High-Performance Inertial Confinement Fusion Target Implosions on OMEGA

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Abstract. The Omega Laser Facility is used to study inertial confinement fusion (ICF) concepts. This paper describes progress in direct-drive central hot-spot (CHS) ICF, shock ignition (SI), and fast ignition (FI) since the 2008 IAEA FEC conference. Cryogenic deuterium–tritium (DT) target implosions on OMEGA have demonstrated the highest DT areal densities yet measured in ICF implosions.

1. Introduction

The Inertial Confinement Fusion (ICF) concept involves using high energy lasers (or other drivers) to implode spherical targets containing a solid deuterium-tritium shell. [1] The drive energy is either converted to x-rays to implode the target (indirect drive) [1] or directly deposited on the target surface (direct drive). [2] The National Ignition Facility has been completed [3] and experiments on it to develop the indirect-drive ICF concept have begun. [4] While it is likely that ignition will be demonstrated with indirect-drive in the next few years, alternative, direct-drive based, concepts have the potential to provide higher target gains and may be optimal for Inertial Fusion Energy. This paper describes research progress in some of these concepts at the Omega Laser Facility, [5] direct-drive central hot-spot (CHS) ICF [2], shock ignition (SI), [6] and fast ignition (FI), [7] since the 2008 IAEA FEC conference.

2. Central hot spot ignition

A triple-picket direct-drive-ignition design that generates four shock waves is the baseline concept for the NIF [8] (similar to the NIF baseline indirect-drive design [1]). It produces a symmetric drive, 1-D gain of 48 for a 1.5-MJ implosion that is within the NIF performance capabilities. The design has been updated for the Polar Drive configuration, (using the current NIF beam locations) [9] in which it will be tested on the NIF. Current simulations including two-dimensional polar drive asymmetries predict a NIF target gain of 18. The density contours near peak compression for this gain equals 18 two-dimensional polar-drive simulation are shown in *FIG. 1*.

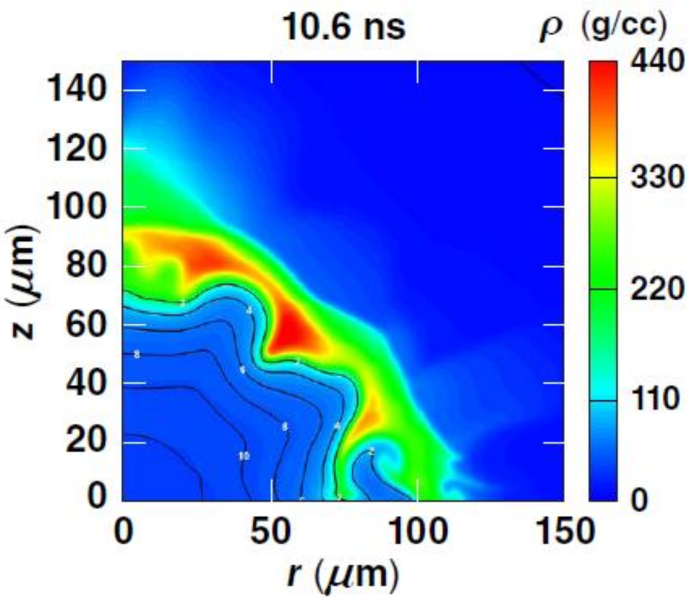

FIG. 1: Two dimensional simulation predictions of the density of a compressed Polar Drive target near peak compression of a target that produces a gain of 18 on the NIF.

The performance of the multiple-picket design is being tested on the Omega Laser Facility. [5] The shock-wave timing is optimized using cryogenic cone-in-shell shock-timing targets that were developed to support the National Ignition Campaign on the NIF. [10] *FIG. 2* shows the triple-picket pulse shape used to launch the shock wave and a comparison of the measured (VISAR) and predicted shock velocities, showing good agreement. [10, 11]

