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Shock Ignition: A New Approach to High Gain Inertial Confinement Fusion on the National Ignition Facility

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Shock ignition, a new concept for igniting thermonuclear fuel [1], is explored as a potential approach to high gain, inertial confinement fusion targets for the National Ignition Facility (NIF). In shock ignition, fusion fuel is separately ignited by a strong spherically-converging shock and, because the capsule implosion velocity is significantly less than that required for conventional ignition targets, more fuel mass can be assembled for a given laser drive energy. The benefits of decoupling compression from ignition on NIF is that an order-of-magnitude higher fusion energy gains/yields are potentially achievable. Initial results indicate thermonuclear yields of ~120-250MJ may be possible with laser drive energies of 1-1.6MJ, while gains of around 50 should still be achievable at only ~170kJ drive energy. The scaling of NIF energy gain with laser energy *E*(MJ) is found to be of the form $G \sim 126E^{0.51}$. This offers the possibility for high-gain targets that may lead to smaller, more economic fusion power reactors and a cheaper fusion energy development path.

In inertial confinement fusion (ICF), a laser delivers an intense pulse of energy to a target containing of the order of a milligram of deuterium-tritium (DT) fusion fuel. The fuel is rapidly compressed over ~10-20ns to high densities and temperatures sufficient for thermonuclear fusion to commence. The goal of present ICF research is to obtain ignition and fusion energy gain from a DT target and will be attainable if the fuel is heated above the ignition temperature (~10-12keV) and confined long enough so that an appreciable portion of the fuel is consumed [2]. Complete burning of a 50:50 mix of DT fuel through the fusion reaction $^2H + ^3H \rightarrow n + ^4He + 17.6MeV$ would release a specific energy of 3.38×10^{11}J/g. The fusion burn of an ignited fuel mass is limited by hydrodynamic expansion but, under appropriate conditions, the inertia of the fuel mass can provide the confinement necessary for the target to achieve thermonuclear energy gain. The gain of an ICF target is defined as the ratio of the fusion energy produced to the laser driver energy incident on the target and is a key parameter in determining the economic viability of future inertial fusion energy power plants [3].

The National Ignition Facility (NIF) is preparing to demonstrate ICF ignition and energy gain in the laboratory for the first time [4]. In the initial phase, this will be performed in indirect drive – that is, where the laser energy is first converted to x-rays in a hohlraum surrounding the fuel capsule [2] – and through ignition generated by fast-compression (to be defined below). Extensive analyses and supporting experiments provide confidence that these conventional targets will achieve the NIF ignition goals [5] but they are predicted to produce only modest gains and yields, viz. gains ~15 and yields ~20MJ at laser drive energies of ~1.3MJ. In particular, given the inherent low efficiency of laser indirect-drive targets, it is not clear that they will directly scale to fusion power applications [3]. Accordingly, in this paper, we seek to establish the physics performance of a new class of advanced targets operating under "shock ignition" [1] for possible implementation on the National Ignition Facility following the achievement of conventional indirect-drive ignition. Shock ignition provides the potential for very high energy gains, thus the purpose of this letter is to explore the scaling of fusion yield and energy gain for candidate NIF target designs. This offers the promise for high-gain ICF targets at low laser drive energies that may lead to smaller, more economic fusion power reactors and a cheaper fusion energy development path.

