3 Background on fusion and the role of IFE

3.1 Introduction

Research into controlled fusion as an energy source has spanned more than five decades and has involved the global scientific community. It represents one of the most important scientific challenges of the 21st century.

Fusion is the combination of two atomic nuclei to form a single heavier element. When two light elements are combined it turns out that their combined mass is less than that of the products. The "missing mass" is converted into energy following Einstein's famous equation, $E=mc^2$. The amount of energy released can be very large, so that only tiny amounts of matter are needed to fuel a power station.

This is the opposite process to fission, where heavy elements (such as Uranium) are split apart to yield daughter nuclei (again with less mass than their parent nucleus). The difference between fusion and fission is essentially two-fold:

- Fission is relatively simple to harness, whereas fusion has proven very difficult
- Fission requires large assemblies of highly radioactive material, creating by-products with very long half-lives, whereas fusion uses only small amounts of fuel with by-products that can be simply managed.

Controlled fusion schemes typically involve two light nuclei, deuterium and tritium, which are isotopes of hydrogen. If the nuclei obtain enough energy to overcome their mutual ("Coulombic") repulsion, they can undergo the fusion reaction shown in figure 3.1:

Deuterim (D) + Tritium (T) → Helium (He) + Neutron (n)

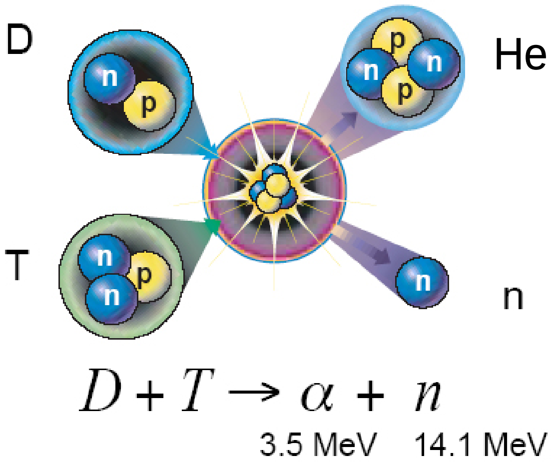

Fig 3.1 The principal fusion reaction

The by-products are thus Helium (also known as an alpha-particle) and a neutron. The helium is used to deposit energy into the rest of the fusion fuel to create a self-sustaining reaction. This means that only a relatively small amount of energy is needed to start the process, so that the reaction is highly efficient. The neutron escapes from the fuel, carrying a large amount of kinetic energy. If the fuel is surrounded by a blanket of material thick enough to stop the neutron then this kinetic energy will be converted into thermal energy. The blanket heats up, and this heat can be used to drive a conventional steam turbine.

The problem is that the fuel must be heated to temperatures of ~100 Million degrees Kelvin for this fusion reaction to occur. It must simultaneously be held at a sufficient density for a sufficient time to allow the process to run for long enough to produce a net amount of energy out.

At these temperatures matter enters the plasma state. Confining plasmas at 100 million degrees K provides the biggest challenge to controlling fusion. Under such conditions the plasma must be isolated away from vessel walls and prevented from expanding into the surroundings, thus quenching the fusion reactions. Many schemes have been proposed over the decades. They fall into two broad categories: Magnetic Fusion Energy (MFE) and Inertial Fusion Energy (IFE).

The leading approach to MFE utilises a torus shaped reactor called a 'tokomak' to produce and confine plasma using electric and magnetic fields. The torus is filled with gaseous DT fuel and is initially heated using ohmic currents, radio-frequency waves, and/or injected particle beams. The plasma is confined using toroidal and poloidal magnetic fields. The goal is to heat the plasma to the point where self heating due to DT fusion reactions allows the reaction to become self-sustaining. This point is known as "ignition" and represents one of the key goals of the ITER project. The intention is to produce energy from fusion reactions for about 8 minutes at the >100 MW level.

IFE takes the opposite approach. Rather than heating low density gases for relatively long periods, the idea is to produce very high densities for very short periods of time. It is therefore a "pulsed" approach, conceptually similar to the repeated cycles of chemical combustion in the engine of a car. The densities required are high: typically 20 times the density of lead, but the timescales are short: measured in picoseconds (10^{-12} s).

To do this, an energetic beam is used to symmetrically irradiate a small DT fuel capsule. The beam can be either a laser, x-rays, or an ion beam. The outer surface of the capsule heats up and expands outwards. Following Newton's laws, the rest of the capsule undergoes an equal and opposite reaction: it implodes. Very high densities can be achieved by imploding the capsule into very small volumes.

