

Multidimensional Modelling of Cross-Beam Energy Transfer for Direct-Drive Inertial Confinement Fusion

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List of Acronyms

LPIs Laser-Plasma Instabilities

ICF Inertial Confinement Fusion

LLNL Lawrence Livermore National Laboratory

CEA Commissariat à l'Énergie Atomique et aux Energies Alternatives

RTI Rayleigh-Taylor Instability

NIF National Ignition Facility

LCOE Levelised Cost of Electricity

MCF Magnetic Confinement Fusion

IFE Inertial Fusion Energy

DPSSL Diode-Pumped Solid State Laser

1 Introduction

1.1 Nuclear Fusion

Nuclear fusion is a reaction which combines multiple light nuclei together into heavier nuclei. If the products of the reaction are more tightly bound than the reactants, excess energy is also released to the products. Broadly, the binding energy per nucleon of common nuclear isotopes increases with atomic mass up to iron, ^{56}Fe , and decreases afterwards, as is shown in Fig. 1.1. The reverse process, nuclear fission, operates by splitting heavy nuclei into lighter products, thus energy is released via fusion by combining elements up to iron and via fission down to iron. In 2023, fission made up approximately 9.1% of the global electricity mix [1]. Like fission, fusion energy would be carbon free at the point of production, but it would also offer further distinct advantages. Fusion power plants would not produce energy via potentially dangerous chain reactions and would generate little-to-no long-lived nuclear waste, depending on the specific fuel that was used. In comparison with other low-carbon power sources, including wind and solar, studies have shown that fusion energy could have a competitive Levelised Cost of Electricity (LCOE), which is a metric that compares the economic costs of a power plant over its lifetime to the value of energy produced [2]. Performing controlled nuclear fusion on Earth for energy production has been an active area of research for many decades and many significant scientific and engineering challenges remain to be resolved, in order to make it a viable energy source.

The likelihood of two reactants undergoing a specific fusion reaction is described by the cross-section of the interaction,

$$\sigma(E) = \frac{S(E)}{E} e^{-E_G/E}, \quad (1.1)$$

which is a function of the centre of mass energy, E , the ‘astrophysical S-factor’, $S(E)$, which is a weakly varying function of energy for many typically deployed reactants and the Gamow Energy, E_G [3]. The exponential term in Eq. 1.1 is related to the probability of reactants tunnelling through the energy barrier, due to electrostatic Coulomb repulsion. One approach to achieving the energies required to overcome this barrier are ‘beam-target’ configurations, wherein a high energy beam of reactants is focussed onto a stationary target, has proven unviable [4]. Thermonuclear fusion is the alternative approach, wherein the bulk fuel is heated to sufficient temperatures that the particles in the high-energy tail of the distribution have sufficient energy to undergo fusion reactions. For a fuel is in thermal equilibrium, the high particle energies required to overcome the Coulomb barrier, $\mathcal{O}(100)$ keV, are well above ionisation energies, 13.6 eV for Hydrogen, so the fuel will be in the plasma state. If the fusion products are able to deposit a sufficient fraction of their energy back into the fuel, then a

