Investigation of the Potential for High Gain, Shock-Ignition on the National Ignition Facility *

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Shock ignition, a new concept for igniting thermonuclear fuel, offers the potential for a near-term test of high gain inertial confinement fusion on the National Ignition Facility at less than 1MJ drive energy and without the need for new laser hardware. In shock ignition, compressed fusion fuel is separately ignited by a strong spherically-converging shock and, because capsule implosion velocities are significantly lower than those required for conventional hotpot ignition, simulations indicate that high fusion energy gains of ~60 may be achievable on NIF at laser drive energies around ~0.5MJ, extending to ~100 at 1MJ. Because of the simple all-DT or DT/CH target designs, their in-flight robustness, the potential need for only 1D SSD beam smoothing, minimal early-time LPI preheat issues, and employment of day-1 laser hardware, these targets may be easier to field on NIF than a conventional (polar) direct drive hotspot ignition target. Like fast ignition, shock ignition has the potential for high fusion yields at low drive energy, but requires only a single laser with less demanding timing and spatial focusing requirements. Of course, conventional symmetry and stability constraints will apply, thus a key immediate step for shock ignition on NIF is to demonstrate the adequacy of low-mode uniformity and shock symmetry in the polar drive configuration. Shock ignition offers the prospects for high-gain targets that may lead to smaller, more economic fusion power reactors and a cheaper fusion energy development path.

1. Introduction – The Potential of Shock Ignition on NIF

The principle of shock ignition [1] is shown in Fig.1. Here we illustrate schematically the laser pulse shape required to drive a conventional NIF hotspot ignition target (dotted curve) in comparison with that for a prospective shock ignition target (solid curve). In the conventional target whether direct or indirect drive, the laser driver pulse is required to assemble the fuel at high density *and* impart a sufficiently high velocity (~3.5-4x10^7cm/s) to the imploding shell so that its *PdV* work creates the central ignition hotspot on stagnation. In this regard, conventional direct- or indirect-drive hotspot ignition could be designated as occurring through "fast-compression".

By contrast, in shock ignition [1], the fuel assembly and ignition phases are decoupled as follows: The cryogenic shell is initially imploded on a low adiabat using a laser drive of modest peak power and lower total energy. While the resulting low implosion velocity yields only a low temperature central region, the low adiabat of the fuel leads to high values of the areal and mass densities. The assembled fuel is then separately ignited from a central hotspot heated by a strong, spherically-convergent shock driven by the high intensity spike at the end of the laser pulse. The launching of the ignition shock is timed to reach the center just as the main fuel is stagnating and starting to rebound. For larger, high yield shock ignited NIF targets at greater than 1MJ total drive energy, the majority of the laser energy is contained in the main portion of the pulse required for initial fuel compression, while only a modest energy fraction (~25%) is required for the shock ignition [2]. For smaller, sub-MJ targets, optimum energy partitioning is closer to 50:50. Because the implosion velocity is significantly less than required for conventional (fast-compression) hotspot ignition on NIF, considerably more fuel

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mass can be assembled for the same kinetic energy in the shell, potentially offering significantly higher fusion gains/yields for the same laser energy or, equivalently, retaining acceptable gains at appreciably lower drive energies.

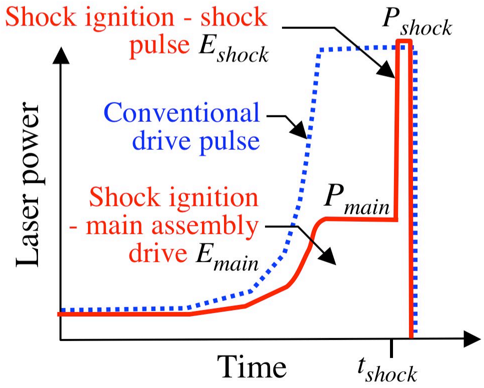

FIG. 1. Schematic laser pulse shape for shock ignition (solid curve) relative to that for conventional indirect or direct drive hotspot ignition (dotted curve). A near-term NIF shock ignited target at ~0.5MJ drive energy would require a main drive power of P_{main}<100TW and a shock drive power of P_{shock}~350TW

