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Ignition studies in support of the European High Power Laser Energy Research Facility project

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Abstract. The European High Power Laser Energy Research Facility (HiPER) project is one of a number of large-scale scientific infrastructure projects supported by the European Commission's Seventh Framework Programme (FP7). Part of this project involves the development of a target area for the exploration of inertial fusion energy. This paper describes some of the research that is being carried out by the author in support of this aspect of the program. The effects of different regions of the fusion target mixing prior to thermonuclear ignition have been investigated using the 1D Lagrangian radiation hydrodynamics simulation code HYADES. Results suggest that even low (few parts per million) levels of contamination of fuel by high-Z ion species may inhibit ignition due to radiative cooling of the ignition spot.

Keywords. Fast ignition; inertial fusion energy; thermonuclear ignition; radiation hydrodynamics simulation.

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1. Introduction

Inertial confinement fusion (ICF) [1] is one of the two mainline approaches for releasing nuclear binding energy by fusing two low atomic number nuclei together for the purpose of generating electrical power here on Earth. The reaction chosen for all terrestrial fusion experiments is the deuterium–tritium (DT) fusion reaction, which results in the production of an α-particle and a neutron. The Q value of the reaction is +17.6 MeV, and this is shared between the α-particle and the neutron in such a way that their momenta balance (14.1 MeV to the neutron, 3.5 MeV to the α-particle). This fuel is chosen because it has a Maxwellian averaged cross-section, which is one hundred times greater than any other fusion reaction cross-section at fuel temperatures of around 10 keV. At temperatures more than an order of magnitude higher, the cross-sections for other fusion reactions become comparable to those for DT. Fuel at significantly lower temperatures, however, has an insufficient Maxwellian averaged cross-section for there to be hope of releasing useful energy. As 10 keV is already an extremely high temperature ($\sim$100 Million Kelvin) the use of the deuterium–tritium reaction is therefore mandatory in terrestrial experiments. The deuterium–tritium reaction is also beneficial because it has a relatively high Q value for a fusion reaction. The energy released per gram, for complete burning, is around 330 GJ. The high Q value is a consequence of the reaction producing He-4 as a daughter nuclide. He-4 is a doubly magic nuclide and sits well above the typical curve of the binding energy. One difficulty with the deuterium–tritium reaction as a choice for terrestrial fusion experiments is the requirement for tritium as one of the raw materials. Tritium decays by β emission with a half-life of only 4500 days. It is therefore found in only trace quantities here on Earth. The tritium that is employed in industry is manufactured in nuclear fission reactors by neutron irradiation of Li-6. Even a single fusion power station would consume tritium at a rate greater than it is currently manufactured here on Earth. Therefore, any realistic nuclear fusion reactor must also breed tritium to sustain the reaction. It is intended that this breeding should take place in the reactor blanket of the reactor. Tritium can be bred, as in fission reactors, by a neutron reaction with Li-6, however, the more energetic neutrons available in fusion systems also enable the use of Li-7 which undergoes an endothermic reaction to form an α-particle and tritium with a Q value of -2.466 MeV. A neutron multiplier is also necessary in order that more than one tritium is on average bred for every neutron that enters the blanket assembly; essential since the consumption of one tritium ion only produces one neutron in the process of thermonuclear burning. Typically, either beryllium or lead is suggested for this purpose.

ICF involves no active confinement of the fuel during its ignition and burn. The fuel is assembled to extremely high densities (typically between about one and five thousand times solid density, which is equivalent to $\sim 10^{32}$ ions per cubic metre). At such high densities, once burn is established, it proceeds rapidly and a satisfactory yield will result provided that the density–radius product (ρr) of the compressed fuel is sufficient that the uninhibited rarefaction wave which propagates inward from the fuel's outer surface does not stifle the burn prior to an acceptable portion of the fuel mass having been consumed. Typically the burn time in laser-driven ICF capsules is expected to be about a few tens of picoseconds at most. Assembled fuel needs to have a ρr of at least 3 g/cm^2 to permit a reasonable fraction of the fuel (greater than about one third) to burn. The alternative approach, magnetic confinement fusion, employs large magnetic fields to confine low density ($\sim 10^{20}$ ions per cubic metre) deuterium–tritium plasma for an extended period of time (minutes or more). Both of these approaches can be seen to approximately satisfy Lawson's criteria [2] for energy release from deuterium–tritium plasma at a temperature of 10 keV, which is that the product of ion number density (m^{-3}) and confinement time (seconds) should exceed 10^{20} s/m^3.

