Shock Ignition – A New Route Towards Laser Fusion Energy

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Abstract

The technologies required for Laser Fusion Energy are advancing rapidly at present and it is expected that net energy gain from laser ignited fusion reactions will be demonstrated within the next few years. New concepts are already being proposed to increase the gain and reduce the laser energy requirements for future full scale reactor systems. This report presents a summary of the status and issues involved with one of these techniques, Shock Ignition, which uses an additional very powerful laser pulse at the end of the main compression pulse to heat and ignite the compressed fuel.

1. Introduction

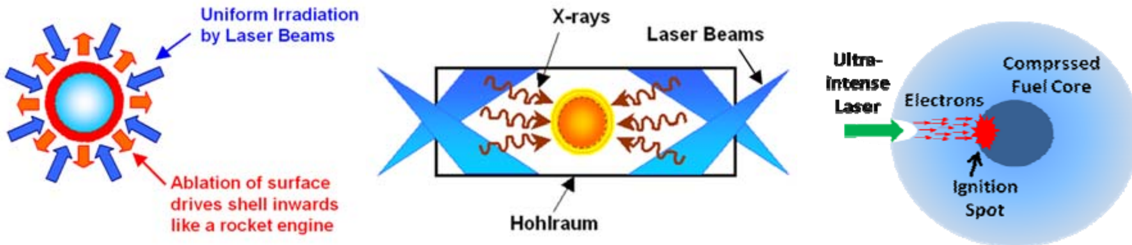
For the past 60 years, researchers have been pursuing the goal of controlled nuclear fusion as an ideal source of energy for mankind. Fusion of light elements, for the most part, results in stable elements with no production of radioactive waste directly from the reactions. At the same time, the reactions require high temperatures and high pressures to initiate and, thus, in systems with limited fuel mass no run-away reactions are possible. The basic fuel source for fusion reactors eventually could be pure deuterium or deuterium and Helium-3 in future advanced concept high temperature reactors. However, initially reactors would rely on mixtures of deuterium (D) and tritium (T) as the fuel combination with the highest fusion reaction cross-section at low ion temperatures (~5-10 keV). The tritium which has a 12-year half life can be produced using the neutrons from the fusion reactions themselves interacting with lithium in a breeder blanket ($n + {}^{6}Li \rightarrow T + {}^{4}He + 4.8$ MeV). Overall a 1 GW-electrical reactor built on this concept would emit no greenhouse gases and would rely on less than 130 kg of deuterium derived from heavy water and 200 kg of tritium bred from lithium per year as a fuel supply. Both the deuterium and lithium are in abundance on earth in all geographical regions. This would provide an abundant, safe and clean power supply for all humanity.

However, creating and controlling the extreme conditions which are required in order to obtain net energy output has proven to be a major scientific and technological challenge for fusion researchers over the past six decades. The approach using lasers to inertially confine the fuel was first publicly proposed in 1972 [1] and has advanced rapidly over the intervening four decades [2-4]. This is due to the rapid advancement of laser technology, improving theoretical understanding of the fundamental processes and continually advancing computer modeling capabilities over this period.

The technologies required for Laser Fusion Energy (LFE) are continuing to advance rapidly at present and it is expected that net energy gain from laser ignited fusion will be demonstrated within in the next two years. This demonstration is expected at the Lawrence Livermore National Laboratory (LLNL) in U.S.A. and will employ the approach to laser fusion energy called central hot spot ignition using indirect drive [2-5]. As shown in Fig. 1(a), in this process a spherical pusher shell (typically plastic or low Z material) containing DT fuel, either frozen as an inner surface layer or as a gas, is imploded by irradiation of laser beams on its outer surface to compress the DT contained within to very high densities above 500 g cm^{-3} and to heat it to temperatures of the order of 5 to 10 keV when the imploding fuel stagnates at the center point of the shell. These conditions allow the fusion reactions to commence and then further heating from the alpha particles depositing their energy in the core causes a burn wave to propagate through the complete fuel mass. This process is referred to as central hot spot ignition [2-4]**.** Indirect drive refers to the fact that the laser light does not directly drive the implosion of the fuel capsule but instead is converted to X-rays within a small high-Z container (gold or uranium), called a hohlraum. The X-ray radiation is absorbed in outer pusher layer surface of the fuel capsule causing the implosion and compression as shown in Fig. 1(b). This approach has been chosen for an initial demonstration of net fusion gain because it is relatively robust against hydrodynamic instabilities, such as the Rayleigh Taylor instability [2-4], which can spoil the compression and heating of the hot spot and quench the ignition process.

