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Executive Summary

Shock ignition [1] is an approach to ignition and thermonuclear burn in inertial confinement fusion (ICF) that has the potential to produce higher fusion energy gains at lower laser drive energies compared with conventional central hotspot ignition. To date, however, it has only been considered feasible in laser direct drive, making it only a long-term prospect for evaluation at the National Ignition Facility (NIF) because of the large investment required in new hardware and facilities. Here, we document initial research into an approach that may permit shock ignition to be obtained in indirect drive in a hohlraum. Our conventional indirect drive ignition platform on NIF uses a single laser pulse shape to compress and ignite a thin shell of fusion fuel at high velocity. By contrast, here we assemble a thick, low velocity shell of fuel in indirect drive that is then separately ignited by a strong shock driven by a subset of the NIF laser beams. By decoupling the compression from the ignition in this way, significantly more fuel mass can be assembled and ignited, resulting in higher fusion yields and energy gains relative to conventional targets. Moreover, the thick, low-aspect-ratio shells may be less affected by symmetry and stability perturbations. Laser plasma instabilities (LPI) driven by the high intensity shock pulse will likely be a central issue. This may provide an additional route to fusion ignition that would enable the rich physics of burning plasmas to be realized at the higher fusion yields needed for inertial fusion energy. Compared to other advanced ICF ignition concepts, not only could this be tested on NIF with present day hardware (in all-blue light) or near-term hardware (in mixed blue/green light) but, being indirect drive, its required knowledge base is underpinned by the extensive experimental database of the present NIF ignition program. Accordingly, this approach could be viewed as just indirect drive ignition at high gain using a different laser pulse shape. Hence, its testability in the near term.

Background and Technical Approach

Shock ignition [1] is an established theoretical – and developing experimental – concept in ICF for igniting fusion fuel with high energy gain, i.e., the ratio of the fusion yield to laser drive energy. However, to date, shock ignition has only been deemed generally achievable in laser-direct-drive [1, 2, 3, 4, 5]. In particular, our earlier radiation-hydrodynamics target physics studies of ca. 2012 suggested that it may not be attainable on NIF in indirect drive with frequency-tripled 3ω (“blue”) laser light because, while the NIF laser is capable of providing the required fast rise of the shock drive pulse, limitations on its peak power in 3ω, plus the inefficiency of the high-gas-fill hohlraums then in use at that time, resulted in the simulated hohlraum radiation temperature rising too slowly to drive a sufficiently strong shock through the fuel to ignite the hotspot. By contrast, the concept here is to use around two-thirds of the NIF beams in 3ω to assemble the fuel in conventional indirect drive but as a thick low velocity shell, and then devote the remaining beams to drive the ignition shock via a separate process in a modern, higher-efficiency low-gas-fill hohlraum.

The principle is illustrated in Fig. 1 where the laser pulse shapes for indirect drive shock ignition (red curves) are compared with that for conventional indirect drive (dashed blue curve). In the conventional case, all 192 NIF beams are employed at 3ω for a single adiabat-shaped pulsed shape. The resulting hohlraum x-ray drive produced by this single laser pulse is required to assemble the fuel capsule at high density *and* impart a sufficiently high velocity (~4x10^7cm/s) to the imploding shell so that its *PdV* work creates the central ignition hotspot on stagnation. In this regard, conventional indirect-drive ignition is a single hydrodynamic process and results through fast compression; a mechanical analog would be a diesel engine.