Inertial confinement fusion relies upon the use of an intense radiation flux to ablate the outermost surface of a spherical capsule containing fusion fuel. In the conventional approach, this capsule typically consists of three principle regions (see figure 1). The innermost region comprises DT gas of radius ~ 1 mm, which is bounded by a layer of DT ice of ~ 100 μm thickness. This DT ice layer is itself surrounded by a layer of low atomic number material (e.g. beryllium or CH plastic) known as an ablator. It is this ablator region that is heated by the external radiation flux (also called the 'drive'). The drive can take the form of laser photons, soft

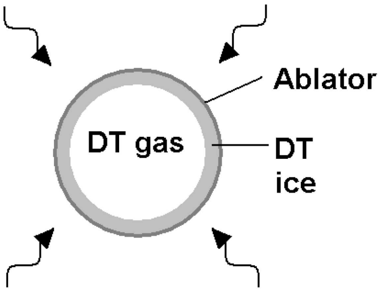

Figure 1. Conventional ICF employs an intense radiation drive to implode a spherical fuel capsule to extreme densities and temperatures.

X-rays, or even focussed ion beams. As the surface of the capsule is heated, and expands outwards, shock waves are driven inwards. These shock waves accelerate, compress and heat the material that they pass through. The result is that the DT regions of the capsule are imploded inwards. Peak illumination intensities on the surface of the ablator are typically around 10^{15} W/cm^2.

Laser-driven ICF takes two major forms: direct drive ICF in which the laser is directly incident upon the outer surface of the spherical fuel capsule, and indirect drive ICF in which the laser is incident upon the interior of a high atomic number canister in which the capsule is centrally suspended [3]. The canister, or hohlraum, is heated by the laser to the point where it radiates thermally in the soft X-ray part of the spectrum. The cavity temperature rises to a peak value of around 300 eV over the course of the implosion. It is the soft X-rays emitted from the hohlraum walls that drive the ablative compression in this case.

In the conventional approach to ICF, the fuel collapses down to form a final 'stagnated' fuel configuration in which an extremely dense shell of DT ($\sim$1000 g/cm^3) surrounds a central region that is at lower density ($\sim$100 g/cm^3), but significantly higher temperature (5 to 10 keV as compared with $\sim$100 eV in the surrounding dense fuel). It is in this hot central region or 'hot spot' where the process of thermonuclear ignition takes place. The ignition process requires that the central hotspot should have a ρr greater than about 0.3 g/cm^2 so that α-particles produced by the fusion reaction will tend to be reabsorbed within the central hotspot. This results in self-heating, otherwise known as 'boot-strapping', causing the fuel temperature to climb from around 10 keV to 70–80 keV in $\sim$10 ps. As the alpha range tends to increase along with the burn rate in this hot fuel, this results in intense heating of the surrounding dense fuel, and a propagating burn wave.

ICF capsule designs for power production purposes typically have thermonuclear yields in the range of 100 MJ to a few GJ. As commercial electrical power production stations typically supply $\sim$1 GW of electrical power to the grid, it is necessary to successively implode capsules and capture their thermonuclear output at a rate of $\sim$1–10 Hz. It is expected that the National Ignition Facility (NIF) [4] at the Lawrence Livermore National Laboratory in California will succeed in demonstrating the principle of laser-driven ICF by the indirect drive route within the next two years. The NIF laser amplifiers however, are based upon neodymium-doped glass gain media, and are therefore incapable of firing more than once every few hours. This is because of the deformation of the optical path through the laser amplifiers that is caused by the slight heating of the slabs of laser glass during each laser shot. The amplifiers must be allowed to cool before the next shot, so that the