A typical ICF fusion target consists of cryogenic solid DT fuel in the form of a thin spherical shell surrounded by an outer ablator region of mass comparable to that of the fuel and of a material selected to optimize the implosion dynamics. Energy is rapidly coupled to the ablator from the driver – either directly in the form of symmetrical laser beams or indirectly in the form of x-rays stimulated by lasers interaction in a surrounding hohlraum – and, as the heated ablator expands outwards, momentum conservation causes the remaining target to be imploded inward by the rocket effect. With a suitable temporal profile on the drive intensity, the fuel can be maintained relatively cold near the minimum Fermi degenerate pressure as it is compressed by the resulting shock waves. At peak laser drive intensity, the capsule approaches a state of uniform acceleration until spherical convergence effects and gas backpressure cause the fuel to stagnate at high density. Providing this cold dense fuel can be ignited from a central "hotspot" at ~10-12keV containing only a few percent of the fuel mass, then the overall fuel burn fraction f_{burn} depends on the balance between the thermonuclear reaction rate and hydrodynamic expansion; it is determined by the tamping effect of the areal density, ρR (g/cm^2), of the assembled fuel mass at ignition and can be written approximately as $f_{burn}(\rho R) \sim \rho R/(\rho R + \mathrm{x})$, where for DT fuel $x \sim 6$g/cm^2 [2]. Thus, a ρR of, say, 2.5g/cm^2 would be required for a fuel burn fraction of ~30%, or for a fusion energy yield of ~100MJ from 1mg of DT fuel. The energy gain G – i.e., the ratio of fusion yield to laser drive energy – depends on the fuel burn fraction and capsule peak implosion velocity V and scales as $G \sim f_{burn}(\rho R)/(V^{5/4} I^{1/4})$, where I is the laser intensity [6]. Note importantly that, providing central ignition occurs, gains increase for lower implosion velocities because a greater fuel mass can be assembled and burned for a given laser drive energy.

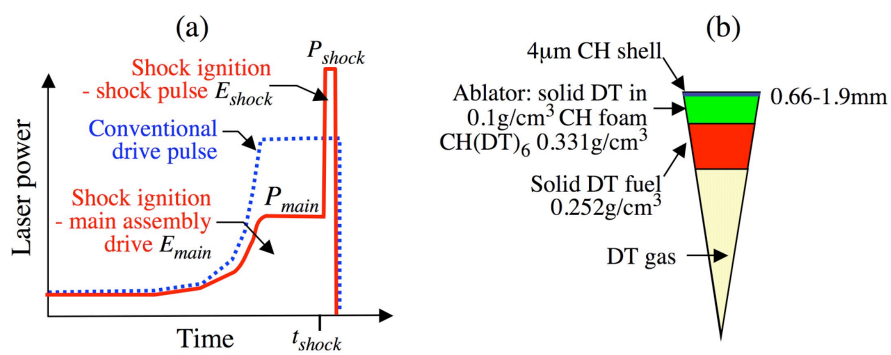

FIG. 1. (a) Schematic laser pulse shape drive for shock ignition (solid curve) relative to that for conventional indirect or direct drive (dotted curve), (b) spherical radial build of candidate NIF shock ignition target

The principle of shock ignition is shown in Fig. 1(a). Here we illustrate schematically the laser pulse shape required to drive a conventional NIF target under either direct or indirect drive (dotted curve) in comparison with that for a prospective shock ignition target (solid curve). In the conventional target, the standard laser driver pulse is required to assemble the fuel at high density *and* impart a sufficiently high velocity (V~3.5-4x10^7cm/s) to the imploding shell so that its PdV work creates the central ignition hotspot upon stagnation [2]; in this regard, conventional direct or indirect drive hotspot ignition might be more formally referred to 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 low 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 mass density and areal density. 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 carefully timed to reach the center just as the main fuel is stagnating and starting to rebound. 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 (~20-30%) is required for the shock ignition. Crucially, because the implosion velocity is significantly less than required for conventional fast-compression ignition, considerably more fuel mass can be assembled for the same kinetic energy in the shell, offering significantly higher fusion gains/yields for the same laser energy or, equivalently, retaining acceptable gains at appreciably lower drive energies.

We note that analogous high gains and yields may also be attainable with "fast ignition", an alternative method of igniting ICF targets presently under study [7]. However, fast ignition requires two physically distinct, time-synchronized laser systems – a main compression laser driver (~20-40ns) and a separate fast, petawatt-class ignition laser (~10's ps), while shock ignition is accomplished with the same laser. Timing and spatial focusing requirements for shock ignition should also be less demanding than those for fast ignition. Moreover, computer modeling for shock ignition depends only on conventional radiation-hydrodynamics 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.