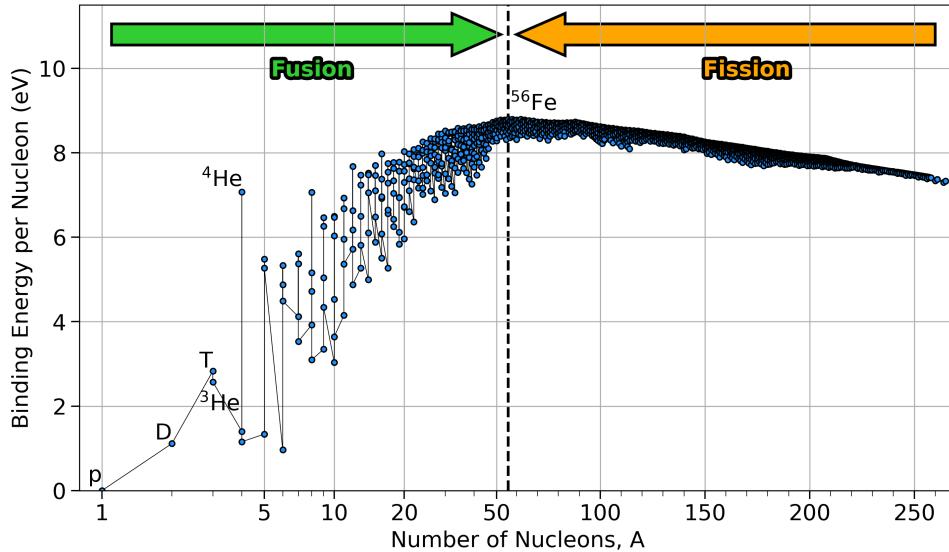


Figure 1.1: Binding energy per nucleon for common nuclear isotopes. Binding energy peaks close to iron, therefore energy is released for reactions which increase binding energy. ^4He has a particularly high binding energy and therefore fusion reactions which result in this isotope are strong candidates for fusion energy production.

self-sustaining fusion reaction is possible, where the high temperatures required for the reactants to fuse is maintained. For a fusion reaction with reactants labelled by 1 and 2, the number of fusion reactions per unit time and volume is known as the ‘volumetric reaction rate’,

$$R_{12} = \frac{n_1 n_2}{1 + \delta_{12}} \langle \sigma v \rangle, \quad (1.2)$$

where v is the relative velocity of a pair of reactants, δ_{12} is the Kronecker delta, which accounts for double counting of species and the ‘averaged reactivity’ $\langle \sigma v \rangle$ is defined as the integral over the velocity distribution,

$$\langle \sigma v \rangle \equiv \int_0^\infty \sigma(E) v f(v) d\nu. \quad (1.3)$$

Eq. 1.2 explicitly demonstrates that achieving a high fuel density, can significantly enhance reaction rates due to the square dependence.

The efficacy of a fusion fuel is dictated by the availability of the reactants, the fusion products, the averaged reactivity of the reactants and the energy released per reaction, Q , which is the difference in binding energy between the reactants and products. Most current, fusion-energy experiments are focussed on demonstrating that fusion power production is possible, thus the choice of fuel is predominantly dictated by the reactivity. Hydrogen-Hydrogen isotope fusion reactions have much higher reactivities than other elements, because the Coulomb repulsion scales as Z^2 , thus the Gamow energy, E_G is significantly smaller. The nuclear physics is particularly favourable for the fusion of deuterium (D) and tritium (T), because there is a nuclear resonance at relatively modest energies for the reaction chain which

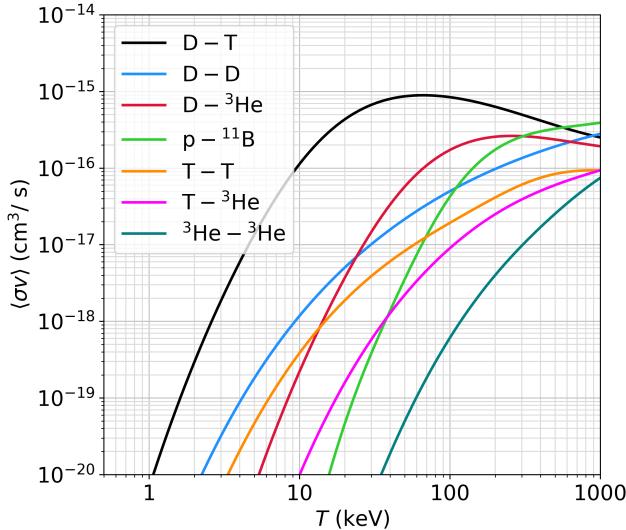


Figure 1.2: Averaged reactivities for important fusion reactions. The deuterium-tritium reactivity is significantly larger than all other reactions up to $T \sim 500$ keV. Averaged reactivities are obtained from cross-section data, available in the ENDF/B-VII.1 library [5].

produces an excited, unstable ${}^5\text{He}$ nucleus, which subsequently decays to ${}^4\text{He}$ and a neutron [6]. Averaged-reactivities of several important fusion reactions, obtained from reaction cross-sections from the ENDF/B-VII.1 library [5], are plotted in Fig. 1.2. The D-T reactivity is at least an order of magnitude larger than the other reactions plotted, up to $T \sim 100$ keV, and it is thus the most commonly used fuel for high-gain fusion experiments. The reaction proceeds as,



where α is a ${}^4\text{He}$ nucleus, which gains 3.5 MeV, and n is a neutron, which gains 14.1 MeV from the fusion energy released, Q . The energy partition is dictated by energy-momentum conservation of the products in the centre of mass frame. The alpha particles typically couple their energy back into the bulk fuel via Coulomb collisions, which has the effect of raising the fuel temperature and thus further raising the reactivity, for fuel temperatures below $T \sim 60$ keV. Neutrons have a much lower reaction cross-section because they are not charged, and thus typically leave the reaction region. However, in fusion experiments with high density configurations such as Inertial Confinement Fusion (ICF), their heating of the fuel can also play a significant role [7].