A second general approach to laser fusion energy is the direct drive approach. In this case a large array of laser beams is used to uniformly irradiate the fuel capsule directly, heating and ablating the surface as shown in Fig. 1(a). While, in principle, the direct use of laser radiation is more efficient than the indirect drive approach, because the losses due to conversion to X-ray radiation are avoided, the hydrodynamic efficiency of coupling of laser energy to the implosion of the fuel shell is less because the density where the laser light is absorbed is much lower than for X-rays and is thus the absorption occurs further out in the ablation corona of the heated capsule. At the same time the interaction of the laser radiation with the expanding low density plasma can excite a number of plasma-wave-based instabilities such as Brillouin scattering, Raman scattering and two plasmon decay instability together with filamentation and cross beam energy transfer, all of which can reduce absorption and degrade the uniformity of energy absorption. Non-uniformities in the energy absorption and in the shell thickness itself can seed the growth of hydrodynamic instabilities during the compression phase, such as the Rayleigh Taylor instability, degrading the degree of fuel compression and heating and thus making the ignition harder to obtain. Thus, the direct drive approach has very stringent conditions in terms of irradiation uniformity on the order of a percent over the complete capsule surface in order to achieve threshold ignition conditions with total laser energies of the order of a Megajoule [4].

In 1995 a modified approach to LFE was proposed by Tabak at LLNL [6,7] to separate the compression and ignition of the fuel pellet. This approach was called Fast Ignition (FI) since it required a second very short but very intense laser pulse to heat the ignition spot. In this case much

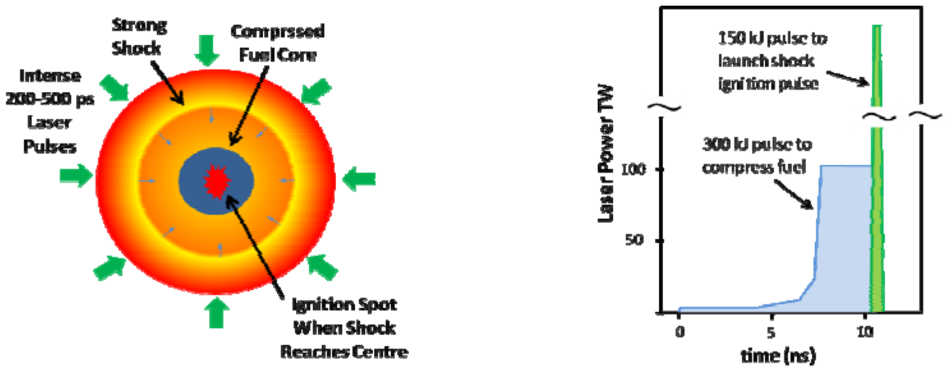


(a) (b) (c)

Figure 1 Laser fusion concepts: (a) direct drive, (b) indirect drive and (c) Fast Ignition.

less energy, on the order of 500 kJ, would be required to compress the fuel mass without self ignition. While the basic concept of rapidly heating (on the time scale of 20 ps) a small (40 micron diameter) spot on the side of the compressed fuel core to a temperature exceeding 5 keV is widely accepted as a potential technique to reach ignition threshold and subsequent burn of the fuel core [7,8], the difficulty is the coupling of the laser energy from the laser to the very high density fuel core region where the electron density is of the order of 10^{26} cm^{-3}. There a few proposals for coupling the energy from the laser to the high density core including the use of relativistic electrons with energy of the order of 2 MeV, as shown in Fig. 1(c), protons with energies of the order of 15 MeV or carbon ions with energies of around 400 MeV [6-9]. Each technique would require the conversion of laser light into a directed beam of particles. The physics basis of these techniques have been investigated in a number of theoretical and experimental investigations over the intervening period and the estimated efficiencies of transport of energy from the laser to the core range from 1 to 20%. Since on the order of 20 kJ deposited energy is required for the heating of the ignition hot spot, clearly a minimum coupling efficiency of the order of 5-10% would be required, necessitating lasers with 200 kJ to 400 kJ of energy, in order to make the technique attractive as an alternative to direct or indirect drive implosion. The study and optimization of these coupling processes is an ongoing area of research today and it will take a few more years before the final answers will be known in terms of the best coupling efficiencies which can be achieved. The University of Alberta research group has been involved in collaborative investigations of the physics of such a Fast Ignition approach at the Titan Laser facility at LLNL [9]. The expected total laser drive energy for a high gain reactor system would be of the order of or less than 1 MJ for the Fast Ignition approach versus the estimated 2 to 3 MJ requirements for direct or indirect drive approaches for high gain.

