Shock Ignition: High Gain Target Performance for Inertial Fusion Energy

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Executive Summary

Shock ignition (SI)[1] is an innovative approach to inertial confinement fusion (ICF) with the potential for high gain at low input laser energy for inertial fusion energy (IFE). SI is a relatively mature ICF design concept explored in detail over the past 15 years both theoretically and experimentally. SI implosions consist of two stages: a fuel assembly phase and an ignitor phase. During assembly, the fuel is compressed to high density at a relatively low velocity compared to standard hot-spot ICF designs. After the capsule has converged by a factor of ~2.5 to 3, a strong spherical shock is launched into the pre-compressed capsule, further compressing the fuel (final convergence ratio of ~25 to 30) and raising the hot-spot temperature and pressure above the ignition threshold. This approach allows for fuel assemblies of higher areal density, and therefore higher fusion gain, compared to standard hot-spot ICF designs with the same input laser energy. Similarly, lower input laser energy is required to reach the ignition threshold. SI implosions may use a single, temporally-shaped ns-scale laser system and may ignite with several 100's of kJ of laser energy. While there are some variants of SI design, typical SI targets are relatively simple to manufacture and field, generally with little or no high-Z materials, making SI an ideal choice for IFE design, given the large quantity of targets required for reactor operations. Furthermore, the higher gain possible with SI would allow for a lower shot rate, thereby reducing the quantity of target shots per day and/or a smaller laser facility operating at the same shot rate, both of which would reduce IFE facility operating costs.

Shock ignition concept and simulation studies

Shock ignition (SI) is an ICF design concept that separates the fuel assembly from the ignition phase of the implosion through the addition of a laser spike pulse at the end of the fuel assembly pulse (see Fig. 1), similar to the concept of Shcherbakov[3] from 1983. The fuel is assembled from a spherical shell driven inward at low laser intensity ($I \sim 0.4$ to 1.0×10^{15} W/cm^2) and low adiabat. SI allows for a fuel assembly at lower implosion velocity ($v_i \sim 2.4$ to 3.0×10^7 cm/s) with a lower-intensity drive pulse less prone to generate hot electrons (HEs) which may

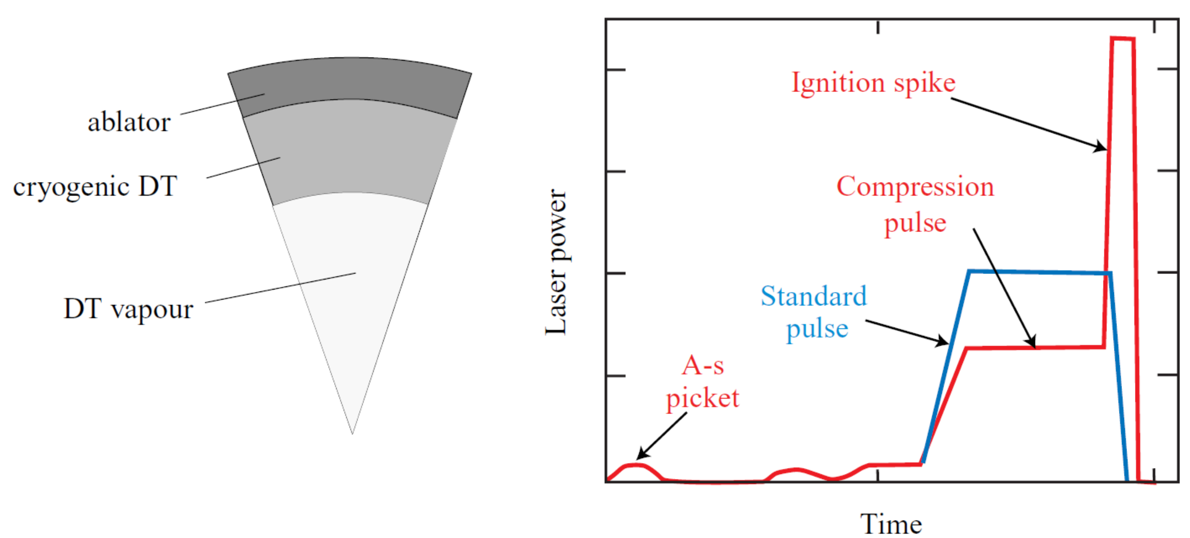

Figure 1. Diagram of the target and laser pulse shape for SI shown with a comparison of standard direct-drive laser pulse [from Ref. 2].

preheat the fuel. SI also assembles fuel with higher areal densities ideal for high gain. The central hot spot created by this fuel assembly pulse alone, however, is generally too cold to reach ignition conditions. To achieve these conditions, a laser spike pulse added at the end of the compression pulse then launches a strong, spherically symmetric shock of ~200 to 400 Mbar into the capsule. The peak intensity of the laser pulse to launch this strong shock is in the range of 5 x 10^{15} watts/cm^2. The timing of this spike pulse must be optimized such that the strong shock collides with the return shock at the inner edge of the shell, amplifying the hot-spot pressure and temperature to achieve ignition. For IFE SI designs, the typical timing window for the launching of the strong shock to achieve ignition is several hundred picoseconds, easily achievable on today's laser systems.[4-10] The spike pulse power and shock pressure required to ignite the fuel assembly are inversely related to the implosion velocity of the fuel assembly. Once ignition conditions are reached in the hot spot, a burn wave propagates through the high-areal-density fuel assembly, leading to high fusion gain.

