.iop.org/NF/53/113021

Abstract
The University of Rochester's Laboratory for Laser Energetics (LLE) performs direct-drive inertial confinement fusion (ICF) research. LLE's Omega Laser Facility is used to study direct-drive ICF ignition concepts, developing an understanding of the underlying physics that feeds into the design of ignition targets for the National Ignition Facility (NIF). The baseline symmetric-illumination, direct-drive–ignition target design consists of a 1.5 MJ multiple-picket laser pulse that generates four shock waves (similar to the NIF baseline indirect-drive design) and is predicted to produce a one-dimensional (1D) gain of 48. LLE has developed the polar-drive (PD) illumination concept (for NIF beams in the x-ray–drive configuration) to allow the pursuit of direct-drive ignition without significant reconfiguration of the beam paths on the NIF. Some less-invasive changes in the NIF infrastructure will be required, including new phase plates, polarization rotators, and a PD-specific beam-smoothing front end. A suite of PD ignition designs with implosion velocities from 3.5 to 4.3 × 10^7 cm s^{-1} are predicted to have significant 2D gains (Collins *et al* 2012 *Bull. Am. Phys. Soc.* **57** 155). Verification of the physics basis of these simulations is a major thrust of direct-drive implosion experiments on both OMEGA and the NIF. Many physics issues are being examined with symmetric beam irradiation on OMEGA, varying the implosion parameters over a wide region of design space. Cryogenic deuterium–tritium target experiments with symmetric irradiation have produced areal densities of ~0.3 g cm^{-2}, ion temperatures over 3 keV, and neutron yields in excess of 20% of the 'clean' 1D predicted value. The inferred Lawson criterion figure of merit (Betti R. *et al* 2010 *Phys. Plasmas* **17** 058102) has increased from 1.7 atm s (IAEA 2010) to 2.6 atm s.

(Some figures may appear in colour only in the online journal)

1. Introduction

There are two primary approaches to laser-driven inertial confinement fusion (ICF) ignition: direct drive, where the laser energy is directly deposited onto the capsule [1, 2] and indirect drive, where the laser energy is converted to an x-ray bath in a hohlraum to drive the implosion [3]. Direct drive is predicted to couple 7–9 times more energy to the compressed capsule than indirect drive [2]. A major US national effort [4–6] is underway to demonstrate indirect-drive

---

[a] Also, Departments of Mechanical Engineering and Physics and Astronomy, University of Rochester, Rochester NY 14627, USA.

ignition on the National Ignition Facility (NIF) [7]. The NIF is configured for the polar illumination that is required for indirect-drive cylindrical symmetry but not for spherically symmetric direct drive. If the NIF beamlines were configured for symmetric illumination as included in its baseline design [8], one-dimensional (1D) calculations predict that the gain could be as high as 48 [9]. The Laboratory for Laser Energetics (LLE) has developed the polar-drive (PD) concept to allow direct-drive ignition to be explored while the NIF beamlines are configured for indirect drive [10]. Some changes in the NIF infrastructure will be required, including new phase plates, polarization rotators, and a PD-specific front end. LLE is spearheading the effort to develop a viable PD-ignition platform for the NIF. This effort provides a comprehensive and well-diagnosed experimental plan, including achieving the required target specifications [11], as well as preparing the NIF laser for highly uniform PD operations. The research and development of PD has three distinct components:

(1) Validation of direct-drive, symmetric, cryogenic target performance on the OMEGA Laser System [12];
(2) Demonstration of a viable PD-ignition platform using warm and cryogenic PD experiments on the OMEGA Laser System [13], including assessing the efficacy of multi-FM smoothing by spectral dispersion [14];
(3) Development and execution of a PD-ignition campaign on the NIF. Initial PD implosions of ‘exploding-pusher’ capsules have been performed on the NIF, providing an initial study of PD symmetry [15].