IFE then takes one of two routes. It either uses a 'diesel engine' approach, whereby the capsule is imploded until it attains a sufficiently high density (and temperature) that its centre undergoes fusion. This approach is called "*central ignition*". Or it uses a 'petrol engine' approach, whereby the capsule is partially imploded and then ignited by a spark plug (typically a high power laser). This is called "*fast ignition*".

A key technology down-selection for HiPER will be driven by the repetition rate requirements of the driving laser. Two options currently exist – based on conventional technology or diode-pumped solid state lasers. A detailed cost-benefit analysis will be performed in the preparatory phase project.

Further details of these schemes are presented in section 3.3 and references therein.

3.2 Significance of fusion energy

Fusion energy is a uniquely attractive, environmentally clean power source. Using sea water as its principal source of fuel, there are no greenhouse gas emissions, nor any long-lived radioactive waste products. The benefits of fusion energy cannot be overstated in the current global setting where climate change, pollution, energy security and the ever increasing demand for consumption represent a principal challenge facing mankind [3.1].

Fusion is not a short term fix, nor will it address the immediate requirement to manage carbon emissions. It is a long-term, sustainable solution that will take a concentrated research and development effort across a range of options to realise its potential.

Fusion is an attractive energy source for a number of reasons:

1) **Low environmental impact** - The fusion process does not produce carbon dioxide and will therefore not contribute further to levels of CO_2 in the atmosphere. It does not produce long lived radioactive waste (as in fission power stations) and the associated problems/costs with storage of such material.
2) **Abundant fuel** – Deuterium, one of the isotopes involved in the fusion reaction is found in seawater in large quantities. A single cubic kilometre of seawater contains enough Deuterium to supply an amount of energy equal to the entire world's oil reserves. As such, fusion is able to meet our long-term requirements for power consumption. Tritium can be directly generated at the reactor site by utilising a Lithium blanket around the vessel[†]. This same blanket is used to extract the heat for the power plant.
3) **Energy Security** - fusion is an intrinsically secure source of energy for almost all nations, since the fuel is extracted from seawater and the reaction cycle at the power plant.
4) **Fusion is safe** – There is very little fuel present at any given time, therefore not enough fuel for runaway reactions. Melt-down or catastrophic release following an accident is therefore impossible. In the event of an accident the plasma will simply cool – the reactions cease immediately and so the process is intrinsically self limiting.
5) **Generation of Hydrogen** – In the future hydrogen is expected to play a significant role in energy generation for local or mobile requirements. The heat from a fusion reactor vessel can be used to generate large quantities of hydrogen for commercial and industrial applications.

Inertial fusion offers the further potential for more advanced fuels (with little or no tritium), and can also make use of liquid walls to contain the reactions, greatly easing two key technological problems. It could also allow more efficient burn (hence greater economy) and the extraction of electricity directly from the plasma products.

The technical problems associated with converting the scientific proof of principle of fusion into a commercial power plant should not be underestimated. As such, the approach is in the research and development phase, requiring international cooperation over the next decade to determine the best technical solutions. HiPER is designed to meet this requirement.

[†] Tritium (^3H) is created by capturing the fast neutrons produced in the fusion reaction, for example in the $^6Li(n,^3H)^4He$ reaction. Because the neutron capture process is not 100% efficient there is a need to multiply the neutron population prior to capture. This is done by introducing elements such as lead into the blanket, which can generate additional neutrons via (n,2n) reactions.

3.3 Confinement schemes - detail

3.3.1 Magnetic Fusion Energy (MFE)

MFE so far has been the most widely researched and well funded method of plasma confinement. Much progress has been made, for example using the JET (Joint European Torus) machine [3.2], in the UK. This device is currently the world's largest tokomak fusion research facility. This report will not focus on this confinement scheme but it is briefly discussed for completeness.

Ignition and gain

Ignition for MFE occurs when the energy derived from thermonuclear fusion products is greater than the energy required to heat the fuel to fusion temperatures in one confinement time. If the reactor operates in steady state, then once ignition has been reached the plasma can sustain itself indefinitely. The condition for breakeven (Q=1) is stated by the Lawson criterion [3.3]. For MFE this depends upon the number of particles, n, and the length of time for which they can be confined, τ, and so can be expressed as $n\tau > 1 \times 10^{20}$ $m^{-3}s$. Fusion devices currently operate their fields in a pulsed mode, where one pulse will typically last ~60 seconds. In the future superconducting coils will be used for steady state operation.