The original SI concept[1] used a target of radius 850 microns imploded by 425 kJ of laser energy to achieve a gain of 60 (fusion yield of 25 MJ). About two thirds of the laser energy is used in the assembly portion of the laser and one third in the ignitor or "spike" pulse. Similar target designs have been shown by other groups for various laser systems to achieve gains between 50 and 150 for laser energies between 250 kJ and 1.5 MJ at a laser wavelength of 351 nm.[5,8-19] Even higher gains are predicted using shorter laser wavelengths.[6-7,20-21] Ablator materials chosen for SI are typically CH plastics, or so-called "wetted foams" (with liquid DT wicked into the foam).

The accessible gains for SI designs are substantially higher than for standard hot-spot designs at the same input laser energy. Results of one such study[11] of SI designs at varying laser energy are shown in Figure 2. Other scaling studies have shown similar results.[6-8,13-14,20-23]

Because of their thicker targets and slower implosion speeds, SI designs are generally less susceptible to hydrodynamic instabilities compared to standard hot-spot designs. The higher mass and lower main-drive pressures lead to lower acceleration, in turn lowering Rayleigh–Taylor instability growth rates. A thicker shell in flight means that instability growth must be faster to puncture the target or feed through to the inner surface and distort the hot spot. Several multidimensional simulation studies have predicted ignition is possible in IFE or near-IFE-scale SI implosions with current levels of non-uniformities in the laser drive and capsule.[1,5,9-10,12,16,18-20,22] It has also been shown that the symmetry of the ignitor shock beam geometry is less important than that of the fuel assembly.[10,12,16]

To date, shock ignition with lasers has generally been considered only using direct drive

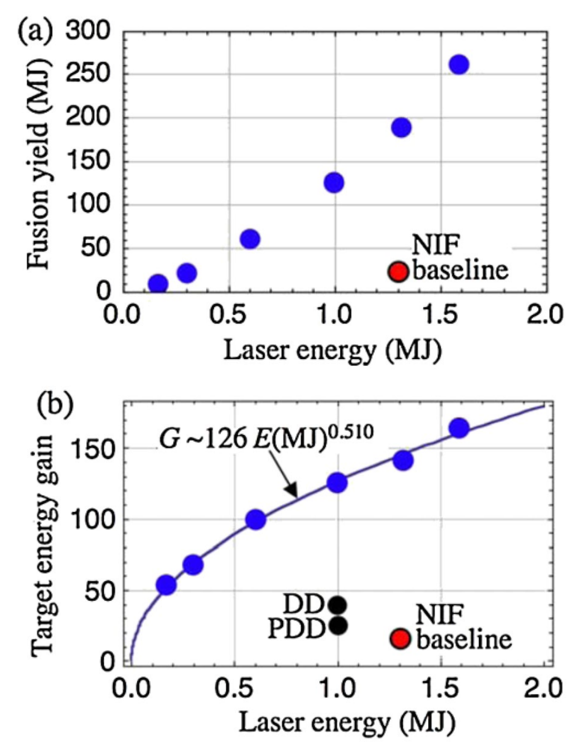

Figure 2. Plot of the one-dimensional (a) fusion yield in MJ and (b) target gain energy versus input laser energy for a family of SI designs, including a NIF (indirect-drive) baseline, a direct-drive (DD), and polar direct-drive (PDD) designs for the NIF, for comparison (from Ref. 11).

and not indirect drive. Hohlraum radiation drive temperature at late time during the spike pulse rises slowly due to the thermal inertia of hohlraum x-ray production. This plus large late-time case-to-capsule ratio in flight results in low radiation coupling efficiency.[24] A potential solution for the first issue was proposed in Ref. 25. In addition, a two-sided hybrid target was designed[26] using a thick, low velocity 240-deg spherical shell segment of DT assembled on a Au guide cone with a central hole by indirect-drive in a one-sided hohlraum. It is then shock ignited on the opposite side by direct-drive on a 120-deg spherical fuel segment inside the cone. Issues of implosion symmetry and high-Z mix from the Au cone still need to be addressed.