In the past half decade yet another proposal has been put forward to improve the gain and reduce the laser drive energy requirements for high gain LFE systems. This approach is to use an additional very powerful shock at the end of the fuel implosion process to heat and ignite the compressed fuel [11-15] and is called Shock Ignition (SI). This approach is similar to the direct drive approach, requiring spherical implosion and compression of a fuel core but again, as in Fast Ignition, does not require as much laser energy for the compression, on the order of 300-500 kJ laser drive energy, since the goal is only to assemble a dense fuel core without self ignition. The heating spike to ignite the fusion reactions comes from an intense shock wave launched late in the implosion process which rapidly propagates and converges through the compressed fuel mass causing the heating and ignition of the central hot spot as shown in Fig. 2 (a). It is initially estimated that a laser pulse with energy of the order of 100-200 kJ in a pulse duration of the order of 200-500 ps would be required to drive this strong shock. This pulse can be generated in the same laser system as used to generate the main drive pulse thus simplifying the laser requirements from that of Fast Ignition which requires a separate, much shorter, laser ignition pulse.



(a) (b)

Figure 2 Shock Ignition approach to LFE showing (a) the converging strong shock and (b) the laser profile used to drive the implosion and strong shock

Such an approach has a number of potential advantages including, reduced overall laser drive energies by a factor of two to three times, the use of the same laser beam lines as for compression, and a potential reduction of the growth of Rayleigh Taylor instabilities. However, other issues of potentially high levels of plasma instabilities driven by this higher irradiation intensities employed, non-local energy transport by multi-keV energy electrons produced at these intensities and fuel preheat from hundreds of keV electrons must be clarified. Many of these issues are currently under investigation to give a more accurate prediction of how viable this approach might be. In the following sections the status of shock ignition will be briefly reviewed in terms of laser absorption and the expected plasma instability levels, hydrodynamic coupling and launching of the shock wave, reduction of hydrodynamical instabilities from the interaction of the fast shock with the precompressed target regions, electron transport and preheat effects of the fuel and the predicted scaling of the required ignition conditions.

2. Absorption, Plasma Instabilities and Fuel Preheat

The first question concerns the intensities required to launch a suitable shock for the ignition spike. It has been estimated that total energies of 100-200 kJ would be required in a pulse of the order 200 to 500 ps in duration for this purpose. Given fuel pellets on the order of 1 mm diameter the surface fluence at the 500 micron radius surface would be of the order of 0.6 – 3.0 x 10^{16} W cm^{-2}. The main collisional absorption mechanism at these relatively high intensities would be through inverse Bremsstrahlung. However, these intensities are well above the thresholds for excitation of various plasma instabilities including stimulated Brillouin scattering (SBS) from ion plasma waves, stimulated Raman scattering (SRS) from electron plasma waves and the two plasmon decay (TPD) instability where the incoming photons are absorbed and create two plasma waves. These will lead to additional absorption and backscatter of the incident radiation. Each process has its own signature in terms of scattered light and all have been extensively studied over the past 35 years as part of the ongoing physics studies related to laser fusion.

Traditional Laser direct drive fusion has taken the intensity of 10^{15} W cm^{-2} as an upper limit for the main compression laser pulse explicitly to avoid these instabilities and the very deleterious high energy electrons generated by the SRS and TPD processes. These electrons penetrate to the centre of the fuel before it is compressed to high density, preheating the fuel, and thus requiring much higher energy to compress the fuel to the high densities required. This process is called fuel preheat and must be avoided for efficient LFE schemes. However, since the shock ignition irradiation pulse arrives when the fuel is already compressed to a high density, the preheating of the fuel core from hot electrons is not as great a concern particularly since fuel density is so high that the electrons cannot penetrate into the core. In fact, as will be discussed in more detail later, the electrons generated deposit their energy in the high density region between the coronal plasma and the high density core and can enhance the shock pressure developed by the laser pulse directly. Thus instead of being a negative factor the fast electrons may be a positive factor in the creation of a strong ignition shock pulse.

