8 Experimental validation of the fusion programme

8.1 Introduction.

The fast ignition concept was first proposed in 1994 [8.1] and received immediate and widespread interest around the world for three reasons. First, more fusion fuel can be compressed to high density for reduced drive energy compared with the conventional central spark ignition concept for inertial fusion, leading to higher fusion energy gain. Second, the drive symmetry requirements can be significantly relaxed because the in-flight aspect ratio of these implosions is significantly larger, thus reducing the growth of the Rayleigh-Taylor hydrodynamic instability. Third, the enormous energy densities of the PetaWatt laser pulse needed to heat the hot spot to ignition temperatures were (and are) of great interest to the fundamental physics of laser-matter interactions and many spin-offs of the research could (and have been) envisaged. To date, thirteen years after the concept was first published, no show stoppers have yet been identified, despite the extremely close experimental and theoretical scrutiny that the concept has undergone. Recent reviews of this scrutiny that includes a full discussion of the concept, associated experiments, theory and computational modelling have been published by Campbell *et al.* [8.2].

This is not to say that there all questions have been fully answered. In this paper, 14 areas of concern for HiPER have been identified. They are listed in order of priority for experimental validation over the next three years of the detailed design phase of the project. We do not expect that answers to all outstanding questions can be addressed fully in this time period, since they will require many PW laser shots to answer in a fully satisfactory manner and there are a limited of shots available across the European laser facilities, but significant progress is likely to be made on many of them. We remain optimistic that these areas of concern can be addressed and that fast ignition will remain a strong candidate for the realisation of inertial fusion energy.

8.2 Absorption and energy transfer to the fast electron beam.

The efficiency with which laser energy is absorbed by (initially) solid targets has long been one of the most fundamental aims of theoretical laser-plasma physics. The calculation of this parameter is of vital importance to any inertial confinement scheme dependent on laser pulses. This is particularly true for the fast ignition approach because this scheme utilises both low and high laser intensities. The absorption efficiency effectively determines the viability of the entire scheme. From an experimental point of view, the knowledge gained to date is very positive. It is now possible, with some reasonable degree of certainty, to say what the absorption efficiency is likely to be for a given experimental set-up, i.e. given parameters such as the type of target, intensity of the laser beam and its associated contrast ratio.

In terms of the energy conversion efficiency from the laser beam to the inwardly directed fast electron beam, Wharton *et al.* measured the absolute K_α x-ray signal that indicated a conversion efficiency of between 20 % – 30 %. [8.3] Kodama *et al.* obtained conversion efficiency with or without a large scale-length preformed plasma of 20 % - 25 % and 40 %, respectively [8.4]. Similarly Norreys *et al.* inferred a conversion efficiency of 20 % - 30 % from bremsstrahlung radiation in solid targets [8.5]. These measurements were performed with intensities on target between 10^{18} Wcm^{-2} and 3×10^{19} Wcm^{-2}. Measurements up to 2.5×10^{20} Wcm^{-2} have been obtained at LLNL (with a 0.5 ps 1 PW laser) and show conversion efficiencies up to 40% with irradiation at ω (1 micron laser wavelength).

A somewhat different result is that reported by Theobald *et al.* By absolute K_α measurements which indicated a conversion efficiency at 10% at 4×10^{20} Wcm^{-2} on target, by comparison with a computational model that includes refluxing and confinement of the fast electrons within the target [8.6]. This is conversion efficiency estimate is somewhat lower than the other measurements, but some caution is needed in interpreting these results, since the conversion efficiency in the modelling is very dependent on the shape of the initial electron distribution used. Clearly at very high intensities more experimental results are needed, but conversion efficiencies still seem to remain quite high.

Another important point is the scaling of conversion efficiency with laser wavelength, a parameter which may need to be changed in order to optimize the average energy of the fast electron beam. Several measurements have been performed with Ti:S lasers, showing high efficiencies again. Irradiation of targets with $2\omega_0$ of Nd:glass laser light, we recall the measurement of Pisani et al. in the range 2×10^{18} Wcm^{-2} to 2×10^{19} Wcm^{-2}, which shows conversion efficiencies perfectly comparable with those obtained at ω_0 [8.7].

Probably the most outstanding issue, however, remains a systematic study of the conversion efficiency as a function of the scale-length of the plasma, which the laser creates and continually interacts with. Low density foams have been shown to increase the absorption (inferred from an increase in the X-ray yield) [8.8], but these structures are difficult to model (and thus optimise) computationally. More controlled structured targets are needed for comparison with theory. In addition, the ~10 ps pulse durations needed for fast ignition provide a new challenge in maintaining high absorption efficiency over the entire pulse length, since hole boring and/or profile steepening will both occur [8.9]. Very recent results also suggest that very high efficiencies are possible, which can only spell good news for fast ignition.