The candidate target build under consideration for shock ignition on NIF is shown in Fig. 1(b) and is based on targets studied for conventional direct drive [8]. It consists of a central region of low density DT gas at its equilibrium vapor pressure (~0.4mg/cm^3 at ~18K) surrounded by a thin spherical shell of frozen DT fuel and an outer ablator comprising DT wicked into low density (100mg/cm^3) CH foam. The capsule is sealed with an outer solid CH plastic coating of 4μm thickness. All-DT targets – that is, DT fuel and pure DT ablator – are an alternative option and would offer ease of fabrication at somewhat reduced laser coupling efficiency and target gain. Shock-ignited targets could be fielded on NIF under the conventional direct-drive or polar-direct-drive campaigns, presently envisaged for >2012, and would leverage the optics and diagnostics planned for those campaigns [8]. Our present simulations indicate that it will not be possible to achieve shock-ignition on NIF using indirect drive within a hohlraum. This is because, while the NIF laser system will be able to accommodate the required fast rise of the shock-ignition pulse (see below), there would be an appreciable time lag in the conversion of laser energy to radiation temperature due to the heat capacity of the hohlraum. Thus the radiation drive would rise too slowly to achieve the required shock synching time relative to the hydro bounce of the stagnating fuel.

Implosion and thermonuclear burn simulations for NIF shock ignition in this paper were conducted in 1-D spherical geometry with the LASNEX radiation-hydrodynamics code [9]. The laser had a fixed focus at the target diameter at t=0; 3-D laser ray-tracing was employed accommodating reflection and refraction so that laser energy transport and absorption was treated correctly in the coronal plasma. The essence of the studies then consisted of mating an optimized laser pulse shape in time and power with an optimized target design subject to maximum power and energy constraints of the NIF laser system. These explorations use appropriate 1-D implosion characteristics as proxies for initial estimates of 3-D stability and symmetry constraints.

Figs. 2(a) and (b) show the resulting fusion energy yield curve and gain curve as a function of the total delivered laser energy (i.e., the sum of the main assembly laser energy and shock drive laser energy) for a range of candidate NIF shock ignition targets from small to large as obtained from the 1-D LASNEX simulations. For comparison in Fig. 2(a) and (b) we also show the predicted performance of the current NIF ignition baseline target operating under conventional indirect drive with fast-compression ignition, viz. a nominal fusion yield of ~20MJ at a drive energy of 1.3MJ and a corresponding modest gain of ~15.

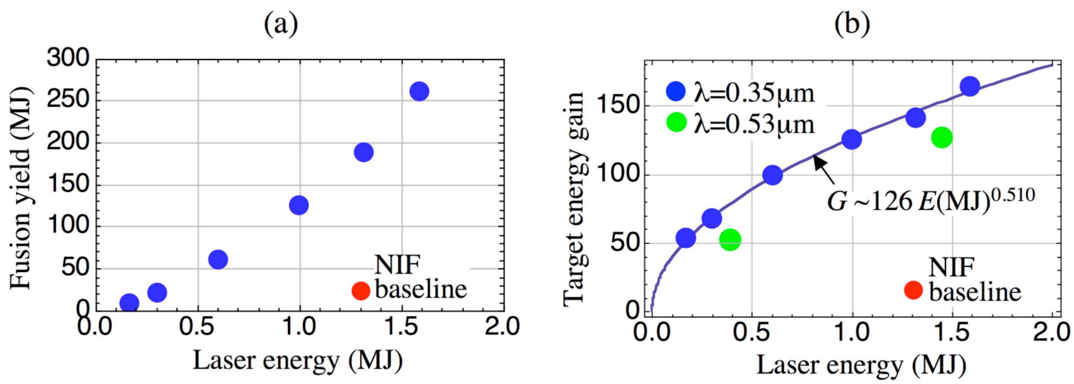

FIG 2. (a) NIF shock ignition fusion yield and (b) target energy gain, as a function of total NIF laser drive energy resulting from the LASNEX implosion simulations. Corresponding values for the NIF indirect-drive baseline ignition target are shown for comparison. The gains of two preliminary shock ignition targets driven in green light (λ=0.53μm) are also indicted.

The center 1MJ-drive shock ignited case was obtained first by seeking a nominal 100MJ fusion yield at a typical burn fraction of ~30%, an ablator mass set equal to the fuel mass, and an initial capsule aspect ratio (defined as the ratio of the mean shell radius to the shell thickness) of 2.5. This is a markedly low initial aspect ratio for an ICF target, made possible by the requirement for only modest implosion velocities; as shown below, such massive thick targets also have good hydrodynamic stability characteristics during the implosion acceleration phase. Given material compositions and densities are known, specification of these three constraints then define the radial build of the target in terms of the outer radii of the gas volume, the DT fuel and the ablator.