This paper describes progress made in symmetric direct-drive cryogenic target implosions [11, 12, 16] on the OMEGA Laser System [17] and the path to PD ignition on the NIF. Since the 2010 IAEA Fusion Energy Conference [18], LLE has made significant progress in improving the understanding and performance of symmetric cryogenic target implosions on OMEGA. Ion temperatures in excess of 3.0 keV have been measured compared to a previous maximum of ∼2.5 keV. The measured areal densities remain around 200 mg cm^{-2} and the neutron yields compared to ‘clean’ 1D simulations up to ∼20%, an increase of more than a factor of 2. The Lawson criterion [19] figure of merit on OMEGA has increased by more than 50% from 1.7 atm s reported at the 2010 IAEA Fusion Energy Conference (FEC) [18] to 2.6 atm s.

Section 2 describes how the phase space available on OMEGA is used to understand the physics of symmetric direct-drive ICF, while section 3 presents the most-recent results. These experiments are used to validate the physics models used in the simulations. Section 4 describes the path to PD ignition on the NIF, including initial exploding-pusher experiments, and the challenges that remain. The conclusions are presented in section 5.

2. Validation of direct-drive physics models

LLE’s plan to demonstrate PD ignition on the NIF is based on a large number of target shots at the Omega Laser Facility to validate the physics models used in multidimensional simulation codes supported by a limited number of shots on the NIF to confirm the underlying physics at the larger energies and scales provided. The main components of this multistage, multi-year program are:

- Validate direct-drive physics models with symmetric cryogenic target implosions on OMEGA, including demonstrating performance that scales to ignition on the NIF [12, 20].
- Extend these results to PD cryogenic target implosions on OMEGA [21–23].
- Demonstrate the technologies required for PD ignition on the NIF.
- Perform initial PD experiments on the NIF with indirect-drive smoothing (phase plates, etc) that validate understanding in the higher-energy and longer-scale-length plasmas.
- Outfit the NIF with the phase plates and other beam smoothing required for PD-ignition target designs and demonstrate ignition.

This manuscript concentrates mainly on progress towards the first task. The three most-important parameters that determine the implosion performance are

- *Target adiabat:* the mass-averaged adiabat of the shell fraction contributing to the stagnation pressure. The averaging is done over the part of the shell that is overtaken by the outgoing return shock during neutron production and calculated at the time when the ablation front is at the position of 2/3 of the initial inner shell radius,

$$\text{adiabat} = \frac{\text{pressure (Mbar)}}{2.2\rho^{5/3}}.$$

- *In-flight aspect ratio (IFAR):* the ratio of the implosion radius to the shell thickness at 2/3 of the implosion radius. The shell thickness is calculated by computing the distance between two points on the shell-density profiles with densities equal to the initial ablator density ($\rho_{\mathrm{CH}} = 1\,\mathrm{g\,cm^{-3}}$),

$$\mathrm{IFAR} = R_{2/3}/\Delta_{2/3}.$$

- *Implosion velocity:* the minimum energy required for ignition [24, 25]

$$E_{\min} \sim 1/(V_{\mathrm{imp}})^6.$$

These three parameters determine the target stability and performance. The adiabat determines the target compressibility and the Rayleigh–Taylor (RT) growth rate [26]. IFAR determines the amplitude of the RT modulations that disrupts the implosion. The implosion velocity is achieved by the target acceleration that determines the number of RT growth factors (Neepers). The increased energy coupling of direct drive with respect to indirect drive for the same laser energy allows for targets with larger mass than indirect-drive targets to be imploded that could lead to increased target gains or margins. It potentially provides a larger area in design phase space to balance the requirements of minimizing the energy required for ignition [24, 25] with the need to ensure that the target is sufficiently stable to ignite. Two-dimensional simulations by Collins *et al* [27] have shown a suite of direct-drive designs with implosion velocities of