In order for net energy gain, sufficient energy must be released by fusion to compensate for the energy required to perform the experiment. This requires a fuel configuration with a combination of high temperatures and densities for a large volumetric reaction rate, that is confined for a period of time, which is sufficient for enough reactions to occur. The method of confinement for fusion energy experiments has two broad streams: Magnetic Confinement Fusion (MCF), where magnetic fields are used to confine steady-state fusion-plasma over long time-scales, and ICF, where dense fusion fuel is assembled for a short time period

and ‘confined’ by its own inertia. The work conducted in this thesis is of relevance to ICF schemes, specifically those in which the plasma is produced by laser irradiation.

1.2 Inertial Confinement Fusion

In the 1950s and 60s, the first devices were built which demonstrated stimulated emission of microwave [8] and optical [9] light. The optical-wavelength lasers were quickly recognised as an ideal driver for a far smaller and therefore less destructive thermonuclear device than was used in warheads, which could thus be used for fusion energy generation [10]. Much of the research was declassified and subsequently published in a 1972 article by Nuckolls *et al.* in 1972 [11]. In these ICF experiments, the high temperatures and densities required to initiate an appreciable number of fusion reactions are maintained over a short timescale, which is set by the inertia of the fuel configuration, before the fuel disassembles due to large pressure gradients. The required fuel density is typically achieved by an implosion process. High temperatures are typically obtained either from the conversion to internal energy of the implosion kinetic energy, which is the central hotspot ignition variant, described in Sec. 1.2.2, or via an external heating source, as described in Sec. 1.2.3. Before describing these schemes in more detail however, necessary criterion for energy gain conditions shall be discussed, which are agnostic of how the fusion fuel is assembled and dictate the plasma conditions which must be achieved.

1.2.1 Ignition Requirements

The point at which alpha heating becomes the dominant term in the power balance of the fusion fuel is termed ‘ignition’ and it is a necessary condition for high gain ICF experiments. Ignition necessitates that the plasma is confined for a sufficiently long period of time, for an appreciable number of fusion reactions to occur, raising the fuel temperatures and reactivities, which results in a propagating burn wave. Estimates for the required plasma conditions which must be achieved for this to occur, can be estimated by considering the timescales of confinement and fusion. Initially, a uniform ion number density n_i and temperature T , spherical fuel assembly, with outer radius R , shall be considered. The ions have an average mass, m_i , such that the mass-density of the fuel, $\rho = m_i n_i$ and the volume of the fuel sphere, $V = 4\pi R^3/3$. Dimensional considerations give an order of magnitude estimate for the timescale on which fusion reactions occur,

$$\tau_{\text{fus}} = \frac{1}{n_i \langle \sigma v \rangle}, \quad (1.5)$$

where n_i is the ion number density of the plasma. A radially inward pressure gradient will exist due to the high temperature of the plasma, which will lead to an inward propagating rarefaction wave, disassembling the fuel. This rarefaction wave will move at the isothermal sound speed, $c_s = \sqrt{2k_B T/m_i}$,¹ from $t = 0$, such that its position is given by $r = R - c_s t$. There-

¹The factor of 2 in $C - s$ is because the pressure is the sum of contributions from ions and electrons.

fore, the timescale on which the burning fuel remains un-rarefied and thus confined is,

$$\begin{aligned}\tau_{\text{conf}} &= \int_0^{R/c_s} \frac{(R - c_s t)^3}{R^3} dt, \\ &= \frac{R}{4c_s}.\end{aligned}\quad (1.6)$$

The ratio of these timescales,

$$\frac{\tau_{\text{conf}}}{\tau_{\text{fus}}} = \frac{\langle \sigma v \rangle \rho R}{4m_i c_s}, \quad (1.7)$$

illustrates that, for ignition and hence gain, ICF reactions require a large ρR value, which is typically referred to as the ‘areal-density’ [12].