We have performed initial studies exploring the scaling of 1D energy gains for candidate shock-ignited target designs on NIF [2, 3]. The results are shown in Fig. 2 where the fusion energy yields and gain curve (blue points) are plotted as a function of the total delivered laser energy (i.e., the sum of the main assembly and shock laser energy) and were obtained from 1D LASNEX simulations. For comparison, we show the present predicted performance of the NIF ignition baseline target (CH ablator) under conventional indirect drive (green point) together with 2D gain predictions from two studies of NIF target designs operating under conventional symmetric direct drive (DD) and polar direct drive (PDD) at 1MJ drive energy. The yield and gain curves in Fig 2 were obtained for NIF shock ignition targets with wetted CH foam ablators. We also indicate the performance for a candidate near term, shock ignited target for NIF (red point) based on a simple all-DT (fuel+ablator) configuration, offering the potential for (1D) gains of ~60 (~30MJ yield) at ~-0.5MJ drive energy .

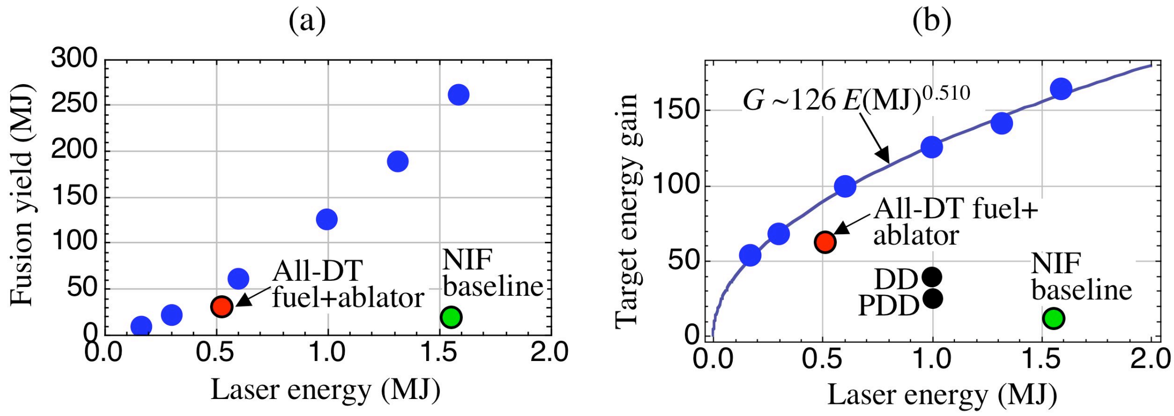

FIG.2. (a) Fusion yield curve, (b) target energy gain curve, versus total laser drive energy for NIF shock ignited targets (wetted foam ablators) from 1D LASNEX simulations [2,3]. Corresponding performance for the NIF indirect drive baseline ignition target with CH ablator (green point) is shown for comparison, together with 2D gain predictions for NIF targets operating under conventional symmetric direct drive (DD) and polar direct drive (PDD). Also shown is a\the 1D performance of a candidate near-term, gain-60 all-DT shock ignited target at ~0.5MJ drive energy with ~30MJ fusion yield (red point)

We caution that although the initial results in Fig.2 indicate the promise for high gain at low drive energies, these were obtained in hydro-equivalent 1D simulations only. As discussed below in this paper, considerable 2D and 3D simulations, plus supporting experimental R&D, remains to be done to fully qualify such designs for NIF.