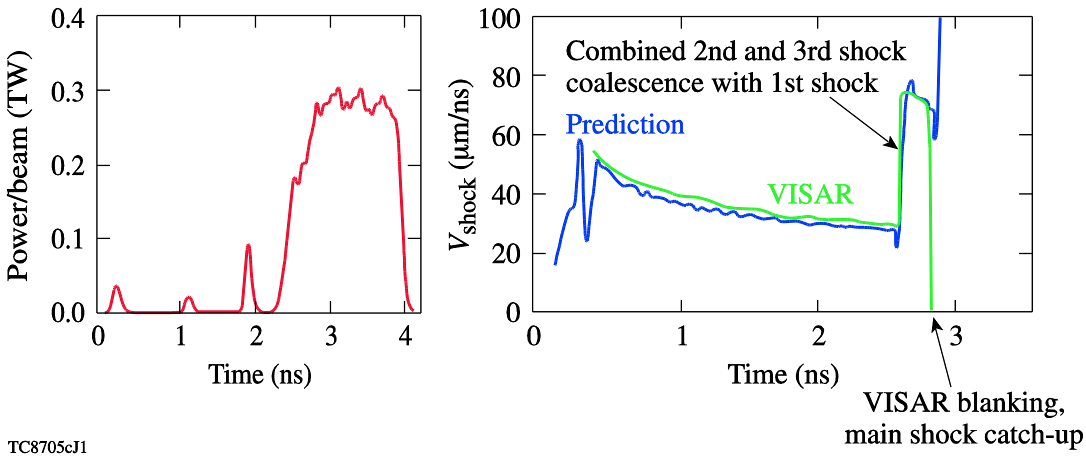

FIG. 2: Comparison of the measured and predicted shock velocity for a triple picket pulse with good agreement found. [10, 11]

Omega is the only facility worldwide that has been performing ignition-scaled cryogenic target implosions that are required for most ICF target designs. Cryogenic-DT-target implosions using the triple-picket pulse shape have produced record areal densities of ~0.3 g/cm^2, corresponding to a peak density of ~250 g/cm^3. [8, 11] This areal density is 50% higher than reported at the 2008 IAEA FEC conference. The laser and target conditions and the experimental results are shown in *FIG. 3*. The pulse shapes for the implosions with velocity of 3x10^7 cm/s are similar to those shown in *FIG. 2*. The good agreement between predictions and measurements provides confidence in the performance of cryogenic target implosions for both indirect- and direct- drive. [8, 11] The areal density was measured with the magnetic recoil spectrometer (MRS), [12] developed in a collaboration between MIT and LLE. These experiments also test the diagnostics required for the ignition campaign on the NIF.

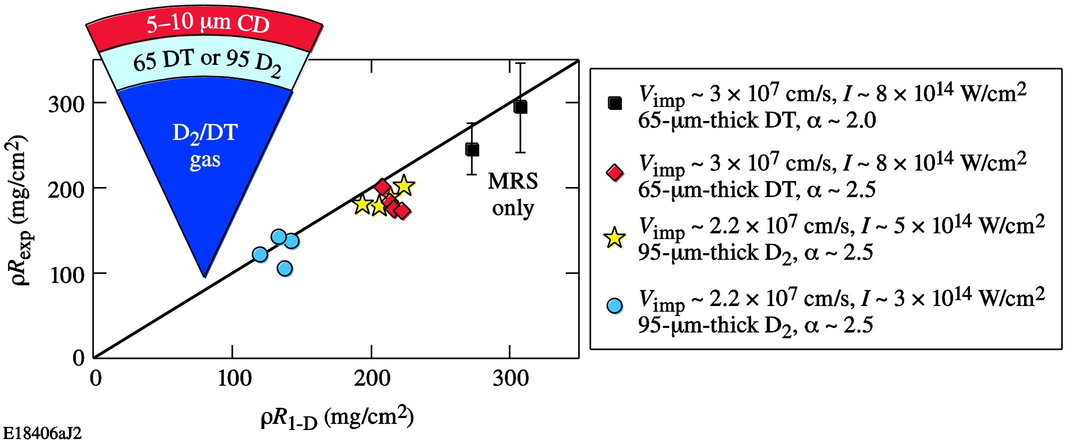

FIG. 3: Areal density performance of cryogenic target implosions on OMEGA compared to 1-D predictions. [8, 11]

These cryogenic deuterium–tritium (DT) target implosions on OMEGA have demonstrated the highest DT areal densities yet measured in ICF implosions. *FIG. 4* shows the progress made from the IAEA FEC 2008 conference to the 2010 one. The solid line shows the hydrodynamic equivalent scaling from OMEGA to NIF performance. [2] The measured areal density is equal to that required to demonstrate the hydrodynamic scaling on OMEGA. Future experiments will increase the ion temperature to demonstrate full hydrodynamic scaling.