The timescale ratio can be used to derive the ‘burn-up fraction’, which is defined as the ratio of fusion reactions, $N_{\text{fus}} = R_{\text{DT}} V \tau_{\text{conf}}$, to the number of DT pairs, $N_{\text{DT}} = n_i / 2$, in the fuel assembly,

$$\begin{aligned}\Phi &\equiv \frac{N_{\text{fus}}}{N_{\text{DT}}}, \\ &= \frac{\langle \sigma v \rangle \rho R}{H_B},\end{aligned}\quad (1.8)$$

where the ‘burn-parameter’, $H_B \equiv \langle \sigma v \rangle / 8m_i c_s$ has been defined. Eq. 1.8 is only valid for $\Phi \ll 1$, because the conversion of DT pairs into non-fusing products has not been considered [3]. A modified form of Eq. 1.8, which approximately accounts for burn-depletion, was derived by Fraley *et al.* in Ref. [12],

$$\Phi = \frac{\rho R}{H_B + \rho R}. \quad (1.9)$$

If solid density DT was used, the mass of fuel required to achieve $\Phi = 30\%$ of the fuel would be 2.5 kg, which would release the same energy as 50 kilotons of TNT [13]. In order to harness the released fusion energy without destroying the surrounding infrastructure, a smaller mass is required, which necessitates compression of the fuel to achieve the ρR constraint. A pellet containing 1 mg, compressed to densities $\mathcal{O}(10^3)$ times solid density, could release 100 MJ of fusion energy at $\Phi = 30\%$. Spherical compression is optimal because the fuel compresses in three dimensions. This minimises the convergence ratio, $CR = R_{\text{init}} / R_{\text{final}}$, which increases the tolerance to a given amplitude of perturbation.

1.2.2 Central Hotspot Ignition

Increasing fuel mass requires larger and larger driver energy to heat to the required fusion temperatures, $T \sim 5$ keV. This necessitates larger and more expensive drivers, limiting both the upfront driver cost and potential target gain. Therefore, schemes which can minimise the driver energy required to ignite a given fuel mass are more practical for current experiments and future power plants. The ‘central hotspot ignition’ scheme is one such target configuration, where the target is isentropically compressed by carefully constructed pulse shapes, such that it maintains a cold dense fuel shell which implodes inward. Only a small mass of central fuel is heated to the required fusion temperatures. The energy required for this heat-

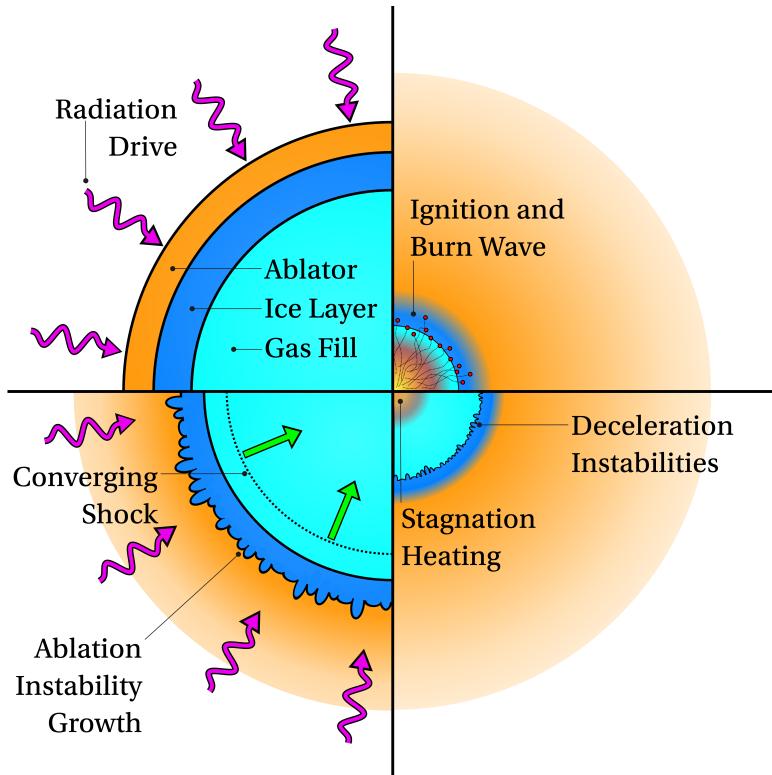


Figure 1.3: Four key Stages of the central hotspot ignition ICF concept. The chronological order of the diagram is top-left, bottom-left, bottom-right and then top-right quadrants, which display the initial configuration, implosion, stagnation and burn propagation stages respectively.