The scattering processes from laser plasmas have been extensively studied since the early 1970's [16] and specifically for the intensity range of shock ignition in a few recent publications [17-21]. The simple scaling laws for the Brillouin scattering threshold and growth rate, γ, are given by the following expressions [16]:

$$\left(\frac{v_{osc}}{v_e}\right)^2 \geq \frac{8}{k_0\, L_n} \quad \Rightarrow \quad I_{16}\,\lambda_{um} \geq \frac{0.34}{L_{n\mu m}}\, T_{keV} \tag{1}$$

$$\gamma = \frac{1}{2\sqrt{2}}\sqrt{\frac{k_0}{\omega_0\, c_s}}\,(v_{osc}\,\omega_{pi}) \quad \cong \quad 1.4\cdot 10^{14}\,\frac{I_{16}^{1/2}\,\lambda_{um}}{T_{keV}^{1/4}}\left(\frac{n_e}{n_c}\right)^{1/2} \ s^{-1} \tag{2}$$

Where $v_{osc}=(e\ E\ /\ m_e\ \omega_0)$ and $v_e = (k_B T_e\ /\ m_e)^{1/2}$ are the oscillatory and thermal velocity of the electrons in the incident electric field, E, at a frequency of ω_0 with incident k-vector, k_0, with electron mass, m_e, L_n is the electron density scale length, $c_s = (Z\ k_B T_e\ /\ m_i)^{1/2}$ is the ion acoustic velocity, m_i is the mass of the ions, $\omega_{pi} = (Z\ 4\pi\ e^2\ n_e\ /\ m_i)^{1/2}$ is the ion plasma frequency, Z is the average charge state, n_e is the electron density, m_i is the average ion mass, $n_c = (m_e\ \omega_0^2/4\pi\ e^2)^{1/2}$ is the critical electron density (the maximum penetration density for light), I_{16} is the incident laser intensity in units of 10^{16} W cm^{-2}, T_{keV} is the electron temperature in keV, $L_{n\mu m}$ is the electron scale length in μm

For the expected plasma conditions of 5 keV plasma temperature and 200 μm scale length, a laser wavelength of 0.5 μm and for a density of $n_c/4$ these lead to a threshold intensity of 1.5 x10^{14} Wcm^{-2} and an e-folding growth times of less than a picosecond and thus would lead to saturated levels of SBS backscatter for these SI conditions. It is known from detailed simulations that the instantaneous SBS reflectivity can reach the order of unity (also verified by early experiments at the University of Alberta

[22]). However, detailed numerical modeling to date has shown that at these high intensities the density modulation becomes somewhat chaotic on the time scale of 10's of picoseconds destroying the coherence conditions for very strong SBS backscatter and thus leading to an average reflectivity of the order of 20% as observed in a few studies to date [16,17,21] (see e.g. see Fig. 11.1 from ref [16]). Brillouin scattering leads to loss of backscattered light and ion and electron heating but does not in itself lead the generation of any high energy electrons. Transverse Brillouin leads to filamentation and cross-coupling of the laser beams modifying the irradiation uniformity. However, in a multi-beam irradiation system this in itself leads to some randomization of the beam energy and thus can homogenize beam asymmetries.

Raman scattering occurs both as a convective instability in the underdense region below quarter critical density ($n_c/4$) and as an absolute instability at the quarter critical density region. The simple scaling laws for the Raman scattering threshold and growth rate, γ, are given for convective growth by [16]:

$$\left(\frac{v_{osc}}{c_0}\right)^2 \geq \frac{2}{k_0 L_n} \quad \Rightarrow \quad I_{16}\lambda_{um}^2 \geq \frac{44}{\lambda_{um}\ L_{n\mu m}} \tag{3}$$

$$\gamma \cong \frac{\omega_0 v_{osc}}{2 c_0}\left(\frac{n_e}{n_c}\right)^{1/4} \quad \cong \quad 5 \cdot 10^{14} I_{16}^{1/2}\left(\frac{n_e}{n_c}\right)^{1/4} \ s^{-1} \tag{4}$$