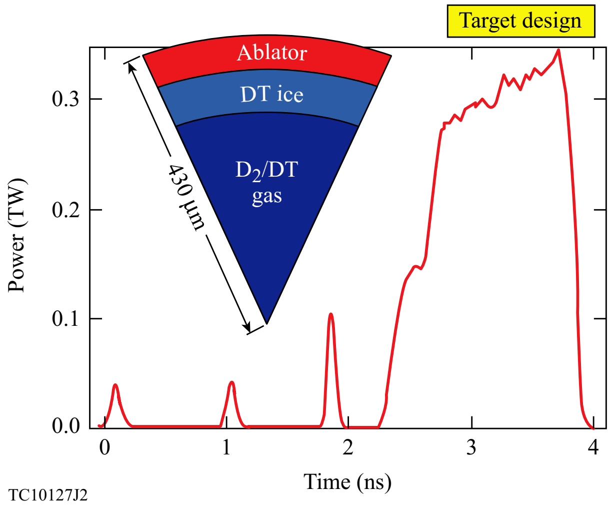

Figure 1. Schematic of OMEGA cryogenic target and typical pulse shape used to drive it.

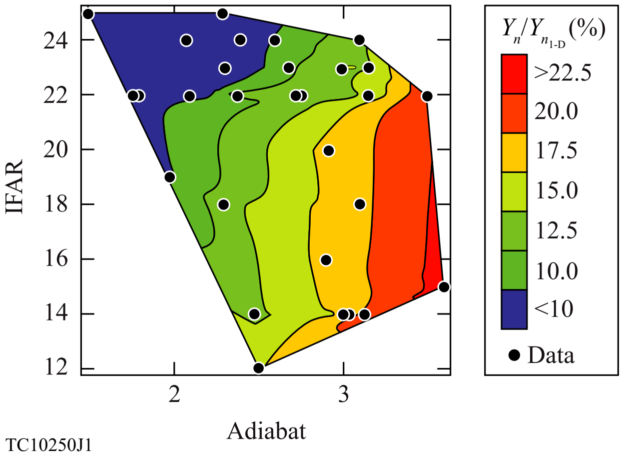

Figure 2. A map of the YOC from OMEGA cryogenic implosions as a function of adiabat and IFAR. The black points are the results of OMEGA implosions, while the colour shows the measured YOC.

(3.5–4.3) $\times$ 10^7 cm s^{-1} that are predicted to ignite on the NIF by varying the three parameters listed above.

Direct-drive cryogenic target implosions on OMEGA explore the target performance as a function of these parameters. Sangster *et al* provide a comprehensive summary of direct-drive progress to date [12]. The implosions of $\sim$430 μm diameter thin plastic ablators (5–12 μm thickness) enclosing a deuterium–tritium (DT) ice layer (50–90 μm thickness) are driven with triple-picket pulses as shown in figure 1. The target adiabat is varied by changing the spacing and power in the pickets and the step on the main pulse rise. The IFAR is varied through changes in the ablator and ice thicknesses, and the implosion velocity is varied through the total target mass and laser intensity. While these variables are not completely independent, they provide a convenient parameterization of target performance that span the space for ignition designs on the NIF.

3. Symmetric cryogenic target implosions on OMEGA

The performance of direct-drive cryogenic target implosions is systematically explored on OMEGA through variations of the target adiabat, IFAR, and implosion velocity, with the highest implosion velocities to date approximately 3.7 $\times$ 10^7 cm s^{-1} [12]. The performance is parameterized by comparing the measured neutron yield and areal densities to those predicted by 1D simulations using the hydrodynamic code *LILAC* [28]. *LILAC* includes the best current models for nonlocal electron transport [29] and cross-beam energy transfer [30–32]. These models agree with a wide variety of experiments. Figure 2 shows a map of the measured yield divided by that obtained from 1D simulations (yield-over-clean (YOC)) as a function of adiabat and IFAR. The black points show the values of adiabat and IFAR for a series of OMEGA cryogenic implosions, while the colour contours shows the measured YOC obtained for this series (e.g., the map is generated from the results of the various implosions at the locations shown by the black dots) [12]. For the same implosions, the areal density is 80% or higher of the 1D predictions for adiabats above $\sim$2.2.

The results are consistent with the expectation that better performance is obtained at higher adiabats and lower IFAR's. The highest-performing targets with implosion velocities of $\sim 3.7\times10^7$ cm s^{-1} had ion temperatures over 3 keV and neutron yields over 2 $\times$ 10^{13}. Both of these results are significantly higher than reported at the 2010 IAEA FEC [18]. The areal densities are in the range 150–300 mg cm^{-2}.