ing is provided from implosion kinetic energy of the dense shell. Fig. 1.3 shows a schematic representation of a central hotspot ignition implosion at 4 important stages. The top left quadrant shows the initial, spherical target configuration, which is comprised of an outer ablator, a solid DT ice layer and an inner DT gas fill. Choice of ablator material is driven by a number of considerations, including mass ablation rate, minimisation of instability growth, radiation coupling and ease of manufacturing [14–17]. Cryogenic temperatures are required to form the ice layer from the DT fuel. The driver should, ideally, uniformly irradiate the outer surface to maintain the optimal spherical compression and to minimise instabilities growth. Specific radiation drives shall be discussed in Sec. 1.3, but for now, the scheme shall be discussed, while remaining agnostic of the driver.

The bottom left quadrant of Fig. 1.3 shows the implosion phase of the scheme. As the radiation from the driver heats the outer layer of the ablator, it heats up and expands radially outward, which imparts a rocket force on the interior target, propelling it inward. A low density gas fill is used to make compression of the target easier such that high convergence ratios can be achieved. Greatest convergence can be achieved if the pressure of the gas fill is minimised and thus high-gain ICF targets aim to limit ‘preheat’ of the interior gas fill ahead of the shock. For example, a poorly pulse-shaped driver will lead to undesired shock heating of the interior fuel ahead of the converging shell, which raises its pressure and thus limits compressibility. Assuming perfectly spherical targets and driver radiation, isen-

tropic pulses maximise the target gains, which are designed to limit shock preheating of the gas-fill. In reality, target defects and short wavelength perturbations in the driver radiation seed the Rayleigh–Taylor Instability (RTI) on the ablation surface, which can grow due to the misaligned density and pressure gradients. Realistic pulse shapes often slightly preheat the target, which increases stability to hydrodynamic instability growth [18, 19].

The stagnation phase of the implosion is shown in the bottom right quadrant of Fig. 1.3. As the remaining relatively cold and dense shell converges on the axis, PdV heating raises the temperature of the compressed interior gas fill. If the implosion velocity is sufficient, this piston heating of the fuel results in fusion relevant temperatures. The deceleration phase is also hydrodynamically unstable, because the high pressure, low density interior pushes on the high density, low pressure shell, which results in further RTI growth. Long wavelength perturbations to the radiation drive result in unstagated kinetic energy in the hotspot, limiting maximum achievable temperatures [20]. Short wavelength perturbations from the RTI, can introduce high-Z ablator material to the hotspot which enhances radiative losses, and if sufficiently large amplitude can puncture the shell, severely degrading confinement [21].

The upper-right quadrant of Fig. 1.3 shows the final, ignition and burn propagation phase of the design. If the density and temperature of the fuel hotspot are sufficient, then fusion reactions begin to occur, generating energetic alpha fusion products. For sufficiently high areal density shells, the alpha particles deposit their energy in the dense fuel shell, raising its temperature and initiating further fusion fuel to the burn process. This leads to ignition, if the confinement holds the fuel together for a sufficiently long period.

1.2.3 Alternative Ignition Approaches

In the central hotspot ignition scheme, the energy required to heat the fuel to fusion temperatures is supplied by the kinetic energy of the imploding shell. The high shell velocities required to result in hotspot fusion temperatures is ~ 300 km/s and results in significant instability growth. Alternative schemes exist, namely the shock- and fast-ignition variants, where the required shell density is obtained via a much slower implosion process, limiting instability growth. Temperatures are then achieved by applying a heating source, separate from the implosion dynamics. For shock ignition, the driver pulse shape is sharply ramped up at the end of the pulse, in order to generate a strong, spherically converging shock, heating the fuel to fusion temperatures [22, 23]. The main issue with this scheme for laser-driven ICF, has been questions over laser coupling at the high intensities required to generate the ignitor shock. At high laser intensities, a mostly deleterious class of laser-plasma interaction known as Laser-Plasma Instabilities (LPIs) dominate. LPIs are introduced in detail Sec. 1.4.2. Recent work has explored the possibility of augmenting the laser pulse shape to add a dip in power, prior to the ignitor pulse rise, which aids in shock generation and thus limits the intensities required [24].