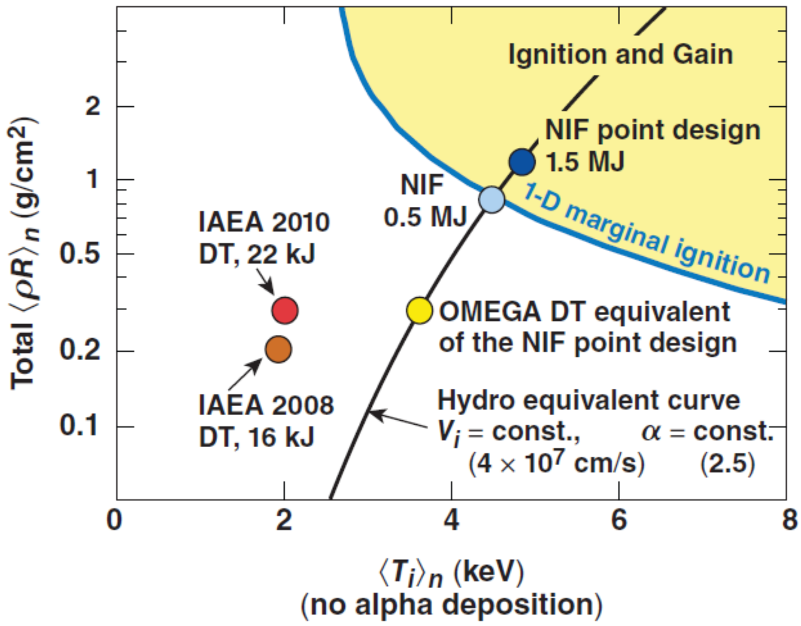

FIG. 4: Performance of cryogenic target performance on OMEGA relative that required to demonstrate hydrodynamic scaling to ignition on the NIF. [2, 8, 11]

The Lawson's performance parameter $P\tau$ (pressure × energy-confinement time) has been inferred from the ion temperature, areal density, and neutron-yield measurements.[13] For implosions with ion temperatures of ~2 keV, areal densities of 0.2 ~ 0.3 g/cm^2, and neutron yields of 5 ~ 6 × 10^{12}, $P\tau$ ~ 1 atm-s, comparable to that obtained in DT discharges on the Joint European Tokamak (*FIG. 5*). [13]

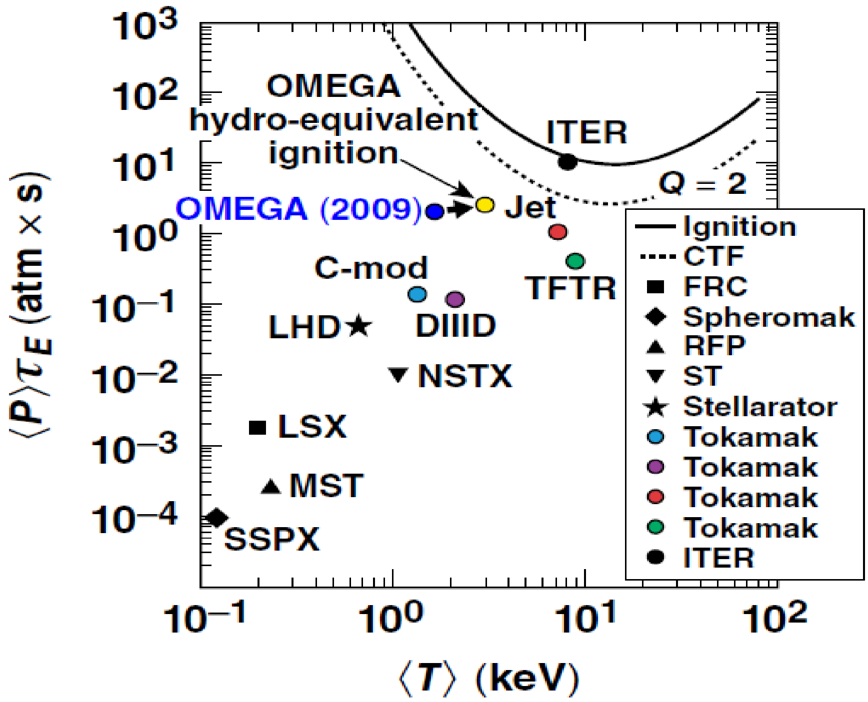

FIG. 5: Comparison of OMEGA cryogenic implosion performance with magnetic fusion devices in the $P\tau$-T_{ion} plane. [13]