Betti *et al* [19] developed an ICF-relevant Lawson parameter that can be determined from quantities that can be measured during the implosion, $P\tau(\text{atm s}) \sim 8[\rho R(\text{g cm}^{-2})T(\text{keV})]^{0.8}\text{YOC}^{0.4}$. A simple and accurate formula for the 1D yield (equation (15) of [19]) can be substituted in the YOC to derive the Lawson parameter $P\tau$ that depends on the areal density, ion temperature, DT mass, and neutron yield, $P\tau(\text{atm s}) \sim 27\rho R(\text{g cm}^{-2})^{0.61}[0.24 \times10^{-16}\text{yield}/M_{\text{DT}}(\text{mg})]^{0.34}(4.7/T)^{0.8}$, where M_{DT} is the unablated DT mass in milligrams. When normalized with the value of $P\tau$ required for ignition and taken to its third power, this formula for a DT mass of 0.17 mg, approximately reproduces [20] the experimental ignition threshold factor [33] derived from fitting the results from hundreds of LASNEX simulations of marginally ignited capsules. At the 2010 IAEA FEC meeting, the highest value of $P\tau$ reported in OMEGA cryogenic implosions was 1.7 atm s [18]. Recent OMEGA cryogenic target implosions have produced Lawson criteria figure of merit ($P\tau$) up to 2.6 atm s—a 50% increase over two years. Figure 3 shows values of $P\tau$ observed on various devices as a function of ion temperature, taken from [19]. It has been updated to compare the $P\tau$ values presented at the 2010 IAEA FEC meeting (OMEGA (2010)) [18] with those described here (OMEGA (2012)). The red star labelled NIF IDI (2012) is from an indirect-drive cryogenic target implosion on the NIF [34]. It is important to emphasize that figure 3 shows the magnetic confinement fusion and ICF paths towards thermonuclear ignition and should not be used to assess progress towards fusion energy. Assessing progress towards fusion energy requires considerations related to thermonuclear gain, wall-plug efficiency, and recirculating power. Furthermore, unlike an ICF reactor, an MFE reactor would probably operate in a subignited state at a value of $P\tau$ $\sim$ 90% of the ignition value [35].

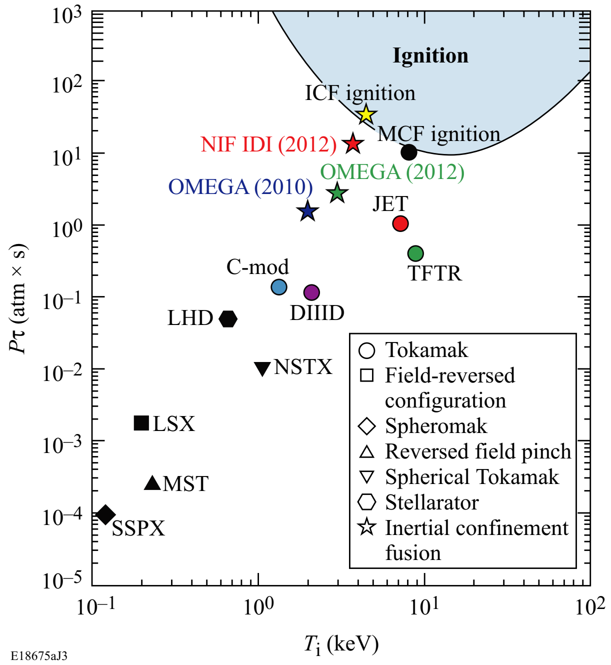

Figure 3. Plot of $P\tau$ observed on various devices as a function of ion temperature, taken from [19], updated to compare the $P\tau$ values presented at the 2010 IAEA FEC meeting (OMEGA (2010)) [18] with those described here (OMEGA (2012)). The red star labelled NIF IDI (2012) is from an indirect drive cryogenic target implosion on the NIF [34]. The expected locations of ICF and magnetically confined fusion ignition are shown.