The theoretical understanding of absorption still poses many outstanding questions. In the early days, theories could be developed based on some expansion parameter (usually the strength of the oscillation) and a given density profile (usually constant or step-like). With the advent of higher-powered lasers, such expansion parameters are difficult to construct, the density profile becomes strongly inhomogeneous and the absorption becomes interlinked with transport processes [8.10]. Furthermore, real experimental situations are likely to involve many processes simultaneously and fully temporally and spatially resolved simulations have yet to be carried out. In particular, our currently available models only tend to be applicable to a given intensity, temperature and scale-length [8.11]. It must be stressed that finding a satisfactory description of the entire process, from low-intensity ablation due to the pre-pulse to high intensity hole-boring within a single model is still outside of our capabilities, even in one dimension.

8.3 Divergence and collimation – novel techniques (shaped targets, etc.).

The fast electron beam divergence is the second vital ingredient to the success of the fast ignition approach. While recent experiments have revealed a large divergence pattern, very promising ideas have been proposed to control this effect and should, if the theory is correct, provide a route to narrower beams with a more suitable divergence angle requirement for fast ignition.

Computational modelling using the two dimensional hydrodynamics code LASNEX of cone-shell implosions have been performed [8.12]. Those simulations showed that if the fast electron beam has too large a beam divergence (i.e. ≥50°) then, for realistic core-cone wall interface distances (~180 μm in those calculations), the PW laser energy requirements approach 150 kJ, which is too far from practical implementation, even on the National Ignition Facility. While there is obviously scope for optimising the core-cone end-wall distance by suitable target design, the simulations confirm that beam divergence plays a crucial factor in the viability of fast ignition.

For example, the pioneering cone-guided experiments at Osaka University by Kodama *et al.* [8.13,8.14] have been successfully modelling using both the LSP [8.15] and ANTHEM [8.16] codes. These models both used an electron beam divergence of 27° and a PW laser to fast electron beam energy conversion efficiency of 20 %. While differing in the details, the fact that both computational models reproduce the experimental observations of the ion temperature is very encouraging.

The divergence of the fast electron beam has been studied by imaging the optical transition radiation and the X-ray K_α emission from laser irradiated metallic targets. The measurements have provided a divergence angle of 34° [8.17] and 40° [8.18] respectively for intensities on target between 10^{19} $\mathrm{Wcm^{-2}}$ and 5×10^{19} $\mathrm{Wcm^{-2}}$. Recent shadowgram and X-ray K_α emission measurements have indicated a larger (64°) beam divergence angle for intensities of 5×10^{20} $\mathrm{Wcm^{-2}}$ on target, albeit with laser pulses of 0.5 ps duration [8.19]. A new study (conducted in Nov/Dec 2006 on the Vulcan PW laser facility) has confirmed a divergence angle of 35 (+/-13)° for pulses of direct fast ignition relevance to fast ignition (5 ps) at intensities on target of 3 10^{19} $\mathrm{Wcm^{-2}}$.

If the results giving a large beam divergence at very high intensities are confirmed, then we may need to limit the maximum irradiance on target to something of the order of 5×10^{19} $\mathrm{Wcm^{-2}}$, unless new techniques are employed to control the beam divergence. This must be seen as a very high priority for the risk reduction investigation over the next three years.

One possible approach was proposed by Campbell *et al.* [8.20]. This uses radial layered targets or vacuum gaps to generate a negative radial gradient in the plasma density. By doing so, strong confining radial electric fields are generated in the radially graded foil. The idea has been tested in implicit hybrid-PIC modelling using the LSP code and has been found to very effective in collimating the fast electron beam. The idea has a great deal of merit, as recent cone-wire targets have shown that the fast electrons are confined to the wire by a combination of radial electric field and azimuthal magnetic fields [8.21]. It therefore appears that vacuum gaps may well provide the confining radial electric field, as expected. A fast ignition relevant concept experiment is shown in Figure 8.1.

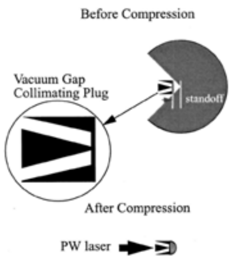

Figure 8.1. Schematic of a vacuum gap concept to collimate the fast electron beam in a cone geometry. From Fig. 5 of Campbell et al. [8.20].