Where c_0 is the speed of light in vacuum. One of the earliest measurements of Raman scattering from laser plasmas at the percent level was performed at the University of Alberta [22]. For the expected plasma conditions of a 200 μm scale and a laser wavelength of 0.5 μm this leads to a threshold intensity approximately $4\text{x}10^{15}$ Wcm^{-2} and an e-folding growth times of much less than a picosecond. Thus the convective Raman starts to become important for SI at intensities above ~$4\text{x}10^{15}$ Wcm^{-2}. However, the threshold for an absolute Raman instability localized at quarter critical density is much lower by about an order of magnitude. From numerical simulations it is observed that such an instability quickly heats the electrons and leads to density modification around the quarter critical density region leading to reflectivity levels of the order of 10-20% [16-18, 21]. For example, a simulation at $I\ \lambda^2 = 2.5 \times 10^{15}$ W cm^{-2} μm^2 leads to a saturated reflectivity of 15% [16].

In addition, SRS generates a hot electron population which can penetrate into the target in advance of the shock. The scaling laws for the hot electron temperature predict electron energies of 20-100 keV for the Raman process. The penetration range of a 100 keV electron is on the order of 17 mg cm^{-2} and the integrated areal density to the fuel core for the compressed target is of the order of 50-80 mg cm^{-2} and thus little penetration of the electrons to the fuel core should occur for these electron energies [25].

The two plasmon decay instability occurs in the quarter critical region density region leading to the growth of strong coupled plasma waves usually at some angle of the order of 45 degrees to the density gradient. The threshold is between that of SBS and SRS and the growth rates for this instability are similar to SRS and as given by [16]

$$(\frac{v_{osc}}{v_e})^2 \geq \frac{12}{k_0 L_n} \quad \Rightarrow \quad I_{16}\lambda_{um} \geq \frac{0.516}{L_{n\mu m}} T_{keV} \tag{5}$$

$$\gamma \cong \frac{\omega_0 v_{osc}}{4 c_0} \quad \cong \quad 2.5 \cdot 10^{14} I_{16}^{1/2} (\frac{n_e}{n_c})^{1/4} \quad s^{-1} \tag{6}$$

In this case the threshold for a 5 keV plasma with a scale length of 200 μm would be 2.6 x 10^{14} W cm^{-2} at 0.5 μm wavelength. Growth times are still well below a picosecond. Again from numerical simulation studies it is found that this instability saturates at a modest level of a few percent due to density perturbations at quarter critical density and nonlinear damping including wave breaking [20]. At the same time the electrons are heated by wave breaking of the plasma waves to an energy given by the local phase velocity of the waves which leads to the order of 50 -100 keV heated electron distributions. These again will not lead to significant target preheat.

While it appears that the hot electrons generated by the above processes may not pose a threat in terms of target preheat, it is important to realize that the transport of energy by these electrons and even by the high energy tail of the thermally heated electrons is not well modeled in hydrodynamic simulations at present. This is the problem of nonlocal transport of energy which arises because the collision cross section of the electrons diminishes with the 3/2 power of electron energy and thus the most energetic electrons are only weakly collisional and can escape the local region where they are generated and deposit their energy at a far point in the plasma. In fact these electrons can help to homogenize the energy deposition due to their scattering in the intermediate density plasma profile leading to a reduction in of any non-uniformities in the initial energy deposition. In addition, it is expected that they can help deposit a fraction of the absorbed energy in density regions well above the critical density region which is the limit of the laser penetration. Coupling of absorbed energy to higher density can lead to higher hydrodynamic efficiency and thus a stronger shock wave for a given laser intensity [11-13, 25]. Little work has been done to date on this non local transport and heating from electrons since it requires the modification of present simulation codes. However, the issues are known and work is beginning on the development of enhanced modeling codes to account for these effects.

3. Hydrodynamic Coupling

The main requirement of the intense shock is to cause a spike in temperature at the centre of the compressed fuel assembly sufficient to ignite the fusion reactions. In the standard case of central hot spot ignition for direct or indirect drive fusion the central ignition spot is a low density (~50 g cm^{-3}) , high temperature (~8 keV) hot spot where the fusion reactions produce enough energy to ignite the surrounding high density fuel region which is much more dense (~500 g cm^{-3}) and much colder (~100eV) [4]. The fuel at the time of ignition is almost uniform in pressure between the two regions, referred to as an isobaric ignition condition. In the shock ignition case the fuel is compressed first to a uniform high density and then the hot spot is generated within this volume. Thus the process is more isochoric in nature. However, both cases are not stationary and thus the kinetic motion plays an important role in the overall dynamics of the fuel ignition and burn. In addition the interaction of the rebounding initial compression shock and the fast shock is very important in the process.