Current target performance is limited by the accumulation of target surface defects during the cryogenic target fills [12, 36]. These appear to be gases entrained in the high-pressure fill that condense on the target surface as it is cooled to liquid DT temperatures. The typical total defect area has ranged from a few thousand up to nearly 15 000 μm^2 (nearly 1% of the total capsule surface area) [12]. An ∼50% increase in YOC was observed in implosions with a limited number of targets that had significantly fewer than the usual number of defects [36]. The defects limit the highest-performing targets to adiabats above ∼2.5 and IFAR's less than ∼20. Significant effort is being devoted to reducing the number of surface defects. This is expected to provide improved target performance, especially at values of IFAR approaching those required for ignition (IFAR $\geqslant$ 25) along with allowing higher performance implosions with adiabats less than 2.5.

As the number of surface defects is reduced, it is expected that laser imprinting will become the dominant determinant of target performance. Recent experiments have shown that doping the outer part of the ablator with Ge or Si can reduce both the imprinting level and RT growth rate [37, 38]. This reduction occurs as a result of the smoothing of the plasma pressure gradients and imprint reduction caused by the increased distance between the critical and ablation surfaces. The effect of doping the ablator with Si on the growth of target nonuniformities is shown in figure 4. In these experiments, planar plastic (CH) foils with or without 7% Si dopant were accelerated and x-ray radiographed to infer the imprint level. The figure shows that the doped targets had lower nonuniformity levels during the target acceleration, indicating a reduction of the imprint levels [37, 38]. The concept is similar to the thin high-Z outer layers proposed by the Naval Research Laboratory for imprint reduction [39, 40].

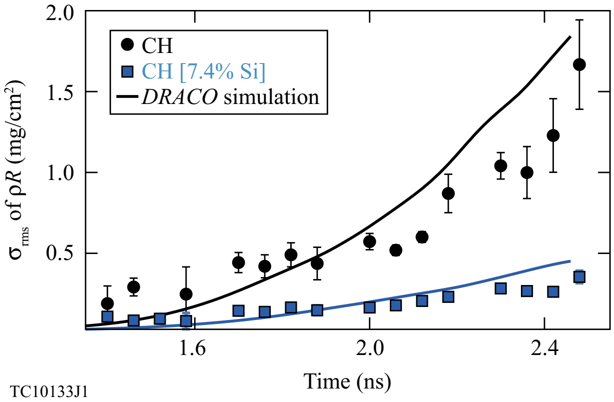

Figure 4. Plot of target nonuniformity as a function of time for pure plastic and Si-doped plastic targets [37, 38].

4. Path to PD ignition on the NIF

The initial PD ignition point design was comprised of a 1.5 MJ, triple-picket laser pulse driving a 3.2 mm diameter plastic shell enclosing a 187 μm cryogenic fusion-fuel layer [41]. Two-dimensional *DRACO* [42] calculations indicate a target gain of ∼32 when all expected sources of nonuniformity are included. The implosion velocity was 4.3 × 10^7 cm s^{-1}. Validation of the physics in these code calculations is the motivation for a large fraction of the implosion experiments on OMEGA, including those described in the previous section. Recent progress has led to a series of PD designs that are predicted to ignite on NIF with an implosion velocity of from 3.5 × 10^7 to 4.3 × 10^7 cm s^{-1}, adiabats of 1.6–2.5, and IFAR ∼30 [27] provided laser–plasma interactions at NIF scales do not provide new challenges as discussed below. The ignition margin for the PD designs can be compared to those of the baseline indirect-drive designs using Haan's definition of the ignition threshold factor (ITF) and of the margin as (ITF-1) [4]. In [4], the margin for the baseline indirect-drive CH design from 1D simulations was ∼2.6, while the margin for the 3.7 × 10^7 cm s^{-1} PD design, including low-order nonuniformities, is 3.6.