The target designs were then scaled up and down from this 1MJ-drive case by setting the DT fuel mass, $m_{DT} \sim 4\pi\, r_{DT}^2\, \Delta r_{DT}\, \rho_{DT}(0) \sim s^3$, to provide a desired nominal fusion yield $\sim m_{DT} f_{burn} \sim m_{DT}\, \rho R/(\rho R+x)$, where s is the scale factor on capsule linear dimensions and $\rho_{DT}(0)$=0.252gm/cm^3 is the initial uncompressed density of frozen DT at 18K. For fixed capsule dimensions, i.e., a fixed value of s, peak areal densities scale as $\rho R \sim E_{main}^{0.33}/\alpha^{0.55}$ [6], where E_{main} is the laser driver energy in the main assembly portion of the pulse and α is the in-flight adiabt of the fuel (that is, the ratio of the in-flight fuel pressure to the irreducible Fermi-degenerate pressure), thus initial estimates of the main drive powers P_{main} scale approximately as $\sim s^1$ to maintain desired peak areal densities around ~ 2.5g/cm^2 for the desired fuel burn fraction of ~30%. Further, given implosion times scale approximately as $t_{main} \sim s^1$, the laser drive energy for the assembly phase could be initially estimated to scale as $E_{main} \sim P_{main}\, t_{main} \sim s^2$. These are close to the actual optimized results from the 1-D implosion simulations below.

With the preliminary power and energy scalings above, the time of attainment of the main drive power P_{main} and the laser flattop time for which this power is maintained was then adjusted in each LASNEX simulation to obtain an areal density of the compressed fuel in the desired vicinity of 2.5g/cm^2 before application of a shock pulse. Finally, for each target variant (that is, given value of the scaling parameter s) a further set of 1-D simulations was performed by scanning the three shock datum parameters – i.e., shock power P_{shock}, the energy in the shock pulse E_{shock}, and the start time t_{shock} of the rise of the shock pulse relative to the end of the main assembly pulse – to optimize the target gain, subject to the NIF laser performance constraints. Accordingly, for each fixed target design, several hundred LASNEX 1-D implosion/burn simulations were performed to tune the laser drive pulse shape.

NIF, an intrinsic 4MJ infrared (1.053μm) laser, is capable of maximum delivered energies/powers at the target of ~2.8MJ/700TW and ~1.8MJ/500TW, when frequency doubled/tripled to wavelengths of 0.53 μm (green light) and 0.35μm (UV), respectively [10]. The majority of simulations described here were performed with UV laser light at the wavelength of 0.35μm due to its higher intrinsic drive efficiency and higher thresholds for the onset of deleterious laser-plasma-interactions (LPI). Because shock ignition is potentially capably of high gains at modest laser energies, only the largest, high-yield targets would stretch NIF to these maximum capabilities.

From Fig. 2(a), potential thermonuclear yields on NIF under shock ignition range from 9.1MJ for the smallest target driven at a total laser energy (main drive plus shock drive) of 0.17MJ, to 261MJ for the largest target driven at 1.59MJ. The corresponding target gains – that is, ratio of output yield relative to laser drive energy – then range from 53 to 164, respectively, around an order-of-magnitude larger than those predicted for conventionally driven targets. Fitting to the gain curve in Fig. 2(b) provides a gain scaling for NIF shock ignition of the form $G \sim 126\, E^{0.510}$ where E is the total laser drive energy in megajoules. We note that the upper design point at 261MJ fusion yield could be viewed as a fully fusion-energy-relevant target with potential application to a future inertial fusion power plant; if qualified on NIF on a single-shot basis, such a target could be fielded on a future rep-rated facility at, say, 10Hz and would then yield a steady-state thermal power of around ~2500MW(th) and, given typical thermal cycle efficiencies of ~0.4, an electrical output power of ~1000MW(e). Of course, fusion yields around 250MJ are an order of magnitude higher than those expected for the NIF indirect drive ignition baseline target with attendant increases in prompt and activation radiological products. However, such targets should be fieldable within the operational regulatory limits of the NIF facility.