High gains and yields may also be attainable with "fast ignition", an alternative method of igniting ICF targets presently under study [4]. Fast ignition, like shock ignition, also decouples fuel assembly from the ignition process, and consequently has similar potential advantages in fusion gains/yields and lower threshold for drive energies. Fast ignition requires two physically distinct, time-synchronized laser systems – a main "slow" compression laser driver (~20-40ns) and a separate fast, petawatt-class ignition laser (~10's ps), whereas shock ignition would be accomplished with the standard NIF laser. Timing and spatial focusing requirements for shock ignition are also less demanding than those for fast ignition, while computer modeling involves only conventional radiation-hydrodynamics implosions on simple target configurations at standard laser intensities so that simulation results should be more tractable in terms of today's models and databases. Of course, shock ignition still requires ignition from a central, high temperature hotspot and thus conventional hydrodynamic symmetry and stability constraints will apply. Thus, as described below, major critical issues for shock ignition include convergence symmetry and stability of the shock pressure drive at the hotspot.

Parallel studies of shock ignition applied to the near term facilities HiPER and FTF have demonstrated the potential for high gain and yield for this new class of target [5,6] and Ribeyre et al. have discussed the fielding of shock ignited targets at low drive energies on LaserMegajoule (LMJ) [5]. Like fast ignition, shock ignition offers the promise for high-gain ICF at low laser drive energies that may ultimately lead to smaller, more economic fusion power reactors and a cheaper fusion energy development path. Such advanced target concepts are now under consideration for future next-step inertial fusion energy facilities such as HiPER[5,7], FTF[6] and LIFE [8].

2. Prospects for Near Term Experiments at High Gain

There exists the potential to test a high-gain shock ignited target on NIF at ~0.5MJ drive energy in the near-term (~4-5 years) with no new laser hardware required. This is due to its simple target design, its prospective in-flight robustness, the potential need for only 1D SSD beam smoothing and little or no early-time LPI preheat issues.

We have examined prospective routes for deploying shock ignition targets on NIF ranging from near term to longer term. The longer-term options have the potential for high fusion yields (>100MJ) using targets that are fully fusion-reactor-relevant, but at the expense of longer lead times due to requirements for new laser hardware. In contrast, the initial high gain target at ~0.5MJ NIF drive energy (Fig. 2 above) is considered a near-term prospect because it can be deployed with: (a) no modifications to laser hardware or signal path routing from the pre-amplifiers to the final optics – that is, no hardware modifications in the path: AWGs → *PAMS* → *PABTS* → *main amplifiers* → *transport filters* → *conversion crystals* → *lenses* → *phase plates*, and (b) no disruption to the baseline indirect drive ignition campaign.

Shock-ignited targets in the next few years would be fielded on NIF under polar drive as proposed for standard NIF direct drive targets [9] but can employ day-1 indirect drive phase plates [3]. A key immediate need for shock ignition on NIF is to verify the adequacy of low-mode drive uniformity and shock symmetry under polar drive for the convergence ratios predicted for these shock ignited targets. Accordingly, as summarized below, the primary objective of near term preparatory experiments should be to determine the optimum laser specifications – i.e., pulse shape, pointings, focusings and power phasing per quad – that will then enable the fielding of a full cryogenic high-gain shock ignition target ≥2014.

3. NIF Laser Requirements and Optimization of Polar Drive Symmetry

Under polar drive (PD), the NIF beams are retained in the present indirect drive port configurations but adequate direct drive uniformity is potentially achievable by a combination of repointing and partial defocusing of laser beams and phasing the independently-programmable power balance from quad to quad. A PD experimental platform has been developed as part of the National Ignition Campaign for commissioning nuclear diagnostics; successful PD shots performed on NIF in 2009-10 with low-convergence "exploding-pushers" were consistent with 2-D simulations. Design studies are now in progress with our hydrodynamic implosion codes to determine the optimum laser drive specifications that can then be experimentally tested in the near term.

A promising initial configuration has been identified wherein half the NIF quads (96 "main beams") are given the compression pulse and optionally some of the shock pulse, and the other half (96 "ignitor beams") are given just the shock portion of the pulse (Fig. 3). Separate focusing and pointing parameters are used for the main and ignitor beams. The ignitor beams are launched at late time when the capsule has converged a factor of ~three from its original diameter, and are focused at the converged capsule radius at that time. The main beams are focused on the initial radius, optimized to provide a uniform compression. This overall configuration provides a "zooming" that should enhance the shock-drive intensity and provide enhanced coupling of the shock pressure pulse to the compressed core. The high-power portion of the main beams, while not optimally focused, would still contribute to the shock drive.