One possible problem with this approach is the possibility of the collimating effect being destroyed by plasma filling of the vacuum gap. Experimental and theoretical studies needed to be done to examine this. If this is unavoidable then other solutions need to be examined. Current theoretical studies in the Plasma Physics group in the CLF are based around controlling the self-generated magnetic field by laser pulse shaping. On the same line, recent experiments performed at CLF in a different context (that of optimization of laser-produced proton sources) have nevertheless shown that by controlling the spatial shape of the laser pedestal it is possible to steer and control proton emission, a result which implies the capability of controlling electric and magnetic fields inside the targets.

The ideas are complementary and would suit experimental campaigns using the Vulcan and LULI PW laser facilities. Both approaches can then be pursued and assessed independently. If successful, this work should be applied to higher energy lasers (OMEGA EP, FIREX and PETAL) for further validation with higher temperature plasmas.

Also, in general, we must still perform experiments, which are addressed to elucidate the origin of the divergence of the fast electron beam, and the possible ways, if any, of controlling it. One interpretation seems to relate the divergence to a Weibel-like instability in the region where the laser is absorbed and the fast electron beam created. However it should also be related to the different absorption mechanisms, the plasma scale length in front of the target, etc.

8.4 Phase control.

The PW beam-line for HiPER will, by necessity of the high energy requirement, be composed of multiple beam-lets, each amplified in its own laser chain. The combination of these beam-lets into a single beam poses questions concerning the overall phase control requirement. The particular issues include the effects on the electron temperature (generated in the laser-plasma interaction) of intensity “hot spots” in the focal plane due to coherence effects, as well as the absorption efficiency and the fast electron beam divergence pattern.

In some ways, this question is similar to the optimisation of the shape of the inner wall of the cone targets [8.22]. In this case, those parts of the intensity profile that lie far outside the focal spot are reflected by a plasma mirror (generated on the inner surface of the cone) to the cone tip. If one thinks of this process in terms of ray-tracing, those rays on the outer portion of the spatial intensity profile will have a different path length compared with those within the focal spot after reflection from the plasma mirror. The intensity profile at the cone tip will then consist of a speckle pattern with superimposed intensity spikes due to the coherent constructive interference.

Experiments need to be performed that examine these issues in a controlled manner to compare with theory and thus assist the design of the facility. We envisage experiments where either random or distributed phase plates are inserted into the high intensity beam. These are used to generate a focal spot of a known diameter comprising beam-lets of either random or known phase. This will “mock up” the full HiPER beam. The effects on the electron temperature, efficiency and divergence can then be determined in an open geometry with plane targets and compared with cone attached targets. The results can then be used as a benchmark for experiments designed on PETAL, whose phased array high energy PW beam is under construction and due for experiments in 2008-2010.

8.5 Hydrodynamics and mixing and tamping of the Au cone material.

A potentially serious impediment to the success of DT filled cone-shell implosions is the ablation of the Au material from the cone walls. This ablation is caused by hard X-rays (generated in the coronal laser-plasma interaction during the acceleration phase of the implosion) that manage to penetrate through accelerating ablator/fuel to the cone wall. If a sufficient amount of high Z material is ablated and swept up into the core at stagnation, then bremsstrahlung losses could exceed those of alpha-particle deposition and quench the thermonuclear burn wave [8.23].

Radiographic and areal density measurements of fast ignition relevant implosions have been performed using the GEKKO XII laser facility in Japan [13] and the OMEGA laser facility in the United States [8.24, 8.25]. The experiments have shown :

1. Cone guided compression works – good agreement with hollow plastic shell implosions has been shown with two-dimensional radiation hydrodynamic computer simulations. Compressed densities of 50 – 100 gcm^{-3} have been achieved. Although further experiments may be needed to show that very high degree of compression are indeed achievable, these are very encouraging results indeed.

2. Adiabat pulse shaping works – thick, 40 μm plastic shells filled with D_2 or DHe mixtures were imploded on a low-adiabat ($\alpha \sim 1.3$) and with a low-implosion velocity to generate massive cores of compressed plasma with high areal densities optimal for fast ignition. The same implosions with empty plastic shells are expected to reach 1.3 gcm^{-2} across the core, which is enough to stop fast electrons with energies up to 4.5 MeV, typical of fast ignition scenarios.

3. X-ray and/or electron preheat causes some gold material across the cone – core gap and that this process is more pronounced for indirect drive. This effect is not expected to scale with IFE implosions (due to the increased thickness of the ablator / DT fuel providing a better attenuation length).