An approximate scaling for the required shock drive can be obtained from the additional energy required to heat a critical fraction of the fuel mass to the ignition temperature. If one considers an ignition volume of 40 microns in diameter at a density of 300 g cm^{-3} of DT fuel it must be heated up to the order of 5 keV to ignite. Thus the energy invested in this heating is of the order of 5 kJ. Considering the hydrodynamic efficiency of coupling to the shock which is of the order of 10% this means a minimum of 50 kJ of absorbed energy is required. If one allows for reflection of up to 50% of the incident laser energy and thus an absorption fraction of only 50%, then a minimum laser energy of 100 kJ would be required for the fast shock ignition pulse. Detailed analytical modeling [13,14] 1D and 2D hydrodynamic simulations [10-14] indicate that ignition can occur with the order of 40 kJ of absorbed laser energy or an incident laser energy of around 80 kJ in agreement with these estimates.

4. Irradiation Uniformity and Reduction in Hydrodynamic Instabilities

One of the unexpected positive results which appears in the simulations is the reduction in growth of hydrodynamic instabilities such as the Rayleigh Taylor and Richtmyer Meshkov instabilities. These grow exponentially during the acceleration and deceleration phases of the fuel capsule implosion and cause mixing of higher Z (mainly carbon) species into the outer regions of the fuel leading to excess radiation cooling and reduce the symmetry of the implosion making the heating of the ignition hot spot less effective. The growth of these instabilities has been extensively studied over the past three decades and good computer modeling capabilities exist in the various 2D and 3D hydro simulation codes used to date. The current symmetry requirements of the order of 1% uniformity for laser irradiation and symmetry of the target shell thickness arises from the fact that this level of seeding of the instability is the maximum that can be tolerated. These same codes have been used to study the case of shock ignition.

Detailed 2D hydro simulations of full scale shock ignition fusion targets has shown that there is an interaction between the converging high intensity shock and the pusher-fuel interface. Normally the peak to peak level of the modulation of this surface continues to grow as the fuel and pusher decelerate into the compressed core region center. However, the interaction of the intense shock causes a reduction in the growth of the modulation. This interaction is quite complex but a number of independent groups have now observed this behavior in different simulation codes [12-14, 26]. Thus its believed that indeed the strong shock will help stabilize instability growth at an intermediate level and thus make the targets more robust to non-uniformities in irradiation and target fabrication.

In fact, a large degree of asymmetry can be incorporated into the shock ignition pulse and still obtain ignition. This has been investigated for the case of incorporating shock ignition into the polar direct drive approach to fusion energy using beam cones from two poles [13]. In this case, illumination is adjusted to give a fairly broad driven region at each pole with decreasing absorbed intensity towards the equator of the target. It is found that the shock itself tends to wrap around the target increasing its symmetry somewhat, like a wave breaking on an island. At the same time, the collision of the two converging shocks from each pole still gives enough extra heating to cause ignition of the target. Simulations of such two sided shock ignition have been carried out [13] and have found that an absorbed laser energy of approximately 100 kJ is required in a 500 ps pulse in order to achieve ignition in this case.

5. Experimental Studies to Date

Thus far, experimental studies of the shock ignition proposal have followed three major thrusts: 1) the study of the plasma instabilities and hot electron generation, 2) the study of the shock creation and strength and 3) the study of integrated target implosions at 1/10 of final required drive energies. All such studies are very recent.