Also plotted in Figs. 2(b) above are the gains for two preliminary shock ignited candidate targets driven in green light at a wavelength of 0.53 μm. As expected for this longer wavelength, the reduced coupling efficiency and greater standoff of the critical surface from the ablation front of the imploding shells reduce the overall gain of the targets relative to their shorter UV wavelength counterparts at 0.35μm. However, operating such targets in green light could enable us to take advantage of the higher laser damage thresholds in NIF final optics through higher NIF drive energies and greater number of experimental shots before the necessity of optics replacement, albeit with lower LPI onset thresholds.

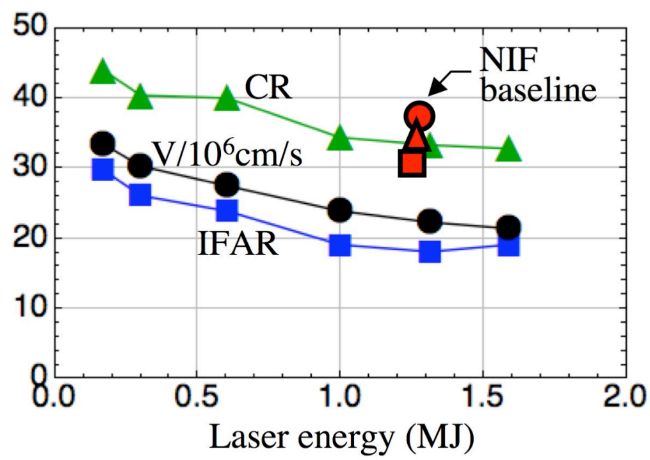

FIG 3. Characteristic implosion parameters for the NIF shock ignited targets: In-flight aspect ratio (IFAR), convergence ratio (CR) and peak implosion velocity (V). Corresponding values for the NIF indirect-drive baseline ignition target are shown for comparison.

Although the purpose here is to explore the energy and gain scalings of shock ignition targets for NIF, the ultimate viability of such targets will require detailed analysis of stability and symmetry in 2-D and 3-D, tasks beyond the scope of this initial paper. However, three characteristic parameters for the imploding shell can be extracted from the 1-D simulations and used as initial guidance to gauge prospective multidimensional behavior, namely the peak implosion velocity *V*, the in-flight aspect ratio IFAR and the convergence ratio CR. These are plotted in Fig. 3. Corresponding values for the NIF indirect drive baseline target are shown for comparison. The IFAR is defined as the maximum value of the ratio of the mean shell radius to shell thickness and is significantly greater than the initial aspect ratio because the shell compresses as it implodes; typically, the maximum IFAR occurs when the shell has traveled around one quarter of the way to stagnation. The CR is defined as the ratio of the initial outer radius of the capsule to the final compressed radius of the hotspot at ignition. Hydrodynamic instabilities impose typical upper limits to the IFAR and CR of the order ~35 and 30-40, respectively [2]. The low initial aspect ratios of 2.5, corresponding thick shells and low implosion velocities of these targets result in the high gains above because more mass has been assembled for a given laser drive energy and so, correspondingly, they exhibit beneficially low peak velocities and IFARs. Thus, these targets should exhibit good hydrodynamic stability during the acceleration phase such that Rayleigh-Taylor (RT) growth of outer surface perturbations is unlikely to penetrate the shell during the implosion. Note, in particular, that the smallest target in Fig. 3 has a velocity and IFAR of only 3.3×10^7 cm/s and 29, respectively, values that are markedly low for cryogenic ignition targets of such small size and drive energy.

The convergence ratios appear acceptable for the larger targets, but are approaching relatively high values in excess of 40 for the smallest variants. This is a consequence of the converging shock driving the hotspot to smaller radii and which is out of pressure equilibrium with the main cold compressed fuel. By comparison, conventional, fast-compression ignition targets such as the NIF baseline are essentially isobaric across the hotspot and fuel at stagnation [2] resulting in a larger hotspot radius but, of course, at the expense of considerably lower gain. High convergence ratios are a potential concern for the smallest shock ignition targets in Fig. 3 as small hotspots will typically be more susceptible to RT growth of perturbations on the inner fuel surface during the late time deceleration phase with potential mix of cold fuel into the hotspot, thus delaying or even preventing the onset of ignition. Future 2-D and 3-D studies will assess these issues.