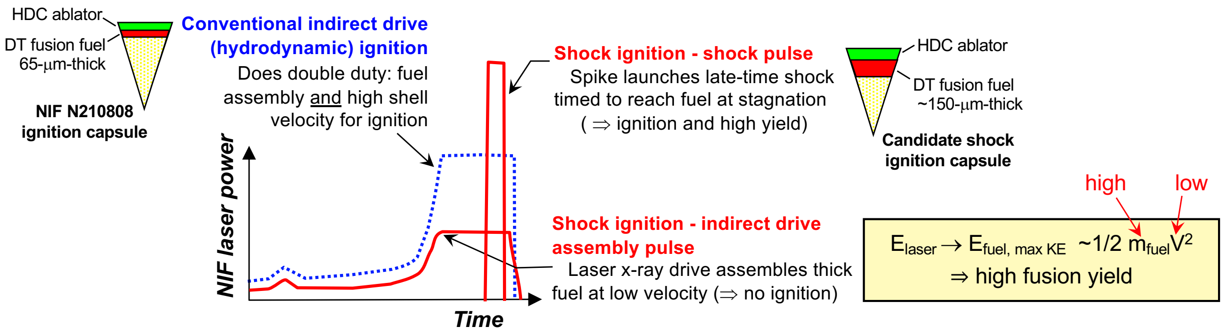

Fig-1. The essence of shock ignition: Assemble thick fuel at low velocity and ignite separately.

By contrast, here the fuel assembly and ignition phases are decoupled as follows: We first employ a fraction of approximately two-thirds (~128) of the NIF beams at modest power/intensity in 3ω blue light to compress a thick, low-aspect-ratio capsule by x-ray-driven ablation in indirect drive. The resulting low implosion velocity (~2.5-3 x10^7cm/s) would result in only a low temperature central hotspot, insufficient for ignition to occur, but the low adiabat of the fuel leads to high values of the assembled areal and mass densities. The remaining fraction of the beams (~64) are then run into the hohlraum in 2ω ("green") light to drive a separate shock pulse. NIF in 2ω green light is capable of significantly higher energies – and, importantly for this application, powers – than 3ω light. Viz., peak NIF energies/powers in 2ω are approximately ~2.5MJ/850TW for a square pulse, relative to only ~2MJ/500TW for 3ω light. (These comparisons are full-NIF-equivalents; determining maximum performance constraints for NIF 2ω green light for shock ignition is an important study area of this present research).

Our latest preliminary radiation-hydrodynamics simulations discussed below indicate this may result in a sufficient ramp-rate in the hohlraum radiation temperature to drive the required sustained shock*. The high-power shock beams are synchronized to launch at late time such that the resulting converging shock is timed to arrive at and ignite the hotspot just as the D-T fusion fuel is stagnating and starting to rebound from the compression drive.

The crucial principle here is that, in the same way as direct drive shock ignition, we have decoupled the compression from the ignition – an analogy is a gasoline engine which is separately ignited by a sparkplug. Thus, because the shell velocity is significantly lower, considerably more fusion fuel mass can be assembled and burned for a given shell in-flight kinetic energy. This offers

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* We note that it may not be possible to exploit NIF's 2ω green energy/power headroom for our conventional indirect drive targets because of the production of deleterious hot electrons at early time that preheat the fusion fuel. By contrast, here the shock pulse is launched at late time and with only 1/3rd of the beams in green. Consequently, the low intensity 3ω drive has already assembled an imploding shell with sufficient density to absorb later-time hot electrons of perhaps up to ~100 keV in its outer ablation surface (the characterization of such LPI hot electrons is an important present research topic).

the potential for higher fusion gains/yields for a given laser energy or, equivalently, the retention of acceptable gains at lower laser drive energies. In addition, the thick, low-aspect-ratio, low velocity shells may be less affected by symmetry and stability issues.

Preliminary Simulations

Our preliminary target physics simulations summarized below with DT fusion fuel layers ~1.5 to 2 times thicker than that of present conventional indirect drive ignition capsules, indicate that shock ignition might be obtainable in such low velocity targets on NIF producing potential fusion yields in excess of 30 MJ. The corresponding low inflight-aspect-ratios of these capsules in these simulations are around only half that of the present indirect drive capsules, suggesting alleviated stability issues at stagnation.

Fig 2 shows the laser pulse shape and resulting radiation temperature drive for the successful NIF ignition shot N210808 from August 2021 in conventional indirect drive. This target obtained a fusion yield of 1.3MJ and gain (ratio of fusion yield to laser energy into the hohlraum) of ~0.7, a profound achievement [7]. Note that following the low power, adiabat-setting foot of the laser pulse, the main drive rises immediately to a peak power of 441TW with total delivered energy of 1.92MJ to drive the shell at high velocity at early time. (NB: while NIF peak available 3ω power would be close to 500TW, the indirect drive ignition campaign has demonstrated that total delivered energy is typically more important than peak power. By contrast, peak power is more important than total energy for indirect drive shock ignition).