Critical issues include symmetric cryogenic target performance and PD room-temperature implosions detailing the drive symmetry of various pointing and defocusing schemes, as well as a series of laser–plasma instability experiments investigating the effects of preheat caused by the two-plasmon–decay instability [43, 44] and cross-beam energy transfer between the incoming and outgoing OMEGA laser beams [31]. These issues are the focus of LLE's research program and will be investigated in detail at the Omega Laser Facility over the next few years. LLE has acquired a set of phase plates optimized for PD on OMEGA to perform cryogenic PD implosions [22]. It is anticipated that a limited number of target shots will be available on the NIF to extend the physics understanding to full NIF energy and scale length beginning in FY13.

PD-ignition designs rely on repointing beams to the equator, using different pulse shapes for different rings of the NIF configuration, and using specialized phase plates (particularly for the equatorial beams). Accurate modelling of oblique beam-energy deposition, the effect of beam obliquity on laser–plasma instabilities in the underdense corona, and heat transport to the ablation surface are critical to achieving adequate symmetry, implosion velocity, and shell adiabat.

High-convergence PD OMEGA implosions and cone-in-shell geometries are being used to validate models of laser deposition, heat conduction, and nonuniformity growth in the ignition designs. Using beams judiciously repointed towards the equator, control of the $\ell = 2$ mode has been experimentally demonstrated through backlit images of the implosion. Experiments are investigating the use of fuel/ablator layer shimming near the target equator [13]. This reduces the laser intensity required to drive this region of the target and allows for more-efficient targets to be deployed on the NIF.

PD target implosions using DT fuel have been designed and fielded for neutron diagnostic development on the NIF [15]. These experiments use thin, room-temperature glass shells filled with low pressures (10 atm) of DT. Initial target implosions on the NIF have produced DT neutron yields in the range of 10^{12}–10^{15}. LLE, in collaboration with LLNL, LANL and GA, has drafted a Polar-Drive Ignition Plan that provides a detailed outline of the requirements, resources, and timetable leading to PD-ignition experiments on the NIF. This plan includes a series of experiments on the NIF that address key physics issues that are unique to the NIF high-energy, long plasma scale-length environment. Initially such experiments will make use of existing NIF hardware, but will transition to more optimally designed components as they become available.

5. Conclusions

Significant progress has been made in understanding and improving the performance of symmetric direct-drive cryogenic target implosions since the 2010 IAEA FEC meeting [18]. Neutron yields have increased to over 2×10^{13} and ion temperatures up to 3 keV have been observed. A systematic study of target performance as a function of adiabat, in-flight aspect ratio, and implosion velocity is validating the physics models that are used for ignition target designs. Target surface defects are currently limiting target performance and efforts are underway to produce reduced levels of the defects in the near future. The highest-performing implosions have a Lawson criteria figure of merit, $P\tau$, up to 2.6 atm s^{-1}.

LLE has a path forward that includes ongoing OMEGA implosions (including polar drive) supplemented by theoretical advances and implosions on the NIF to develop PD ignition.

Acknowledgments

This work was supported by the US Department of Energy Office of Inertial Confinement Fusion under Cooperative Agreement No DE-FC52-08NA28302, the University of Rochester, and the New York State Energy Research and Development Authority. The support of DOE does not constitute an endorsement by DOE of the views expressed in this article.