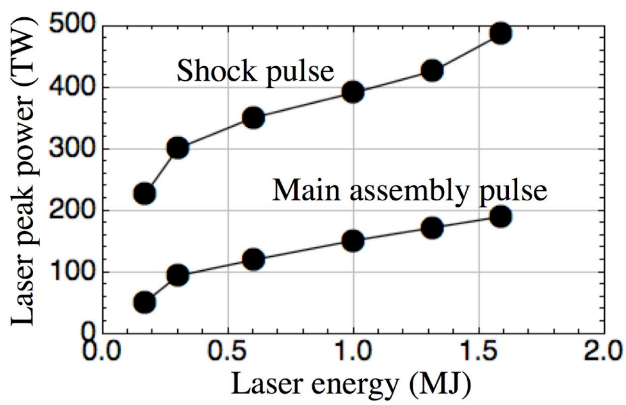

Fig 4. Peak laser power of the main assembly drive (P_{main}) and the shock ignition pulse (P_{shock}) for the NIF shock ignited targets.

Fig. 4 shows the required peak laser powers in the main assembly pulse and the shock pulse resulting from the optimized implosion scans. Only the largest high yield target would approach the NIF power limit of 500TW. Operating NIF in green light at 0.53 μm with its higher power extraction capability would extend the operating headroom to ~700TW. We have performed an initial validation of these shock-ignition laser pulse shapes with the NIF Laser Performance Operations Model [11]. Results indicate that the temporal contrasts should be achievable in the main amplifiers and that the proposed pulse shapes do not pose any equipment protection issues. The shock launch time parameter t_{shock} above determines the arrival of the shock ignition pulse relative to the hydro bounce of the stagnating fuel. More precisely, to obtain the optimum hotpot ignition conditions, it is necessary that this ignitor shock collide with the returning stagnation shock from the main fuel assembly near the inner surface of the dense fuel. The ignition shock launching window – that is, the permissible spread of t_{shock} – ranges from ~0.5ns for the larger targets to ~0.3ns for the smaller targets. Gains increase with increasing t_{shock} up to the late time bound because the fuel is permitted to stagnate to higher areal densities ρR before decompressing under the ignition burn wave resulting in higher fuel burn fractions. Thus, shock synching requirements indicates that required risetimes for the NIF laser shock pulse should be around ~0.1ns. Given present risetime capabilities are ~0.25ns, such specifications will necessitate modification to the NIF front-end pulse shape generators – fortunately, a low cost item.

Because of the high laser intensities during launching of the shock pulse, one potential concern for NIF shock ignition targets is the stimulation of plasma parametric instabilities through laser-plasma interactions (LPI) including stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS) and two-plasmon decay (TPD) [12]. SBS and TPD can result in the generation of suprathermal electrons which, for conventional NIF direct and indirect targets, can be a serious source of preheat in the precompressed fuel as soon as the laser pulse approaches it main drive power. However, for shock ignition it is important to note that the high laser intensity is not applied until late time where the fuel is approaching stagnation. Thus, the now dense imploding shell will be capable of absorbing SRS or TPD-generated hot electrons up to high energies, shielding the inner DT fuel from preheat. Moreover, the generation of such hot electrons may enhance the shock drive performance due to enhanced ablation pressures, strong ablative stabilization of R-T instabilities and symmeterization of the converging shock drive pressure. Formal investigation of LPI-generated hot electron source terms is beyond the scope of this exploratory paper but we have performed an initial parametric study for the 0.3MJ, gain-68 target above in which a fraction of the shock laser energy was taken as being converted to isotropic SRS electrons at a given kinetic energy and born at the critical surface. Subsequent transport of this hot electron population with the LASNEX suprathermal electron package showed no appreciable degradation of the target gain for up to 100% conversion into 50keV electrons, or up to 45% conversion into 100keV electrons. Moreover, the 50keV source appeared to be a more beneficial ablation drive than the original laser; viz., the gain dropped slightly with increasing hot electron fraction only because the target was igniting too early and, therefore, at lower assembled areal density and fuel burnup fraction. Retuning the laser drive would likely increase target gains above 70 here.

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