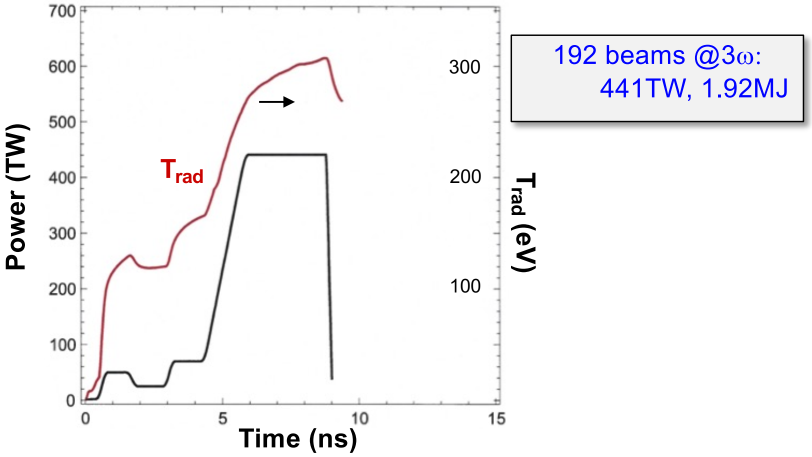


Fig 2. Conventional indirect drive: Laser pulse shape and resulting radiation temperature drive for the NIF N210808 ignition shot

Fig 3 shows an example of the approximate energy-power operating space of the NIF laser taken from Ref 8. These are full NIF equivalent (FNE) parameters for all 192 beams. The approximate boundaries for high contrast ratio, adiabat shaping pulses are shown for blue (3ω) and green (2ω) light. (The 1ω red boundary illustrates the fundamental infra-red capability of the laser but cannot be utilized for driving targets due to issues of backscatter regeneration in the main amplifiers). The green triangle point at ~3.5MJ/750TW illustrates potential NIF capability in green light for a square pulse; this was validated by Lava Lamp II, an off-line version of the NIF LPOM laser chain code, for application to the Los Alamos double shell target [8]. Given high peak power is the fundamental requirement for indirect drive shock ignition, for our initial studies here we trade energy for power, translating this point to the associated green triangle at ~2MJ/850TW (we have yet to validate this pulse shape with Lava Lamp/LPOM).

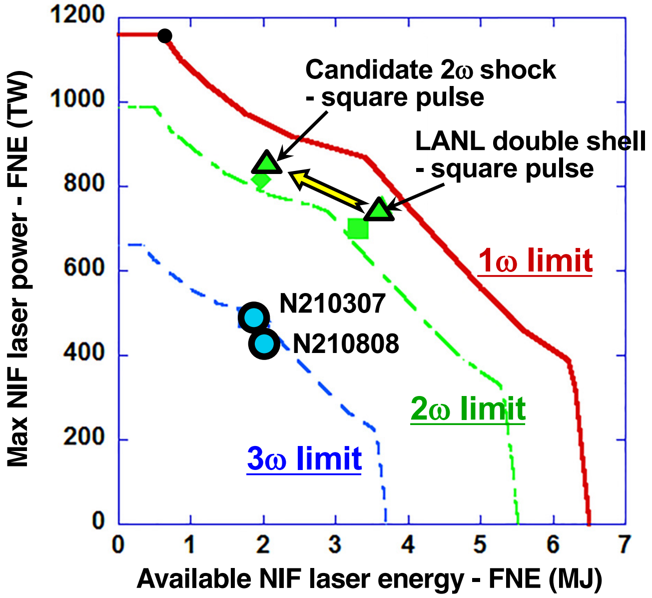


Fig 3. Approximate NIF energy-power operating space (full NIF equivalent, FNE, for all 192 beams) [8]. Green triangles show potential operating points for square pulses in 2ω green light and the trading of energy for increased peak power for shock ignition here