Progress

The JET [3.2] facility has operated over the last 20 years and represents a significant step towards demonstrating the feasibility of MFE as a power source. The facility has partners from 22 different countries in Europe and is currently run on behalf of them by the UKAEA [3.4]. JET has achieved three major milestones 1) 22 MJ of fusion in one pulse 2) 16.1 MW of peak fusion power 3) Q=0.65. Recently, JET has been used to investigate parameters for the International Thermonuclear Experimental Reactor (ITER) [3.5] such as plasma shaping and divertors for removing impurities in the system.

The ITER project is a massive global undertaking by Europe, Japan, China, India, Russia, South Korea, and the USA to build a next step reactor to demonstrate the feasibility of MFE as a future energy source. This reactor is designed to produce 500 MW of peak fusion power and this will result in a net gain of Q=10. The project will also develop technology needed make MFE work in a power plant scenario. ITER will be built in Cadarache, France with the first plasma expected by 2016 and ignition by ~2022.

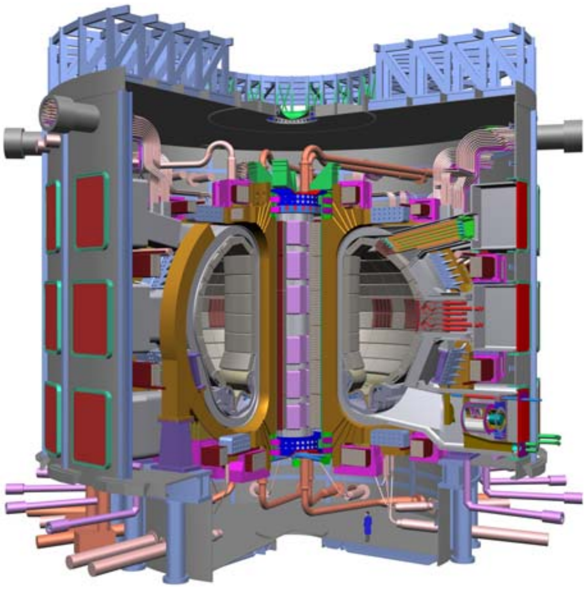

Fig 3.2 – Cutaway diagram of the ITER facility

3.3.2 Inertial Fusion Energy

The concept of Inertial Confinement Fusion (ICF) was developed independently in the USA and Russia. John Nuckolls published a seminal paper in 1972 [3.6].

An energetic beam is used to symmetrically irradiate a small DT fuel capsule. The beam can be either a laser, x-rays, or an ion beam. The outer surface of the capsule heats up and expands outwards. Following Newton's laws, the rest of the capsule undergoes an equal and opposite reaction: it implodes. Very high densities can be achieved by imploding the capsule into very small volumes.

Net energy production from inertial fusion has already been demonstrated on Earth in an offshoot of the US defence mission in the 1980s. Demonstration of net energy production using a laser is now anticipated in 2010 on the National Ignition Facility: just 3 years away. The process is represented schematically in figure 3.3.

There are two main irradiation schemes for IFE: indirect (x-ray) drive and direct (laser) drive. The physical principal behind indirect drive is to mount the DT fuel capsule inside a hollow high-Z cylinder called a hohlraum. Nanosecond duration lasers are used to irradiate the inner hohlraum walls to produce a relatively uniform thermal x-ray source (with a temperature of ~ 3 million degrees). The x-rays irradiate the capsule inside the hohlraum causing it to implode and finally to reach ignition due to shock heating. With this x-ray scheme there is some overlap with the physics of nuclear weapons. However, most of the physics associated with inertial fusion was declassified in 1995 [3.7], such that development for peaceful, energy applications is now possible.

Direct drive uses the lasers themselves to irradiate the capsule and thus to implode and ignite the fuel. This "all-optical" approach breaks the principle link to weapons science and is intrinsically more efficient. As such it has long been the focus for energy studies, with notable efforts in Japan, Europe and the USA.

Ignition and gain

The concept of ignition for IFE is slightly different to that described for MFE. Ignition occurs when the deposition of the helium nucleus in the fuel is enough to produce a self sustaining burn wave that propagates into the surrounding fuel. In an energy production scenario this would operate in a pulsed mode.

In IFE an equivalent criterion exists that determines the requirements for 'break even'. In this case Q=1 will be achieved when $\rho R > 3\mathrm{gcm}^{-2}$, where ρ is the fuel density and R is the radius of the fuel.