Fast-ignition is an alternative concept which utilises an external ignitor-beam, of charged particles, to provide the hotspot heating [25]. Scientific research related to this scheme include studying how the high energy charged particles are generated via ultraintense laser

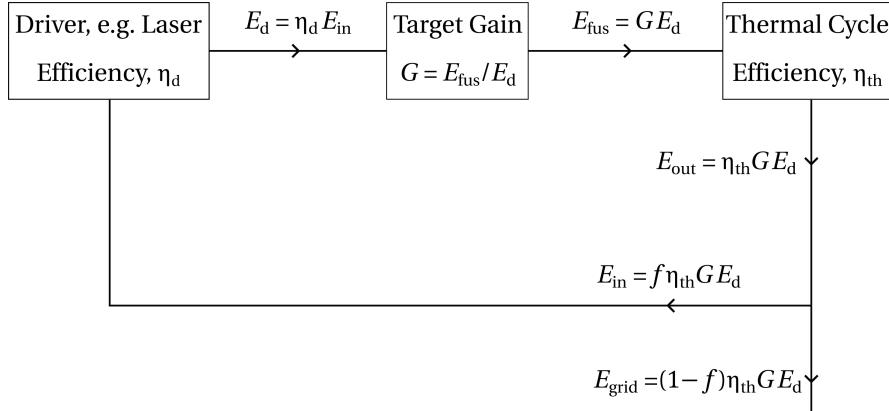


Figure 1.4: Energy balance of an IFE power plant. Based on a similar figure from Ref. [3].

interactions and they can be focused and couple their energy to the fuel [26, 27]. The overall complexity of many of proposed driver and target configurations would also likely have to be reduced, in order to make Inertial Fusion Energy (IFE) relevant targets.

All of the ignition concepts introduced so far focus on igniting a small central mass, which then initiates a propagating burn wave into surrounding fuel. The volume-ignition variant, instead proposes igniting the entire fuel volume simultaneously [28, 29]. This is achieved by assembling a large, dense fuel mass, kept at a much lower temperature than the hotspot in other schemes. A large and dense fuel assembly has minimal radiative losses and can thus ignite at $T \sim 1.5$ keV, as opposed to the ideal ignition temperature of hotspot schemes, $T = 4.3$ keV [3]². One issue with this scheme is that significantly more laser energy is required to ignite a given fuel mass, because the entire volume must be brought to ignition conditions at the same time.

1.2.4 Inertial Fusion Energy Considerations

For a power plant to produce net energy from ICF implosions, the energy from each target must of course be greater than the energy to drive the implosion. In reality, additional inefficiencies in power plants set more stringent constraints on the energy which must be produced. The energy balance of an IFE power plant is shown in Fig. 1.4. A driver, such as the lasers which are considered for the work conducted in this thesis, converts an input energy, E_{in} , to a driver energy, $E_d = \eta_d E_{in}$, where η_d is the energy efficiency of the driver. The driver energy initiates a fusion reaction, which releases energy E_{fus} , with gain, $G = E_{fus}/E_d$. The released fusion energy, for example in the form of energetic neutrons, is converted into thermal energy in an encompassing ‘blanket’, and then into output electrical energy, E_{out} by a thermal-cycle (such as steam turbines), with efficiency, η_{th} . Some fraction f of this generated energy is recycled back into the plant to power the driver and the remaining fraction is sent to the grid,

$$E_{grid} = (1 - f) \eta_{th} \eta_d G E_{in}, \quad (1.10)$$

²The ideal ignition temperature is the value at which alpha heating balances alpha heating.

with the constraint, $f\eta_{\text{th}}\eta_d G \geq 1$ for net energy production. Power plants must also produce a sufficiently large volume of energy to be economical. Therefore, several ~ 100 MJ reactions must occur each second for a 100 MW plant, which necessitates a driver that can operate at ~ 10 Hz.

The Diode-Pumped Solid State Laser (DPSSL) concept, could feasibly produce laser energy at ~ 10 Hz repetition rate, with an efficiency $\eta_d \sim 10\%$. Assuming a thermal cycle efficiency, $\eta_{\text{th}} = 40\%$ and a recycled energy fraction, $f = 1/4$, this means that a target gain of approximately $G \sim 100$ is required for power production. Additionally, the plant must be economically profitable, thus for a $G = 100$ reaction, which releases $E_{\text{fus}} = 100$ MJ = 28 kWh, the energy sold to the grid would make about £1.50³. Therefore, targets must cost approximately £0.10, which limits the tolerable manufacturing complexity. IFE target concepts exist, which could feasibly be mass-produced for an acceptable cost, for example initially uniform density liquid spheres, known as ‘dynamic shell’ targets [30, 31].