Fig 4 shows one example of a resulting composite blue/green pulse shape we envisage for indirect drive shock ignition. Here 2/3rd (128) of the NIF beams are used in 3ω blue, at 180TW to drive the main assembly pulse, accelerating the capsule inwards. At late time, 1/3rd (64) of the beams are then launched in 2ω green at 0.67MJ/290TW to drive the shock pulse, supplementing the 3ω beams which, at this time, are also ramped to their peak power capability of 333TW (500TW FNE); the combined blue and green powers give a composite shock drive of ~620TW. The total energy under the blue 3w pulse is 1.33MJ (2MJ FNE). (See below regarding the time synching of the shock pulses)

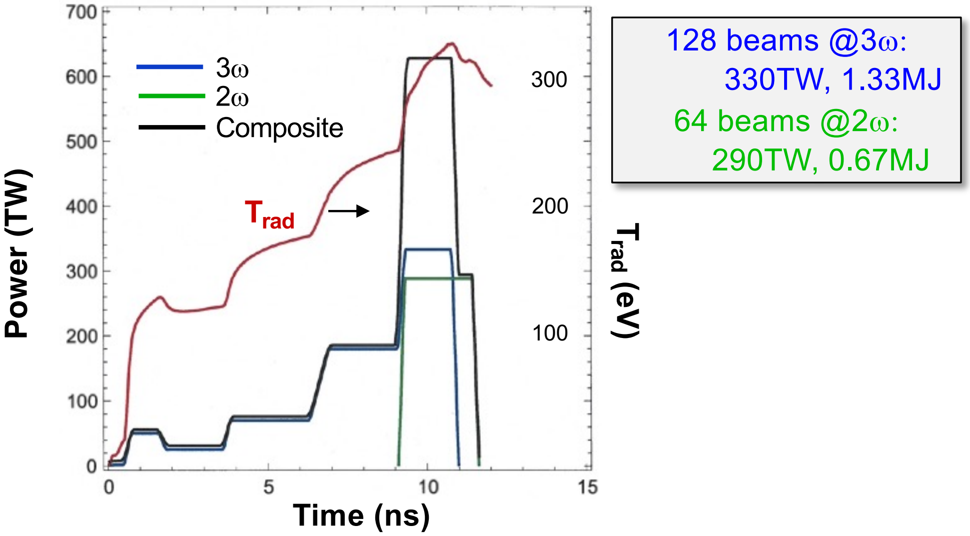
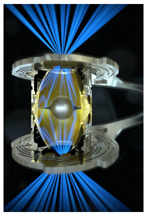
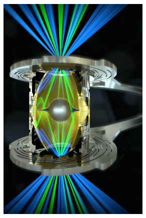


Fig 4. *An example of a NIF composite blue/green pulse shape for indirect drive shock ignition*

Table 1 columns 2-4 show initial examples of simulations for prospective NIF indirect drive shock ignition targets driven by the generic pulse shape example in Fig 4. The computations were performed by the LASNEX radiation-hydrodynamics code [9] in 2-D with only x1 roughness on the outer ablator surface and the inner ice surface. In each case, we tune the foot picket and pedestal to set the fuel adiabat, optimize the power of the main drive assembly pulse for maximum areal density at stagnation, and then scan the launch time of the green shock pulse and simultaneous ramping blue shock pulse for maximum fusion yield. The latter times optimize when the resulting converging shock arrives to ignite the hotspot as the D-T fusion fuel is stagnating and rebounding from the assembly drive. The timing precision of the shock launch window is ~500ps – this window delineating the FWHM of the maximum fusion yield – and is fully achievable by the laser. (The actual pulse shape in Fig 4 was used for the capsule in column-3 of Table 1).