References

[1] Nuckolls J., Wood L., Thiessen A. and Zimmerman G. 1972 *Nature* **239** 139
[2] McCrory R.L. *et al* 2008 *Phys. Plasmas* **15** 055503
[3] Lindl J.D. 1998 *Inertial Confinement Fusion: The Quest for Ignition and Energy Gain Using Indirect Drive* (New York: Springer) p 61 chapter 6
[4] Haan S.W. *et al* 2011 *Phys. Plasmas* **18** 051001
[5] Edwards M.J. *et al* 2011 *Phys. Plasmas* **18** 051003
[6] Landen O.L. *et al* 2011 *Phys. Plasmas* **18** 051002
[7] Moses E.I. 2008 *Fusion Sci. Technol.* **54** 361
[8] Miller G.H. *et al* 2004 *Opt. Eng.* **43** 2841
[9] Goncharov V.N. 2009 *Laser–Plasma Interactions* (*Scottish Graduate Series*) ed D.A. Jaroszynski *et al* (Boca Raton, FL: CRC Press) p 409
[10] Skupsky S. *et al* 2004 *Phys. Plasmas* **11** 2763
[11] Sangster T.C. *et al* 2010 *Phys. Plasmas* **17** 056312
[12] Sangster T.C. *et al* 2013 *Phys. Plasmas* **20** 056317
[13] Marshall F.J. *et al* 2012 *Bull. Am. Phys. Soc.* **57** 155
[14] Marozas J.A., Zuegel J.D. and Collins T.J.B. 2010 *Bull. Am. Phys. Soc.* **55** 294
[15] Cok A.M., Craxton R.S. and McKenty P.W. 2008 *Phys. Plasmas* **15** 082705
[16] Goncharov V.N. *et al* 2010 *Phys. Rev. Lett.* **104** 165001
[17] Boehly T.R. *et al* 1997 *Opt. Commun.* **133** 495
[18] Meyerhofer D.D. *et al* 2011 *Nucl. Fusion* **51** 053010
[19] Betti R. *et al* 2010 *Phys. Plasmas* **17** 058102
[20] Betti R. *et al* 2012 *Proc. 24th Int. Conf. on Fusion Energy (San Diego, CA, 2012)* Paper OV/5-3 and www-naweb.iaea.org/napc/physics/FEC/FEC2012/html/fec12.htm
[21] Radha P.B. *et al* 2011 *Bull. Am. Phys. Soc.* **56** 242
[22] Radha P.B. *et al* 2013 *Phys. Plasmas* **20** 056306
[23] Radha P.B. *et al* 2012 *Phys. Plasmas* **19** 082704
[24] Herrmann M.C., Tabak M. and Lindl J.D. 2001 *Nucl. Fusion* **41** 99
[25] Zhou C.D. and Betti R. 2007 *Phys. Plasmas* **14** 072703
[26] Betti R. *et al* 2005 *Phys. Plasmas* **12** 042703
[27] Collins T.J.B., Marozas J.A. and McKenty P.W. 2012 *Bull. Am. Phys. Soc.* **57** 155
[28] Delettrez J. 1986 *Can. J. Phys.* **64** 932
[29] Goncharov V.N. 2009 *Laser–Plasma Interactions* (*Scottish Graduate Series*) ed D.A. Jaroszynski *et al* (Boca Raton, FL: CRC Press)
[30] Michel P. *et al* 2009 *Phys. Plasmas* **16** 042702
[31] Igumenshchev I.V. *et al* 2012 *Phys. Plasmas* **19** 056314
[32] Kruer W.L., Wilks S.C., Afeyan B.B. and Kirkwood R.K. 1996 *Phys. Plasmas* **3** 382
[33] Spears B.K. *et al* 2012 *Phys. Plasmas* **19** 056316
[34] Glenzer S.H. *et al* 2012 *Phys. Plasmas* **19** 056318
[35] Freidberg J.P. 2007 *Plasma Physics and Fusion Energy* (Cambridge: Cambridge University Press) p 73
[36] Sangster T.C. *et al* 2011 *Bull. Am. Phys. Soc.* **56** 241
[37] Hu S.X. *et al* 2012 *Phys. Rev. Lett.* **108** 195003
[38] Fiksel G. *et al* 2012 *Phys. Plasmas* **19** 062704
[39] Mostovych A.N. *et al* 2008 *Phys. Rev. Lett.* **100** 075002
[40] Obenschain S.P. *et al* 2002 *Phys. Plasmas* **9** 2234
[41] Collins T.J.B. *et al* 2012 *Phys. Plasmas* **19** 056308
[42] Radha P.B. *et al* 2005 *Phys. Plasmas* **12** 056307
[43] Kruer W.L. 2003 *The Physics of Laser Plasma Interactions* (*Frontiers in Physics*) (Boulder, CO: Westview Press) p 39
[44] Michel D.T. *et al* 2012 *Phys. Rev. Lett.* **109** 155007