For the study of plasma instabilities the French group at Laboratoire pour L'Utilization des Lasers Intenses (LULI) at École Polytechique, Paris, has carried out studies at various harmonic wavelengths of the glass laser from 1057 nm to 264 nm. Only preliminary results are available [26] and indicate that instability levels are limited to the tens of percent range. Recently, we have also carried out experiments at the Titan Laser facility in the intensity range of 10^{15} W cm^{-2} to 10^{17} W cm^{-2} observing the Brillouin, Raman and 3/2 harmonic (from the TPD instability) backscatter levels. These results are currently being analysed but a preliminary assessment indicates that the Brillouin scattering levels are on the order of 20% and the Raman scattering levels of the order of 10% or less. Thus preliminary results of the backscattering levels tend to support the computer simulation predictions of SBS limited to the tens of percent level and SRS to the 10% level [16,20,21]. Our experiments also measured the generation of hot electrons through observation of hard X-ray emission and electron spectrometer measurements. However, these diagnostics suffered from large background signal levels from the main, several nanosecond long, laser pulse used to create the hot interaction plasma. It appears that the additional hot electron contribution is not large but careful analysis will be required to quantitatively assess the levels.

The most encouraging experiments are the integrated compression experiments carried out at the Laboratory for Laser Energetics (LLE) at the University of Rochester [27-29]. These have involved shaping a number of their implosion beams as a short shock driver pulse at the end of the initial compression pulse. In this case an energy of 40 kJ was used in a 3ns long compression pulse and 10 kJ of energy was used in a 500 ps shock ignition pulse. Both beams used the third harmonic of their laser system at 353 nm. Simple plastic shell imploding pusher targets were used and it was found that the neutron yield increased by a factor of 3 times with the addition of the shock ignition pulse within a timing window of 100 ps relative to the implosion pulse. At the same time the backscattered levels were monitored showing that indeed absorption was on the order of 70% and that Brillouin scatter was observed at around the 20 percent level. X-ray measurements have indicated that the hot electron temperature remained below 100 keV as required for shock ignition. In these experiments the irradiance intensity was on the order of 4×10^{15} W cm^{-2}. In addition, shell targets of different thickness were imploded and normally thin shell target with large aspect ratios show much poorer neutron yield than thicker shell targets due to the premature shell breakup from the growth of hydrodynamic instabilities. In the case of the shock ignition driven targets it was found that even such thin shelled targets performed well compared to 1D modeling in terms of neutron yield. This marked improvement in performance for such thin shelled targets may be an indication stabilization of the hydro instabilities due to SI. Model calculations of these results have recently been carried out and show qualitative agreement with the results [29].

6. Conclusions

Ignition of fusion reactions and net energy generation by LFE is expected within the next year or two at the LLNL NIF facility [5] opening the door for the design of first generation engineering design reactors [31]. One of the newest proposals to give higher efficiency is that of Shock Ignition, using an intense laser pulse of ~100kJ energy and several hundred picosecond duration to cause the final heating of the fuel at the centre of the compressed core. This technique has the advantage that a separate laser driver system is not required. The required peak power is still within the operating range of typical proposed laser systems. The main compression laser pulse would be of the order of 200 kJ for a total laser system drive energy of the order of 300 kJ under ideal conditions. Allowing for a factor of two extra energy for additional inherent inefficiencies this would require of the order of 600 kJ in total laser energy which is much below the multi-Megajoules required for indirect and direct drive approaches to LFE.

Extensive 1D and 2D simulations of this technique have been carried out highlighting important advantages for this technique including increased robustness against the growth of plasma instabilities and the potentially positive effect of hot electron deposition. Potential problems of electron preheat modeled by detailed kinetic and particle in cell simulations appear to be controlled by the nonlinear saturation of these strongly driven instabilities at 10% to 20% backscatter levels which appears to be acceptable.

Because of the optimistic scaling of this new approach it has now been adopted as the mainline approach for the European HiPER LFE project [13, 32], which has been proposed as a facility to demonstrate an advanced high gain and low energy approach to fusion energy. The smaller total energy released per laser shot also allows for the fabrication of reactor vessels with lower wall loading conditions than those required for multi-Megajoule laser driver systems which can significantly accelerate the development time for suitable reactor vessel technology.

These new techniques such as shock ignition also give an entry point for new players in the field to investigate improved approaches to LFE, complementing activities in laser fusion research around the world. In particular, it would allow Canada to initiate a fusion energy R&D program focussed on the development of one or more of these advanced techniques. The research group at the University of Alberta have been involved in several collaborative experiments recently related to both the Fast Ignition and the Shock Ignition approaches to laser fusion energy. Thus, there is an initial core of expertise being built up in these areas in Canada and this can be used to help initiate a new laser fusion energy program in Canada in the future.

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