1.3 Current Experiments/ Main Approaches

In Sec. 1.2, the basic principles of ICF were introduced without specifying the driver technology. Although heavy ion beams have been proposed as a driver technology [32], most current research focusses on the direct-drive and indirect-drive approaches, which use laser light to directly and indirectly irradiate the target respectively. For the direct-drive approach, lasers are focussed upon the outer surface of the target, whereas in indirect-drive, they illuminate the interior surface of a high-Z material ‘hohlraum’, which generates a thermal bath of x-rays. The indirect-drive approach was developed in order to relax requirements on laser beam uniformity and sensitivity to hydrodynamic instabilities in direct-drive [33]. Sources of degradation and implosion dynamics are somewhat different in each of these approaches. Each approach is introduced below, and progress on the main experimental facilities is summarised.

1.3.1 Indirect-Drive

The National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory (LLNL) in the United States of America, is the largest ICF facility and high power laser system in the world, which mainly focusses on the indirect-drive approach. It is comprised of ... The **LMJ!** (**LMJ!**) is a newer facility at Commissariat à l’Énergie Atomique et aux Energies Alternatives (CEA) in France, which ...

Talk about all that jazz and give the diagram. Talk about NIF and ignition, gain etc.

1.3.2 Direct-Drive

Say its the assumed version for IFE. Give a much more detailed anatomy of implosion, incl diagram. Talk about hydro-scaled ignition etc.

³The UK April 2024 energy price of £0.25 per kWh was used.

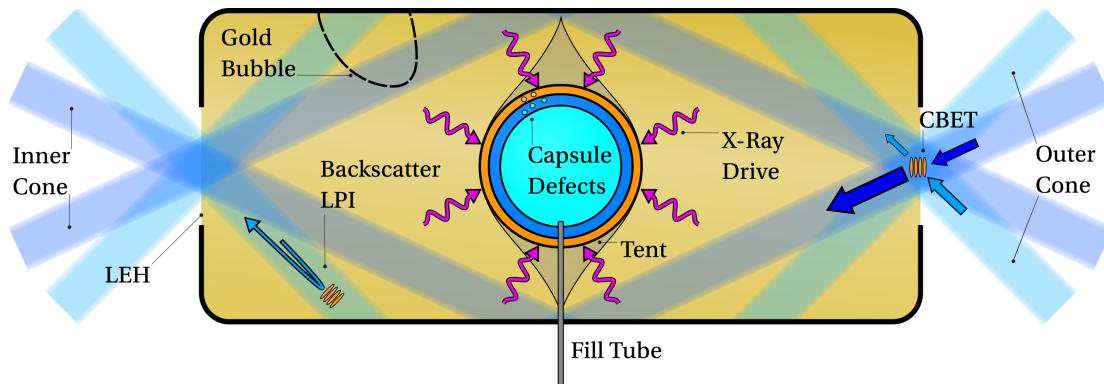


Figure 1.5: Schematic of the indirect-drive approach to ICF. Laser light, represented as blue transparent rectangles, irradiate the interior of a high-Z (e.g. gold) hohlraum, which produces thermal x-rays that drive the capsule implosion. A number of important physical effects, typical to indirect-drive experiments, are also illustrated on the diagram.