A few other alternative SI designs have also been proposed. In one, a double shell fuel assembly is ignited by a strong shock.[27] The addition of the spike in this design lowered the ignition threshold energy, providing more margin. Another variant, "shock-augmented ignition" (SAI)[28] uses a dip in power to precondition the ablation plasma before launching the strong shock. Simulations indicate this enables SI with substantially reduced laser power and intensity requirements in comparison to conventional SI, reducing the impacts of LPI and increasing the implosion scale which can be fielded on existing facilities. Yet another variant generates the strong SI shock solely by directing HEs into the pre-compressed fuel assembly.[29-30] In this design, the fuel assembly is of sufficient areal density to stop HEs near the outer surface, raising the pressure of the external portion of the shell enough to generate the ignitor shock. A shock ignition variant of the dynamic shell liquid filled foam concept has also been proposed.[31]

The potential for high gain with smaller, less energetic laser systems makes SI an excellent design choice for inertial fusion energy (IFE) applications. Experiments conducted over the past 15 years have shown optimistic results for the SI concept, improving yield and addressing physics concerns with high-intensity laser energy coupling, scattering, and LPI hot-electron coupling to the fuel. A continued and focused effort is required to fully validate SI at scale for IFE applications.

Scientific challenges to the SI approach

While the results of one- and multi-dimensional radiation hydrodynamics simulations have been optimistic for the prospect of high gain with shock ignition, SI designs have some scientific challenges, which are currently being addressed in both simulations and experiments. One major physics question of the SI approach is that of laser–plasma interactions[32] (LPIs), particularly during the high-intensity laser spike pulse, and LPI-associated hot-electron preheat. Another is demonstrating that the laser energy in the spike pulse can efficiently generate a sufficiently strong ignitor shock. Finally, low-adiabat implosions for standard direct-drive and indirect-drive capsules have not performed well, and it is not known whether 1-D physics effects contribute to this.

At intensities of the order of the SI spike pulses, LPIs such as two-plasmon decay (TPD), stimulated Raman scattering (SRS), stimulated Brillouin scattering (SBS), and cross beam energy transfer (CBET) are expected to play roles in scattering laser light away from the absorbing regions of the target's corona. TPD and SRS can generate high-energy HEs, which can penetrate deep into the cold fuel layer, preheat it, and preclude the additional compression needed for ignition. SRS, SBS and CBET cause energy losses to the system in the form of scattered light and can produce compression asymmetries. All of these are highly nonlinear processes dependent on laser intensity and the coronal plasma temperature, density, and temperature and velocity gradients. As such, their effects can be also strongly affected by the laser filamentation instability, which is expected to be driven at intensities typical of the SI spike pulse and can strongly modify local conditions of interaction. In addition, these mechanisms compete with each other, and their growth may be affected by electron kinetic effects, making it even more difficult to quantify them theoretically. The generation and transport of HEs by SRS and/or TPD is a particularly complex issue for SI. Understanding the coupling of HEs to the cold fuel requires not only a knowledge of the energy spectrum and directional distribution of the accelerated electrons, but also a model to track the deposition of the electrons' energy as they move through the plasma background.

Shock coupling in integrated SI implosion simulations has largely focused on inverse bremsstrahlung laser absorption modeling of the spike laser pulse and either ignored LPIs or heuristically approximated LPI-scattered energy losses using data obtained from dedicated, short-scale LPI simulations and/or experiments. The effect of LPI-generated HEs on shock formation and capsule preheat have been better characterized using in-line HE transport models in radiation-hydrodynamics codes.

Studies of the baseline HIPER target design[21] at CELIA suggest that HEs generated during the spike may prevent ignition due to insufficient target areal density. This conclusion was also found considering a CELIA SI design with a plastic ablator. Even with the enhanced areal density at the time of the spike pulse, a significant part of the high energy spectrum of HEs was able to ablate the inner DT ice interface and increase significantly radiative losses, preventing ignition.[33] These conclusions were confirmed recently using a rigorous Monte Carlo approach to describe HE transport.[34] On the other hand, low energy HEs (<50 keV) do not produce such deleterious effects, but rather amplify the shock strength, leading to increased margin.[4,10,29-30,35-37] Other implosion simulations including Monte-Carlo HE transport, while also indicating detrimental preheat of the fuel, showed that shock retiming could help to reduce the impact of HE preheat.[33,38-40] These results highlight the care that must be taken in designing SI targets, taking into account the details of HE generation, distribution and transport, and how the LPI must be correctly characterized.