Ignition and gain can be achieved when the energy balance equation is satisfied [3.7],

$$P_W + P_\alpha - P_e - P_b > 0$$

where P_W is work done on the fuel to compress it, P_α is thermonuclear heating rate per unit volume, P_e is loss per unit volume due to electron conduction, and P_b is the loss per unit volume due to bremsstrahlung emission.

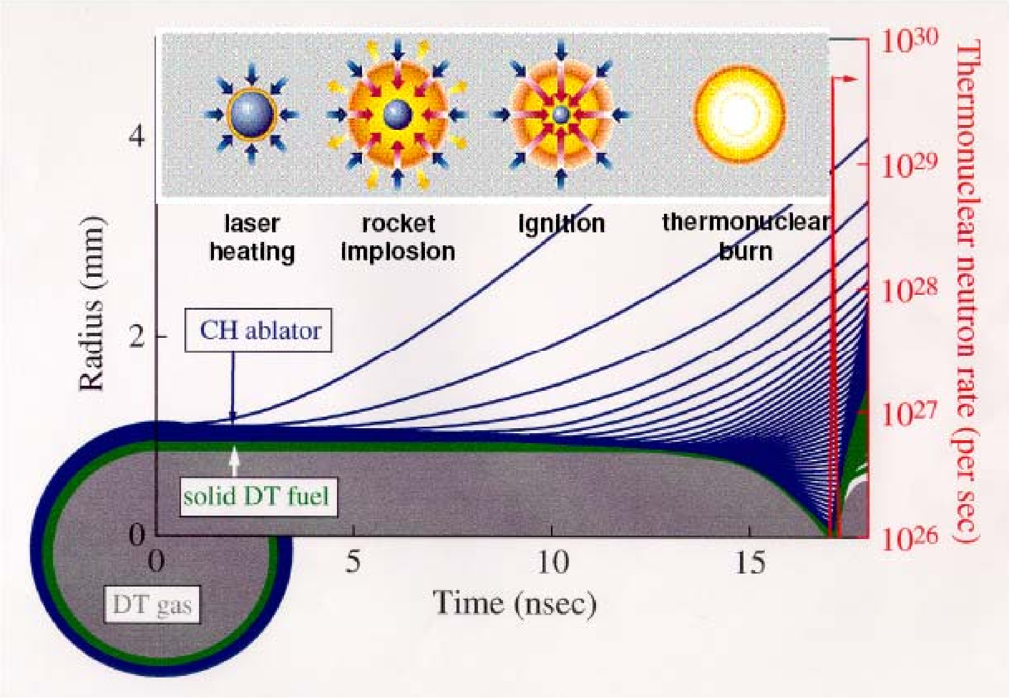

Fig 3.3 Generic implosion for a central ignition target [courtesy LLNL]

Important physical parameters

When a laser of intensity greater than 10^{14} Wcm^{-2} interacts with the capsule, the laser energy is absorbed at the critical surface in the coronal underdense (less than critical density) plasma. This energy is then conducted to the higher density plasma which heats and expands ("ablates") causing the rest of the fuel to converge to high density (ideally ~1000g/cc). The position of absorption is determined by the laser wavelength, λ. Shorter wavelengths are absorbed closer to the ablation surface and hence will produce more efficient implosions.

For conventional "central ignition" IFE, shocks launched by the lasers converge on the centre of the fuel capsule to heat the material to fusion temperatures. In order for this to work the symmetry requirements of the beams are very high – both in terms of energy balance (< 3 %) and temporal synchronisation (< 10 ps). Capsule surface roughness must be < 1 μm on the inside surface, and at the nm level on the outer. If these parameters are not achieved then instabilities such as Rayleigh-Taylor growth (RT) can be seeded (i.e. rippling of the capsule surface and mixing of hot and cold fuel). This limits the peak implosion velocity, and can quench ignition and burn. The ablation velocity can partially stabilise RT growth [3.8] and so this parameter must be optimised. However, in order to exert as much pressure as possible without a high change in entropy, Δs (which would limit compressibility), the laser pulse must be shaped to launch a series of shocks increasing in size [3.7].

This conflict between achieving high density and 'hot spot' formation means that the energy required to drive these capsules with conventional ICF is at the megajoule scale. Lasers of this size are now under construction (figure 3.4):

- National Ignition Facility, NIF, in the USA. 192 beams delivering 1.8 MJ at 351nm.
- Laser Mégajoule, LMJ, in France. 240 beams delivering in excess of 2 MJ at 351nm.