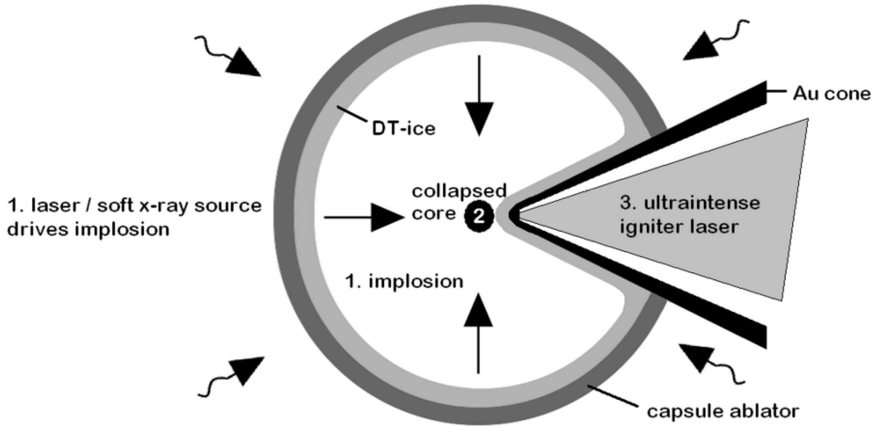

Figure 2. HiPER will use the fast ignition approach to ICF in which an ultra-high intensity igniter laser is employed to heat the fuel separate from the implosion drive laser; this could result in more efficient heating of the fuel.

correct optical path is restored. In addition the efficiency of the Nd-glass amplifiers is rather low; about 1%. This is unsatisfactory given that typical capsule level gains by the ICF approach are usually about 100. The only other laser system of similar scale, Laser MegaJoule (LMJ) [5] in France is based on similar technology and has almost identical limitations.

2. The European High Power Laser Energy Research Facility (HiPER)

To bridge this gap between the current generation of high-energy laser systems, and any prospective ICF-based power station, the European High Power Laser Energy Research Facility (HiPER) [6] has been proposed. One of the goals of this project is to build a high repetition rate, high efficiency laser driver, and employ it to demonstrate the successive ignition of fusion capsules by the ICF approach at a rate of around 1 Hz. This would only be maintained for a short period however (∼seconds), since HiPER is not intended to breed tritium (or produce electrical power).

The HiPER project is currently in the preparatory phase; funded to conduct studies that will support the submission of a more detailed plan to the European Commission. The author is funded to conduct some of the modelling work related to the fuel capsule design for HiPER.

Unlike NIF and LMJ, HiPER intends to utilize a slightly different approach to ICF, known as fast ignition [7] (see figure 2). Fast ignition differs from the conventional approach to ICF in that the ignition process takes places in isochoric rather than isobaric fuel. In conventional ignition, the implosion process is terminated by the stagnation of the relatively cold dense region of fuel against the central hotspot. The fuel stagnates as pressure balance is reached between the imploding shell and the hotspot that is being compressed by its motion. Therefore, the process of ignition takes place in fuel that is isobaric. In fast ignition, on the other hand, the fuel is compressed cold and to a uniform density (at least in the ideal case). Energy is then delivered rapidly to a small portion of an assembled fuel mass, raising it to the ignition temperature, by a separate process. This results in steep pressure gradients at the surface of the hotspot, and rapid expansion of the hotspot. The fact that the hotspot therefore does substantial hydrodynamic work on the surrounding fuel when it is at the point of igniting, means that the hydrodynamic losses of the hotspot are increased relative to the isobaric case. Therefore, a somewhat higher ρr is required for the hotspot (around 0.5 g/cm^2). The point of fast ignition is that the compressive heating of the hotspot in conventional ICF is inefficient ($<1\%$). The use of a separate process to form the hotspot may therefore be advantageous in so far as that it may allow for far more efficient heating. This may therefore result in a smaller laser being required for ignition, and more energy being available for supply to the electrical grid. The appeal of a cheaper, more efficient power plant is obvious.