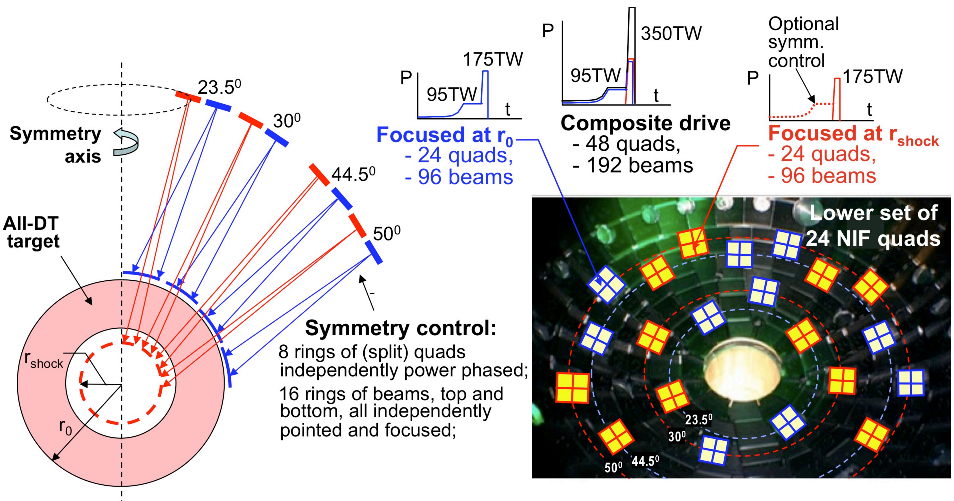

FIG.3. Initial configuration for optimizing polar drive symmetry for 0.5MJ-class shock ignited targets. Half of NIF quads (96 beams) focused at capsule radius at t=0 while the other 96 beams are focused at the reduced capsule radius at shock launch.

Using this configuration, initial optimizations with the two-dimensional hydrodynamics code *SAGE* carried out in a similar way to Ref. 10 have identified parameters for the compression beams that provide good uniformity for the initial phase of the compression, for an all-DT design. The parameters include two repointings (vertical and horizontal) and a defocus distance for each ring of beams. These initial results are shown in Fig 4 at a time just before the launch of the shock pulse. Note the potential for good shell uniformity – viz. 0.7% polar uniformity in the shell center-of-mass. The laser PD parameters will be adjusted as the 1D and 2D designs evolve.