These are being designed to achieve "central ignition" with an energy gain of Q~10-30.

Fig 3.4 The National Ignition Facility

Fast ignition

Because of such stringent energy and symmetry requirements for conventional IFE ("central ignition") a new scheme was proposed in 1994 [3.9]. Termed "Fast Ignition" (FI), the compression and heating phases are separated. This is shown schematically in figure 3.5.

In the compression phase the density requirements are significantly less than conventionally (typically 300-400 g/cm^3 rather than 1000 g/cm^3) and there is no longer a need to ensure high symmetry of compression and shock convergence. This greatly eases the demands on the uniformity of both the laser and target. The driver energy can be as low as 200-300kJ. As laser energy translates relatively directly to cost, this could substantially reduce the capital cost of an IFE plant.

In the heating phase, a high power laser is used to produce an intense beam of electrons or protons. This particle beam must deposit sufficient energy in the imploded fuel to induce ignition and thus a propagating burn wave. The physics associated with the generation, transport and energy deposition of this particle beam are not well understood and represent the principal challenge facing Fast Ignition.

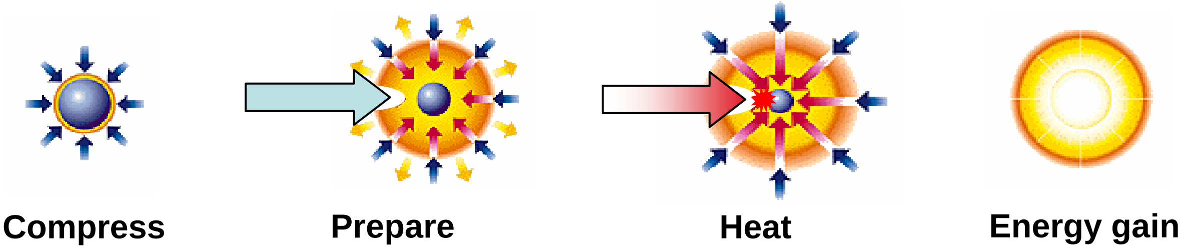

Fig 3.5 Stages of a Fast Ignition fusion implosion

Major laser facilities around the world are currently being upgraded to investigate the physics associated with Fast Ignition. The results from these studies will be used to optimise the design of HiPER. The three largest facilities are:

- FIREX [3.10] in Japan is an upgrade of the current GEKKO XII system at the University of Osaka, Japan. The phase 1 upgrade facility will consist of the construction of an ultra intense laser capable of delivering 10kJ in 10ps in conjunction with the compression beams which will deliver 10kJ of green light in 2ns. This should be completed for full operation in 2008. The phase 2 upgrade, if approved, will deliver 50kJ in 10ps for the heating laser and 50kJ of UV light in 3ns for the compression system. This is expected to demonstrate ignition after 2012.
- The OMEGA facility in the USA is adding a petawatt class laser (2.6 kJ, 1ps) to the existing 40 kJ compression system. Called OMEGA-EP [3.11], this system is expected to be operational in 2007.
- The PETAL laser facility in Bordeaux will couple a high energy petwatt laser (3.5 kJ in a few ps) with the existing LIL laser (60 kJ in 8 beams) and will come into operation in the period 2008-2010.

Recent research into Fast Ignition has centred on a target design in which the fuel is compressed around a gold cone (to keep a channel free from plasma and thus ease the particle beam transport phase) [3.12]. At stagnation an ultra intense laser is fired into the tip of the gold cone, producing copious amounts of hot electrons. These hot electrons need to have a mean energy that will allow them to stop and deposit energy in the dense fuel, raising it to fusion temperatures. A typical FI capsule geometry is pictured in figure 3.6.

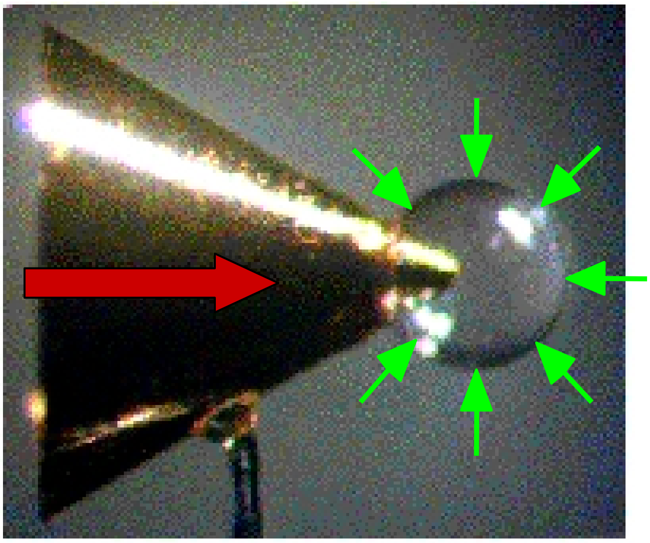

Fig 3.6 – Typical fast ignition capsule. Green arrows indicate compression beams and red arrow indicates heating beam.