3. Two-Step Ignition

SI [6] and FI [7] are two-step concepts where the fuel is assembled by one laser pulse followed by a second pulse that initiates ignition, allowing the possibility of higher gains than CHS ignition. [2] In CHS ignition, approximately 50% of the drive energy is used to heat the central region that ignites and provides the burn wave that propagates into the high density cold shell. Because two-step ignition processes use second pulse to heat the fuel to ignition conditions, the implosion velocity can be lower, reducing the first pulse drive energy. [2] This allows more massive targets to be imploded for a fixed laser energy, leading to higher gains as the cold fuel is consumed. SI uses an intensity spike at the end of the laser pulse that compresses the target, [6] while FI requires a high-intensity, high-energy petawatt beam to provide an electron or ion beam to ignite the compressed fuel. [7]

3.1 Fast Ignition

The initial integrated fast ignition [7] experiments were carried out at ILE-Osaka. [14, 15] They observed a significant increase in neutron yield when a 0.5 kJ high energy petawatt laser system was injected into a cone-in-shell target that was imploded by ~ 3 kJ of laser energy. Up to 10^7 neutrons were produced. These conditions have been extended using the OMEGA/OMEGA EP laser system. [16] Integrated FI experiments have quadrupled the neutron yield, to ~2x10^7 neutrons, in cone-in-shell FI deuterated-plastic (CD) shell implosions with 1-kJ, 10-ps, OMEGA EP heating pulses with a target compression energy of ~20 kJ. [17] The initial results are shown in *FIG. 6*, showing the neutron yield as a function of the timing of the OMEGA EP shot pulse beam, relative to the compression pulse. They show a clear signature of High Energy Petawatt laser heating of the compressed core and represent the first experimental confirmation of the ILE-Osaka results. The energy and focal spot of the OMEGA EP HEPW laser are currently being improved to provide a more stringent test of the FI concept. Separate measurements have shown that the cone-tip remains intact during the target compression. [17]

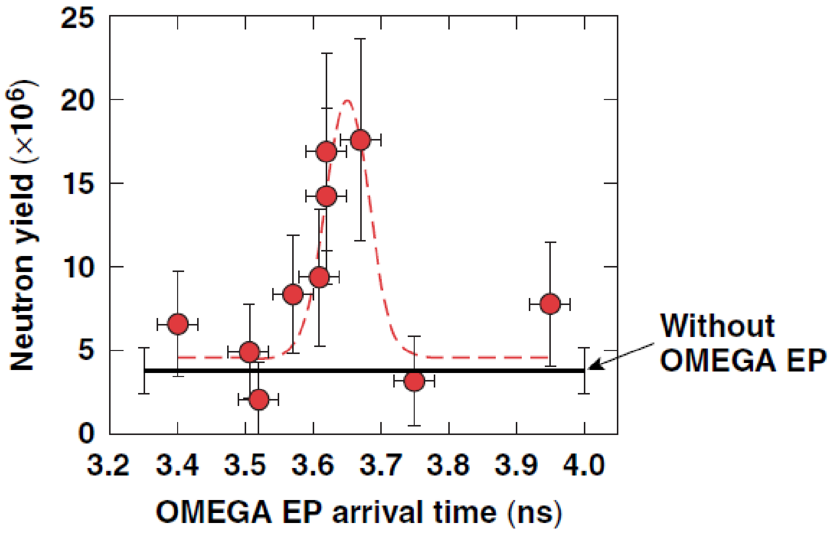

FIG. 6: Increase in neutron yield in integrated OMEGA.OMEGA EP experiments with a 10 ps, 1 kJ OMEGA EP HEPW laser beam. [17]

3.2 Shock Ignition

The shock ignition ICF concept relies on a high intensity “spike” that follows a compression laser pulse to shock-heat the compressed core to fusion ignition conditions. [6] Initial SI experiments are being performed on the OMEGA laser system [5] have shown significantly increased neutron yields and areal densities compared to those without the SI high-intensity spike. [18] The laser pulse shape is shown in *FIG. 7*.