For comparison, in column-1 of Table 1 we show analogous simulation results for the NIF N210808 hohlraum and capsule driven by the conventional indirect drive N210808 pulse shape in Fig 2, under the same assumptions of only x1 roughness, with no other symmetry and stability impositions. This is not intended to be a benchmark of the N210808 shot as we obtain a yield of 5.3MJ, a factor of ~four higher than the actual N210808 yield of 1.3MJ with its real experimental symmetry and stability perturbations. Rather we use this as a datum result with which to compare the shock ignition cases on the same basis. The shock ignition targets in columns 2-4 use the same Hybrid-E hohlraum dimensions, same capsule outer radius and same high density carbon ablator as N210808, but with increasing DT fuel thickness from x1 (65μm) to x2 (130μm)





	“N210808”	**Indirect drive shock ignition**		
DT fuel thickness	**x1 (65μm)**	**x1**	**x1.5**	**x2**
Yield (MJ)*	5.3* ¶	16.9*	35.5*	30.6*
Velocity (10^7 cm/s)	4.1	3.2	3.0	2.9
In-flight aspect ratio: shell / fuel	28 / 62	21 / 48	21 / 45	17 / 27
Fuel adiabat	3.2	2.0	1.5	1.6
Areal density (g/cm^2)	0.7	1.3	1.2	1.0
Fuel temp T_{brysk} (keV)	16.5	22.9	36.2	30.2

* 2-D LASNEX with x1 roughness on fuel and ablator only ¶ N210808 actual yield =1.3MJ

Table 1. Initial radiation-hydrodynamics simulations for indirect drive shock ignition. For comparison, the first column shows N210808 hohlraum, capsule and conventional pulse shape (from Fig 3) run under the same assumptions of only x1roughness on fuel and ablator surfaces

From Table 1, these preliminary results indicate that higher gains and yields might be obtainable with this approach, and for the same reason as direct drive shock ignition – viz. the ability to assemble and ignite slow, thick fuel with greater DT fuel masses. Moreover, such targets with their thicker shells may be less susceptible to stability perturbations at late time (note that inflight aspect ratios are up to a factor of two lower than that for the conventional indirect drive simulation).

Anticipated Challenges and Future Research Tasks

This is an emerging fusion ignition concept based today on preliminary initial radiation-hydrodynamics code simulations and with wide scope for contributions from the ICF community. Validation data for the conventional assembly phase of this target platform is well in hand from the wealth of results from the present NIF ignition program. Thus, from the viewpoint of inertial confinement ignition physics, there may be plausible reasons to suppose that, in the same way as direct drive shock ignition, higher fusion yields and target gains might be realized with this approach, *if* appropriate late-time shock coupling physics pertains. Hence, the risks underlying this research direction are that we are unable to locate a viable design point for the shock drive once either full 2-D and 3-D radiation-hydrodynamic simulations or follow-on experiments are performed with all attendant symmetry, stability, and laser plasma instability (LPI) constraints. Accordingly, planned research tasks include:

- Analyses with radiation-hydrodynamics codes to map out and optimize the initial target design space – commensurate with NIF peak power capabilities for all-blue drive and for optimum blue/green beam mix – with follow-on integrated capsule/hohlraum simulations.
- Determination of maximum energy/power tradeoffs for the specified NIF shock-drive beams in 2ω green light and fuel assembly beams in 3ω blue light and via LPOM and Lava Lamp II (NIF laser chain analysis codes)
- Modeling of potential LPI issues, including: SBS backscatter losses, SRS/TPD hot electron production, late-time fuel preheat, Langmuir-driven cross beam energy transfer from blue/green beam interactions, etc
- Experimental assessments, including potential precursor experiments on Omega, single beam and single quad tests of NIF pulse shape in green light, and near term NIF experiments. Latter will be conducted with all-blue shock pulse shapes, at sub-energy-scales $\leq$1MJ (but at maximum power capability), and with surrogate, scaled capsules and hohlraums. NIF experimental measurements will include: Tr ramp-rate in the hohlraum for the shock pulse at late time, shock speed/pressure in the capsule, gas reactions with and without the shock pulse to gauge stagnation pressures, and characterization of resulting LPI (backscatter loss and hot electrons)

Acknowledgements

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Disclaimer

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