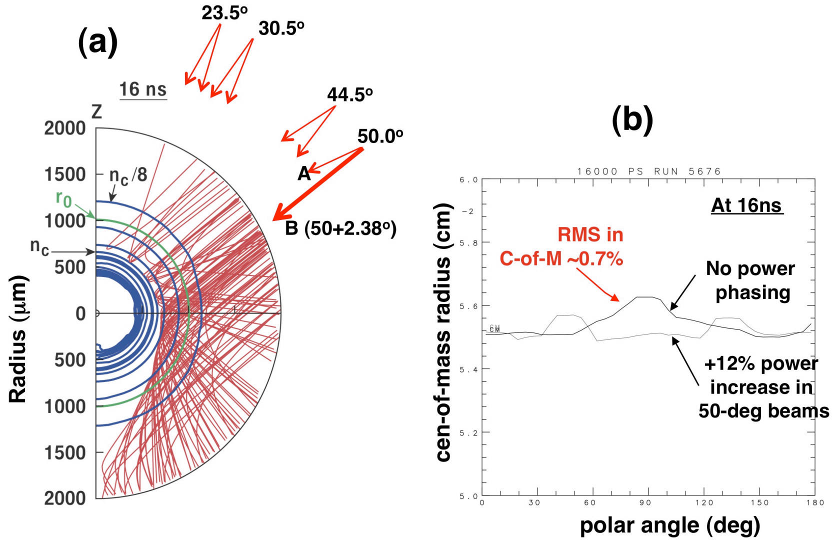

FIG 4. Initial simulations of NIF polar drive for the 0.5MJ-class all-DT target with SAGE [see, for example, ref 10]: (a) Electron density contours versus radius at 16ns, just before the launch of the shockpulse; the laser raytrace is shown for the 50-deg split-quad B at a polar angle 50+2.38deg (b)Resulting center-of-mass radius versus polar angle at this time indicating the prospects for an RMS of less than 1%. Phasing of polar-dependent power offers an addition optimization control knob in addition to beam pointing and focusing

In terms of NIF laser power requirements, the main drive pulse for fuel assembly will be at a modest peak power P_{main}~50-90TW while the shock pulse P_{shock} will require higher peak powers of ~250-350TW, for a total drive energy of ~0.5-0.7MJ. For comparison, the baseline NIF indirect-drive ignition target with a CH ablator requires equivalent peak powers/beam of ~420TW at ~1.5 MJ drive energy. These are relative to maximum NIF peak powers at 3w of ~450-500TW depending on scenario. We have performed initial validations of our preliminary shock ignition pulse shapes with the NIF Laser Performance Operations Model (LPOM) [11]; results indicate that temporal contrasts should be achievable in the main amplifiers and that proposed pulse shapes do not pose any equipment protection issues. The shock launch time t_{shock} determines the arrival of the shock ignition pulse relative to the hydro bounce of the stagnating fuel. For the targets envisaged in this proposal, ignition shock synching requires a shock pulse launch window – that is, the permissible spread of t_{shock} – of ~0.4ns with a 10-90% rise-time requirement of ≤0.35ns. An initial simulation of the pulse shape to be supplied by the NIF AWGs – that is, the pulse shape required as input to LPOM – indicates that the fast risetime can be delivered with no hardware changes in the front end [3].

4. Beam Smoothing and Higher Mode Stability

Higher mode beam imprint at early time is an issue for direct drive as, together with outer surface roughness, it forms a seed for later-time Rayleigh-Taylor (RT) growth. Shock ignited NIF targets may be less susceptible to imprint relative to regular hotspot ignition targets because of the thicker low aspect ratio shell which is resistant to outer surface perturbations and in-flight breakup (inflight aspect ratios are only ~15) and, possibly, the potential for enhanced ablative stabilization from later time SRS-generated hot electrons (below).

Ideally, 2D SSD (smoothing by spectral dispersion) at a bandwidth of 1THz would be implemented to smooth the laser speckle for conventional higher aspect-ratio direct drive targets but would necessitate modifications to all 48 NIF preamplifier modules (PAMs) plus the employment of dual tripler crystals at the final focus. Thus, this is probably not an option for a near-term experimental test of shock ignition.

An alternative near-term beam smoothing scheme for NIF is currently under investigation and employs simple 1D multi-FM SSD at ≤0.5THz [12]. Compared with 2D SSD, it has reduced complexity (no second dimension), is applied in a fiber in the front end rack mount unit (no new bulk optics required in the PAMs), takes advantage of multiple color cycles without the disadvantage of coherence maxima in the spectrum, and would use the present day-1 tripler crystals. As shown in Fig 5, simulations by Marozas et al [12] indicate that imprint reductions are comparable to 2D SSD in direct drive and will be applicable to polar direct drive. Experimental validation in 2010-2011 at LLE/University of Rochester will be an important test of this method.