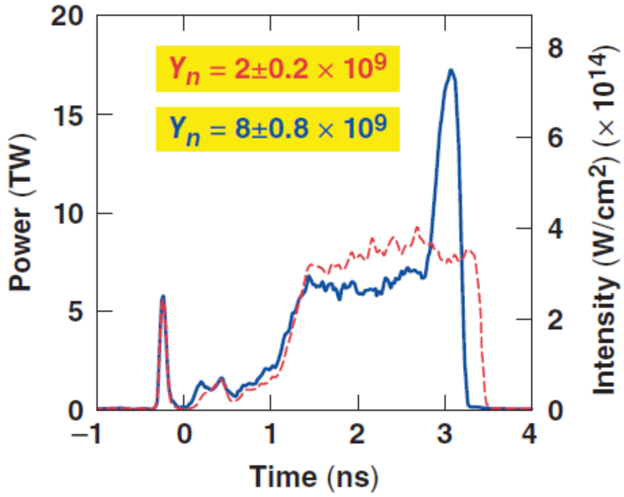

FIG. 7: Comparison of "standard" (red) and shock ignition (blue) pulse shapes used in OMEGA experiments. [18]

A comparison of the performance of target implosions with and without the shock ignition "spike" is shown in *FIG. 8*. The addition of a "spike" at the end of the laser pulse appears to improve the implosion performance as measured by the areal density and the neutron yield. [18]

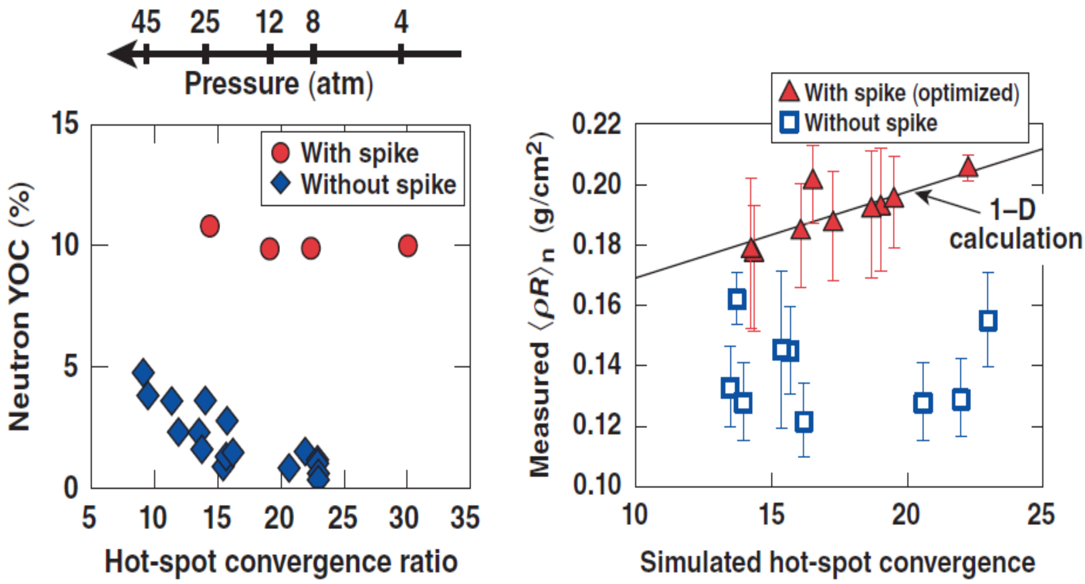

Fig. 8: Performance improvements of OMEGA target implosions using a shock ignition pulse shape. [18]

4. Conclusion

Experiments on the Omega Laser Facility are validating the performance of direct-drive central hot spot ICF, Fast and Shock Ignition ICF target designs. Significant progress has been made since the 2008 IAEA FEC conference.

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