Four possible approaches to fast ignition have been identified. The first, and most pursued, option involves the use of the ponderomotive force of an ultra-high intensity laser ($\sim 10^{20}$ W/cm^2) being used to accelerate electrons in plasma located near the dense compressed fuel to $\sim$MeV energies. Some fraction of these electrons will then fly into the fuel and cause the formation of a hotspot. In order to couple sufficient energy into the fuel (a few kJ must be deposited in a ρr of around 0.5 g/cm^2), laser pulse durations of about 10–20 ps are required. Given expected coupling inefficiencies, this suggests that an ultra-high power laser of about 100 kJ energy output would need to be constructed. This is well in excess of contemporary facilities whose peak output energies are about 1–2 kJ at most.

The second approach to fast ignition involves the use of laser-generated energetic protons [8]. High-energy protons are generated as a by-product of energetic electron acceleration in thin solid density layers. Energetic electrons emerge from the back of such targets, and the electric field created by the loss of these electrons leads to ion acceleration. Of all the ion species, protons can be accelerated most efficiently, and are therefore considered optimal for fusion applications. In other respects the approach is similar to its energetic electron heated counterpart. The high-energy protons fly into the fuel and raise the temperature of a portion of it to the required temperatures for ignition. A significant advantage of protons is that, unlike electrons, protons tend to stop at a particular depth in the dense fuel, at a location known as the Bragg peak. This results in the formation of a compact hotspot. Electron heating tends to produce a more extended hotspot. Energy spent in heating the fuel outside the optimal ρr for ignition is largely wasted; the bulk of the fuel should be heated by the propagating burn. The proton heated approach to fast ignition relies upon the use of a cone to protect the proton producing foil, and to permit a clear path to this foil for the igniter laser. A similar cone may be employed in electron-heated fast ignition to prevent the propagation of the igniter laser to near the dense fuel mass being impeded by plasma generated during the course of the implosion [9]. Lasers cannot propagate past the critical surface at which the electron plasma frequency equals the laser frequency. This critical surface typically lies at densities around 10^5 lower than the compressed fuel. It is possible that the igniter laser pulse may be able to bore through much of the plasma between the critical surface and the dense fuel mass, and, so the cone is not yet considered an indispensible component of electron fast ignition.

The third approach to fast ignition is known as shock-fast ignition [10]. This involves launching a strong, spherically convergent shockwave into the fuel mass as it approaches stagnation. This shock most strongly heats the central portion of the fuel, due to convergent strengthening, and can result in the formation of a hotspot in the stagnated fuel that is out of pressure equilibrium with the surrounding material. Finally, impact fast ignition [11] involves the acceleration of a dense slug of material to extreme velocities ($\sim 10^8$ cm/s or more, as compared to the typical peak implosion velocity for a capsule of around 3.5×10^7 cm/s). This dense slug, typically accelerated within a coned-off region of the spherical capsule, impacts the dense plasma formed by the lower velocity implosion of the rest of the fuel. This collision forms the hotspot.

Cone-based electron-driven fast ignition is the favoured option for HiPER. The author has been investigating some of the physics associated with the interaction between the material that makes up the cone and the DT fuel, specifically the effect of such mixing on ignition thresholds.

3. Ignition studies

In order to resist the extreme pressures associated with the implosion, a dense, high atomic number (high Z) material is typically selected for the cone. There is substantial concern over the effect that this high-Z material may have, however, if it becomes mixed with the DT fuel. The presence of much higher Z material will tend to greatly increase the radiation losses from the fuel, and can thereby inhibit the ignition process, in which the power deposited by α-particles must exceed the energy loss from the hotspot, which includes radiative cooling.

Ignition calculations have been performed using the 1D radiation hydrodynamics simulation code HYADES [12]. HYADES is a Lagrangian code, which employs a multi-group diffusion model for thermal radiation. Electron conduction is treated with a flux-limited diffusion model. In these calculations a burn model was employed which incorporates thermonuclear fusion, beam-like (secondary) fusion and scattering processes as shown in table 1.

The burn model employs a multi-group treatment of ions. Neutrons are allowed to escape the problem, which is reasonable given their long mean free path in the fuel.

Figure 3 shows some of the results of these studies in which the normalized change in the ignition threshold hotspot ρr is plotted for fuel at 5 and 10 keV with differing levels of uniform Au contamination. A central hotspot configuration is used, for ready comparison to existing ignition calculations such as those of Frolov [13]. The fuel density is 300 g/cm^{-3} and the total fuel radius (hot and cold) is 400 μm. It was found that increasing the total fuel radius beyond this resulted in no significant change in the ignition threshold.