In Fast Ignition the fuel assembly is relatively isochoric, with more mass assembled to a lower peak density [3.9], rather than isobaric in the case of central ignition. Greater fuel mass means greater fuel content and thus greater energy output. This translates into a higher gain (= energy out / energy in) for a given laser energy, with a threshold far smaller than conventional (central) ignition. This is shown in figure 3.7, which provides a generic prediction for the performance of Fast Ignition, if successful.

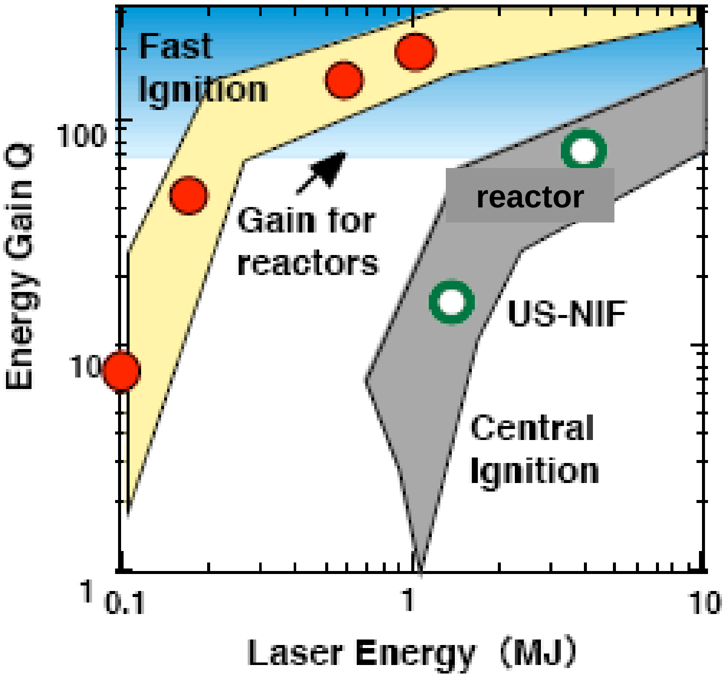

Fig 3.7 Energy gain as a function of laser size for "central ignition" and "fast ignition".

Isochoric compression also has the advantage that the capsule implosion is less susceptible to hydrodynamic instabilities. The ratio of capsule radius to shell thickness is smaller. This parameter, known as the In-Flight Aspect Ratio, IFAR plays a role in the stabilisation of the implosion to RT instability and a smaller IFAR means a more stable implosion.

Experiments on this Fast Ignition scheme have now been underway for over 5 years, with very encouraging results. The first integrated fast ignition experiments with full compression and heating beam geometry were performed as part of a UK-Japanese collaboration using the GEKKO XII facility at Osaka University in Japan [3.12].

These experiments demonstrated the principle of the geometry and also showed that as the heater beam laser power increased from no laser to 0.5 PW the neutron yield obtained from D-D fusion reactions in the fuel increased from 10^4 to 10^7. This showed that the injected electrons were contributing to the heating of the compressed fuel. However, MeV energy electrons would not classically be stopped in the density of fuel that was achieved in this experiment (~50-100g/cc). This suggests that an anomalous stopping mechanism may have been responsible for the energy deposition and heating via the electrons. Electron energy transport and heating in ultra intense laser interactions with solid matter is now a wide and critical field of study to de-risk the concept of fast ignition.

In summary, Inertial Fusion Energy offers an attractive complementary solution to our long-term power production requirements. The physics of IFE is well understood, with net energy production due to be demonstrated using a conventional laser system in ~2010 on the National Ignition Facility in the USA. The path from there to a commercial power plant is still uncertain, with a large number of scientific and technological challenges. An advanced form of IFE known as "fast ignition" offers a particularly attractive solution, combining low capital facility cost with high efficiency and high energy output. HiPER is designed to explore the science of this approach and thus enable a future path to IFE power.

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