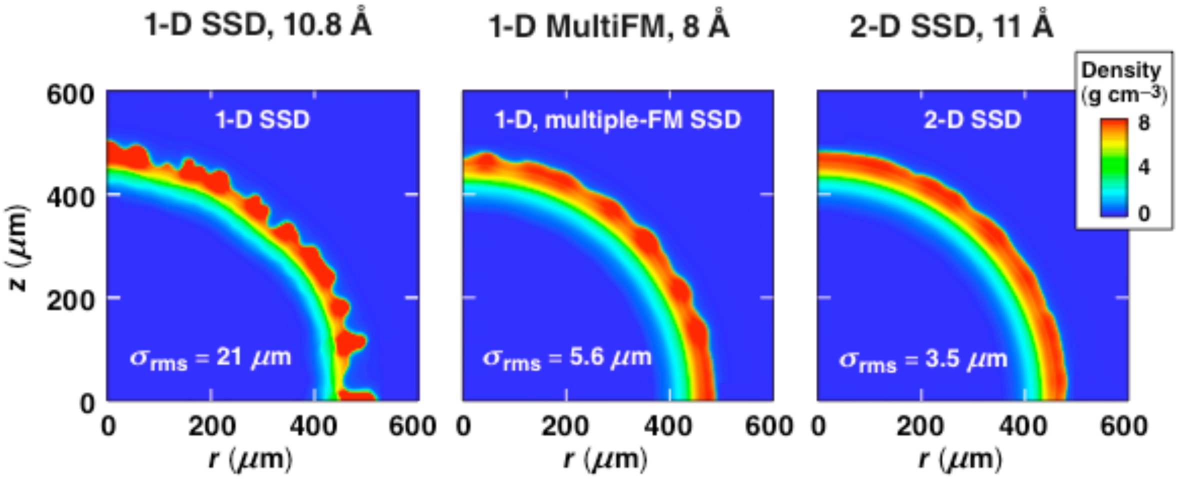

FIG. 5. Simulations of multi-FM 1D SSD beam smoothing on a candidate NIF 1.5MJ-drive CH foam/DT target [12]. Late time imprint at the end of the acceleration phase reduces to 2D SSD levels

Preliminary 2D stability studies have been performed on shock ignition implosions [5, 13]; they suggest that stability of the hotspot boundary can be quite insensitive to RT at stagnation due to non-linear interference between RT and a stabilizing opposite-phase Richtmyer-Meshkov stage. In general, multimode calculations of high mode beam imprint and inner ice roughness are an important data need in parallel with the lower mode symmetry studies

5 Laser Plasma Interactions

Because of high laser intensities during shock launch (~several $x10^{15}W/cm^2$ to greater than $10^{16}W/cm^2$ [2,3]), a potential concern for NIF shock ignition is the onset of laser-plasma instabilities (LPI) including stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS) and two-plasmon decay (TPD). SRS and TPD can result in the generation of suprathermal electrons. For conventional NIF direct and indirect drive hotspot targets, such hot electrons can be a serious source of preheat in the precompressed fuel as soon as the laser approaches its main drive power.

By contrast, it is important to note that in shock ignition the high laser intensity is not applied until late time where the fuel is approaching stagnation. Thus, the now dense imploding shell is capable of absorbing SRS or TPD-generated hot electrons up to high energies, shielding the inner DT fuel from preheat. Moreover, providing their energies are less than ~100keV, generation of such hot electrons might actually enhance shock drive performance due to increased ablation pressures, strong ablative stabilization of R-T instabilities and symmeterization of the converging shock pressure front. Of course, with its relatively low onset threshold, TPD must also be monitored at earlier times during the low intensity main pulse. If this should prove to be a substantive issue then recourse may then be necessary to the use of a wetted-foam CH ablator or all-CH plastic ablator to shield the main DT fuel.

New Fokker-Planck calculations exploring non-local hot electron transport relevant to shock ignition [14] indicate that the relatively collisionless energetic electrons have long path lengths around the surface of the target and that the tangential heat flow around the target is comparable with the radial heat flow into the target even though the temperature gradients are more gentle. In particular, even with two-sided asymmetric laser drive, the drive pressure appeared quite uniform.