LPI mitigation strategies to both reduce laser energy losses and to diminish/tune HE generation need to be investigated. The manipulation of laser coherence time and the development of broadband lasers appear particularly promising. Increasing laser bandwidth between a few tenths of a percent to several percent can progressively switch off laser filamentation and LPIs. Lowering the intensity of the spike laser pulse, as in SAI, is another strategy for reducing LPIs. Laser zooming[41] for the spike pulse has also been shown to improve laser–shock coupling[6-7] and is anticipated to significantly reduce CBET losses.[41-43]

Shock-Ignition Experiments

Shock ignition physics has been tested in a variety of experiments at various laser facilities over the past 15 years. Spherical implosion experiments adding an SI-like spike pulse at the end of the laser drive on the OMEGA laser facility resulted in a two-fold increase in yield compared to a no-spike-pulse design at the same laser energy.[44] Areal densities also increased by 30 to 50% with the addition of the spike pulse. While the laser intensity in the spike pulse of these implosions was only about 8×10^{14} W/cm^2, well below typical SI intensities, these experiments showed encouraging results for SI. Further spherical implosions were performed at OMEGA using 40 beams for the fuel assembly and 20 tightly focused beams to launch the shock and study LPI effects in SI implosions at higher laser intensities.[38,45] Results showed HEs were produced with an approximate temperature of 30 to 40 keV at a conversion efficiency of 1 to 2%.

Planar target experiments on OMEGA,[46-47] OMEGA-EP,[48] NIF,[49] LMJ-PETAL,[50] PALS,[51-56] LULI2000,[57] and Vulcan[58] studied HE generation and LPI in SI-relevant laser intensity with density scalelength up to ~1 mm. For scalelengths shorter than envisaged in SI, and temperatures between 1 keV and 5 keV, interaction with a single-UV beam showed significant TPD and convective SRS, with SRS reflectivity usually in the percent range. HE conversion efficiencies were in the range of ~0.1 to a few % and temperatures from 20 to 50 keV, in agreement with those expected from SRS. Single-beam experiments with longer wavelength light tended to produce a hotter electron population with higher conversion efficiencies.[48,52,56] Backscattering measurements at PALS with a 1ω IR pulse[55] showed a rapid onset of TPD in the saturated regime at early times of interaction, followed by an abrupt damping of TPD and by the growth of convective SRS, included side-SRS at the higher laser intensities, driven at densities $n = 0.12$ to $0.18\ n_c$. Overlapping many beams also tended to increase the conversion efficiency and temperature.[59] Less data are available on LPI scattering losses. OMEGA 40+20 beam experiments observed high losses that reached up to ~10% for both SBS and SRS backscattering.[45] Similar high SBS backscattering losses were observed in planar target experiments on PALS[51] and LULI2000.[57]

A few experiments carried out at NIF,[60-61] LMJ,[50] OMEGA,[46] and Vulcan,[58] studied LPI in longer scalelength plasmas with $L_n \sim 400$-500 µm, ignition-scale SI interaction conditions. In these experiments, TPD is not observed, while convective SRS is strong, producing reflectivities up to 10-20%. SRS is driven down to low plasma densities of $0.05\ n_c$ where kinetic effects are dominant, which can result in the generation of lower energy electrons, as observed in Vulcan and partly in LMJ experiment.[50,58] Efficiency of HE generation in these experiments remains in the percent range. The growth of SRS at low densities can also be driven by laser filamentation, potentially resulting in laser–plasma smoothing, capable of explaining the absence of TPD.[58]

Strong spherical shock experiments were conducted on both OMEGA and NIF using solid-sphere, non-imploding targets.[40,60-61] Low-intensity laser power created coronal plasma conditions similar to that of SI, followed by a high-intensity spike pulse. Shock coupling efficiency was assessed using the timing of the shock collapse at the center of the target and using in-flight backlit radiography to determine the speed and position of the shock. The experimentally observed shock trajectories were well modeled by simulations and showed an absorption fraction,[62] including CBET losses, of approx. 55% at $I = 2.5 \times 10^{15}$ W/cm^2. These experiments significantly (when scaled appropriately) exceed the strength of the required ignitor shock.[40]

Roadmap toward inertial fusion energy with shock ignition

To achieve ignition with SI, a dedicated international effort is needed to refine previous physics simulations and field experiments at full SI scale, intensity, and relevant beam geometries. Large scale particle-in-cell simulations are needed to address and optimize the laser intensity regime for SI, refine characterization of LPI's, and to assess LPI-mitigation strategies such as broadband lasers[63-65] and mid-Z ablators.[66] Improved integrated modeling of LPIs in radiation–hydrodynamics codes, including inline scattering, HE generation, and transport is required for the design work to eliminate the need for ad hoc or artificial coefficients.

An integrated experimental plan needs to be developed, funded and supported. This includes continued LPI experiments in both planar and spherical geometries and with multiple laser beams. HE generation and coupling experiments will assess the level of preheat and shock coupling. No-spike spherical implosions at ignition scale will address questions about the viability of low-adiabat fuel assembly, evaluate achievable areal densities, and shell stability. Implosions including the SI spike will demonstrate the shock coupling to a converging capsule, in preparation for a demonstration of full cryogenic ignition experiments.

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