As can be seen from figure 3, the ignition process is highly sensitive to the presence of Au ion contamination. Uniform contamination levels in excess of 10 parts per million (ppm) result in more than a 10% increase in the required hotspot

Table 1. Ion interactions included in the HYADES burn model.

Thermonuclear (Maxwell-averaged) reactions	Elastic scattering reactions
$d(d,n)$He-3	p,p
$d(d,p)t$	d,p
$t(d,n)$He-4	t,p
$t(t,2n)$He-4	He-3,p
He-3$(n,p)t$	He-4,p
He-3(d,p)He-4	d,d
He-3(t,d)He-4	t,d
He-3(t,np)He-4	He-3,d
He-3(He-3,2p)He-4	He-4,d
	t,t
	He-3,t
In-flight reactions	He-4,t
	He-3,He-3
$d(d,n)$He-3	He-4,He-3
$d(d,p)t$	He-4,He-4
$t(d,n)$He-4	
He-3(d,p)He-4	
$d(t,n)$He-4	
d(He-3,p)He-4	

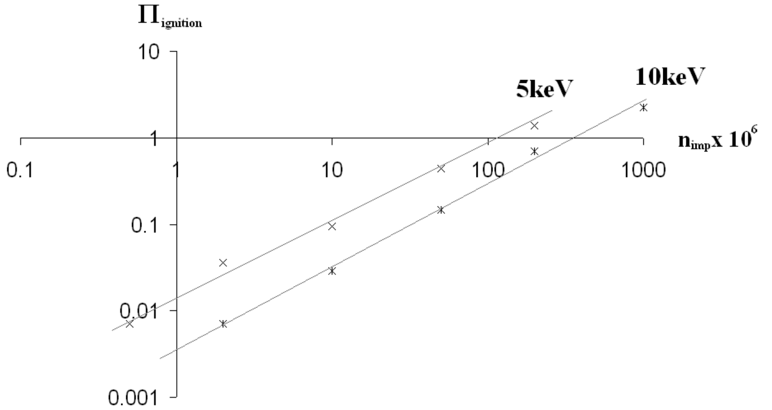

Figure 3. Normalized change in the ignition threshold hotspot ρr, Π_{ignition}, for Au contamination at hotspot temperatures of 5 and 10 keV. Contamination was uniform and is expressed in terms of n_{imp}, the ion number density fraction of Au.

ρr for ignition at 5 keV. At 10 keV the ignition process is slightly more robust (as would be expected given the strong scaling of fusion reaction cross-section with temperature). Uniform ion number density concentrations of around 50 ppm still result in more than a 10% increase in the required hotspot ρr for ignition.

Table 2. The multigroup structure for ions employed in HYADES. $n1$ is the number of cold groups and $n2$ the number of hot groups for each species. The cold ions are grouped up to $e1$ and the hot to $e2$ (log arrangement).

Sym	Particle	$n1$	$n2$	$e1$	$e2$
n	Neutron	5	8	2449	14060
p	Proton	5	8	3023	14670
d	Deuteron	5	8	2180	13050
t	Triton	5	8	1011	12540
He-3	He-3	5	8	820	12540
He-4	α	5	8	3542	12300

4. Conclusions

The HiPER project seeks to advance further down the road to commercial fusion energy by the ICF approach. The fast ignition variant of ICF that is to be employed in HiPER enables higher efficiency operation and reduced plant cost by increasing the efficiency with which the fuel is heated. The high-Z cone interface which enables the ultra-high intensity laser to heat the fuel without the impediment of ablated plasma formed during the implosion poses a potential hazard to the ignition process. High-Z ion species when mixed with the DT fuel can hamper ignition by significantly increasing radiative cooling of the fuel as ignition is attempted. Here we have described simulations that have sought to determine the acceptable levels of cone-fuel mixing in fast-ignition-relevant fuel conditions. It was found that uniform contamination at the level of 10 s of ppm or greater has a significant effect on ignition in some cases (>10% increase in the required hotspot ρr).

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