Recent shock-ignition-relevant experiments on Omega at NIF-relevant intensities on low adiabat CH shells containing D_2 gas showed a factor of 20X increase in neutron yield on application of the shock pulse [15]. While not a test of shock *ignition* per se, the experiments demonstrated that compression assembly and shock pulses can be successfully synchronized and the results illustrated a significant improvement in the performance of low-adiabat, low velocity implosions compared to conventional hotspot implosions. In these experiments, approximately 35% LPI backscatter was seen at a shock laser intensity of ~$1\text{x}10^{16}$W/cm^2, reducing to about 20% at ~$5\text{x}10^{15}$W/cm^2. At the highest intensities, the reflection was dominated by SRS with a smaller contribution from SBS; there was no detectable contribution from TPD. A SRS hot electron population of ~10% of the incident energy was generated around 40-45keV, with temperature independent of laser intensity. As above, we believe hot electrons in this energy range may be beneficial to both the hydro efficiency and symmetry of shock drive for NIF targets. Note also that our candidate near-term NIF design (Fig. 3) has total drive energies of only ~0.5MJ and is not power limited in the shock spike (see below), so reductions in absorbed energy due to increased backscatter can be compensated by increases in shock launch power.

6. Preliminary Experimental Plans and Objectives

Our preliminary plan for ≥2011 is to seek to field four phases of experiments as shown in Table 1. The objective of Phases 1-3 is to obtain optimized drive geometries and power pulse shapes together with an assessment of LPI and electron transport issues that will then enable the fielding of full cryogenic shock-ignition targets in Phase 4, ca. ≥2014. This latter campaign (to be defined) aims at reaching the Ignition Threshold Factor required in cryo-THD leading to full shock ignition attempts in cryo-DT at high gain at around 0.5MJ drive energy [3]. We will also benefit from on-going and future NIF-PD-like shock ignition preparatory experiments on the OMEGA laser facility [15].

Table 1. Shock ignition on NIF - Proposed experimental plan (Phases 1-3) to optimize polar drive symmetry and shock coupling together and characterize associated laser-plasma interactions.

	Phase 1 ≥2011	**Phase 2 ≥2012**	**Phase 3 ≥2013**	**Phase 4 -≥2014**
Experiments	PD Symmetry: (i) Low CR (ii) High CR. Characterization of TPD	Integrated implosions w/shock. Optimization of laser geometries and shock timing. Characterization of late time SRS SBS	Integrated implosions w/shock. Final tunings.	Cryogenic shock ignition
Targets	Room-temp CH shells	Room-temp CH shells	Room-temp CH shells	(i) Cryo THD, (ii)Cryo DT
Fill gases	Ar, D-^{3}He	Ar, D_2, D-^{3}He	Ar, D_2, D-^{3}He	N.A
Laser Energy Requirements	250-500kJ (compr.)	250-500kJ (compr.) 250-300kJ (shock)	250-500kJ (compr.) 250-300kJ (shock)	TBD
NIF Power Requirements	50-90TW (compr.)	50-90TW (compr.) 200-350TW (shock)	50-90TW (compr.) 200-350TW (shock)	TBD

Other requirements: *Phase plates* - day-1 (indirect drive) partially defocussed. *Beam smoothing* – 1D SSD (→ Multi-FM 1D SSD when available). *Bandwidth* – 0.2THz (→0.5 when available). *Pulse lengths* – ~15ns (compression) ~0.8ns (shock),; shock pulse risetime ≤0.35ns

The first set of implosion shots in Phase 1 would be devoted to the validation and initial tuning of PD configurations suitable for the compression phase of shock ignition. They would employ surrogate room-temperature CH targets that are hydro-equivalent to the cryogenic targets envisaged for Phase 4. Main observables will be the shape of the imploding shell, the shape of the compressed core and the areal density. The success of this first phase is a condition for integrated implosion experiments in 2012- 2013 in Phases 2-3 using both compression and shock pulses.

The experimental campaigns for Phase 4 – i.e., fielding of full cryogenic THD and DT ignition targets – will be defined at a future stage as the definitive results become available from Phases 1-3

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