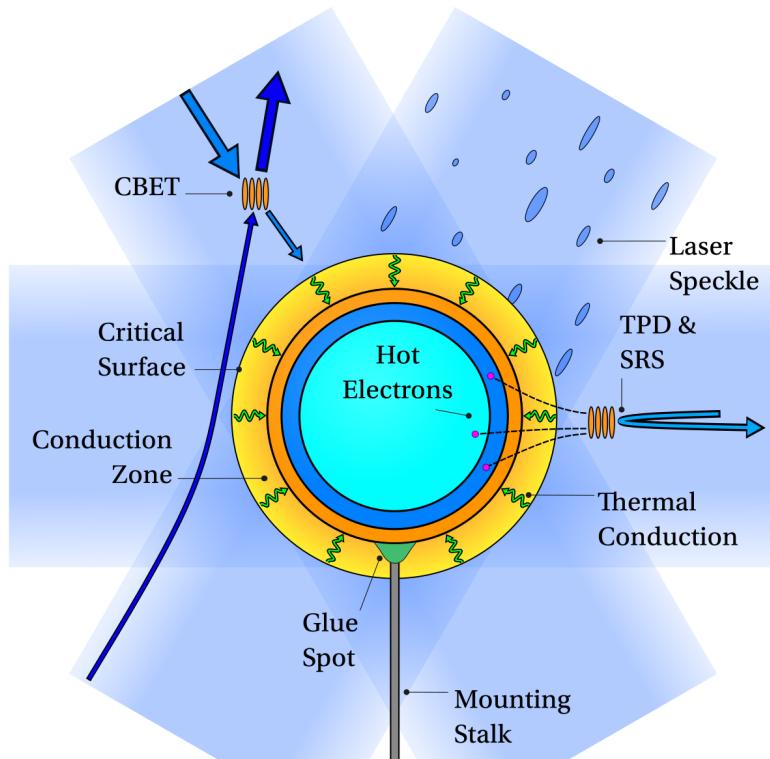


Figure 1.6: Schematic of the direct-drive approach to ICF.

1.4 Laser Interaction with Plasmas

Understanding lasers is obviously crucial for Direct, indirect and hdp more generally.

1.4.1 Regime of interest

Want collisional absorption and to avoid LPIS. Therefore short wavelength, high power lasers, with limits to peak intensity. Balance between P_{abl} and high $I * lam^2$.

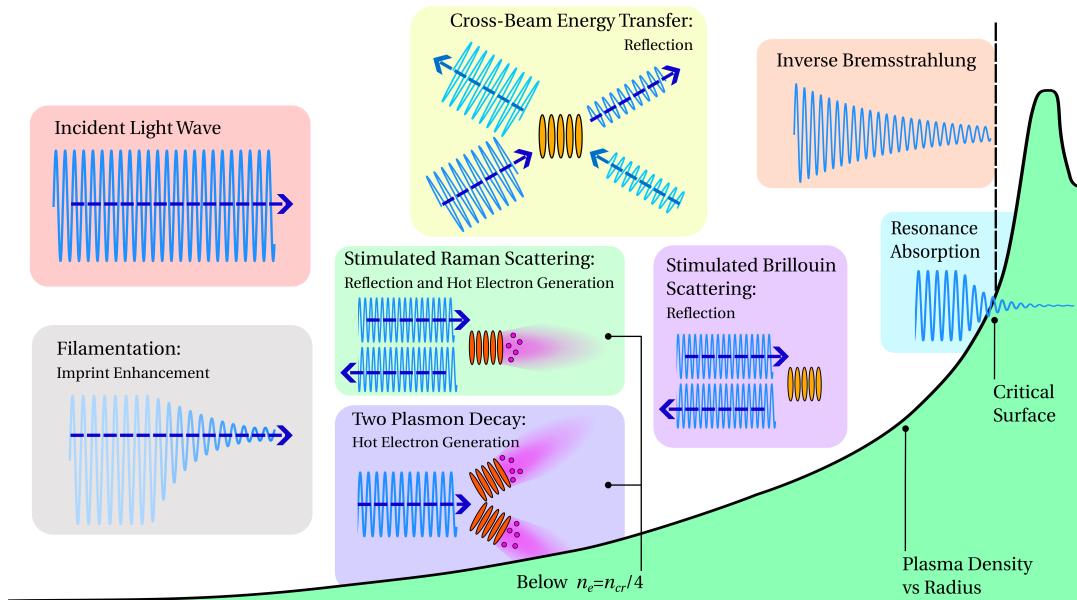


Figure 1.7: Important LPIs for direct-drive ICF.

1.4.2 ICF Relevant LPIs

Damaging class of laser-plasma interactions for ICF. Give diagram of how they work micro-physically. Include direct-drive LPI diagram. Introduce each in turn and say what they do for direct and indirect.

1.5 Objective of the work

LPIs are important for current experiments. Need to include models for them in integrated codes. Also, next gen lasers will eliminate LPIs hopefully with bandwidth, so need to understand how they degrade current experiments to accurately extrapolate. Create laser module for CHIMERA, specifically capable of modelling LPIs, and then see what their effect is for direct-drive.

Appendices

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