4. Misalignment of the cone axis or drive symmetry imbalance degrades the compressed density and can lead to turbulent mixing into the cone-core gap.

Two possibilities have been suggested to mitigate the ablation of the gold material – either tamping the cone with a thin plastic (CH) layer [26] or to use an intrinsic DT ice layer that forms on the cone wall as the tamp material [27]. In addition, at early times in the acceleration the Kelvin Helmholtz instability could be generated at the interface of the gold cone and the ablator/fuel capsule. Additional material tamping may need to be added closer to the initial shell diameter position to mitigate this effect.

We envisage experiments that use a shaped laser pulse (similar to that needed for the HiPER baseline target design) to irradiate a plastic foil to simulate the X-ray and hot electron production in the laser-plasma interaction. The ablation of material from a gold foil placed at different distances from the primary foil, with the ablated material being diagnosed using a monochromatic backlighting source. The opacity of the ablated gold plasma to the backlighting source can then be used to infer the dynamics and suitability of tamping by different thickness plastic and Be-coatings.

We also envisage similar experiments (e.g. V-groove type open geometries) to test whether Kelvin Helmholtz instability is important in the early stages of the implosion. In the context of hydrodynamical experiment for fast ignition, a first experiment has recently been performed using the Alisé laser of CEA in Bordeaux, in which the sliding of a laser-accelerated target attached on a support has been studied in order to mimic the sliding of the pellet shell along the cone surface. Although very preliminary, this experiment gives the idea of what can be done using already existing European laser installations. Relevant experiments in this field are probably limited only by our ability to imaging them. More experiments could also be performed during the next preparatory phase for HiPER on non-European facilities in the U.S. and in Japan in collaboration with researchers from those countries.

8.6 Fast electron transport in dense deuterium plasmas.

Most studies of laser-solid interactions to date have been performed with medium – high Z metallic targets. They have shown the divergent fast electron beams discussed in section 3. These irradiated materials have a resistivity that rises between 1 eV and 10 eV, plateaus between 10 eV and 100 eV and then falls thereafter [8.28]. Even in the high temperatures above 100 eV, their resistivity is at least an order of magnitude higher than that of the compressed deuterium-tritium fuel in the HiPER base line design. Consequently, fast electron energy transport in compressed deuterium or deuterium-tritium mixtures is likely to be very different to those in current day laser-solid experiments.

This is illustrated by a number of transport experiments in lower Z plastic targets. In the initial plasma production phase in low temperature plasmas, the transport is complicated by ionisation induced instabilities [8.29]. In higher temperature plasmas, experiments have shown a transition from a uniform beam pattern with a 20° divergence angle to one with an annular beam structure [30]. This indicates the beam propagation inside the target is hollow at intensities on target of 3×10^{19} Wcm^{-2}. Norreys *et al.* concluded that this effect was most likely to due to a fall in resistivity (η) with target heating. The electric field set up to draw the return current is given by Ohm's law $E = \eta j$ (where j is the current). Ohmic heating is given by ηj^2, so if the resistivity falls faster than linearly with temperature then the electric field will change from increasing with current density to decreasing with current density (once the temperature has risen significantly). This causes the magnetic field to fall and to change sign, leading to hollowing of the beam instead of focusing of it.

In addition to beam hollowing, other effects become important, particularly when the beam density approaches that of the background plasma. Filamentation of the fast electron beam can occur when there is a change in background density and this has been confirmed experimentally [8.31]. Filamentation of the fast electron beam has also been observed in a number of other experiments [8.32], although the real origin of such filamentation really still remain an open question, partially because of the inability of the computational models that are currently available to fully simulate the experimental conditions. Filamentation has been shown to be important in the beam transport between the gold end wall and the fuel plasma in the cone-core gap of the 3D simulations of Honrubia of the HiPER baseline target design. Such simulations also showed how, in those conditions, most of the fast electron beam is prevented to cross the density gap at the cone-wall plasma interface, and therefore cannot reach the compressed core. This happens both because of the (filamented) self induced magnetic field at the interface, and because of the charge separation at the gap.

Experiments to explore the transport physics between the cone-core gap are essential in the risk reduction period. Such experiments require a cylindrical implosion of a deuterium filled capsule and different cone-diagnostic foil distances. A concerted design effort is needed to match the density and temperature conditions of the cone-core gap in the baseline design with those generated in the compressed plasma of the cylindrical implosion. It will make it possible to benchmark hybrid-PIC modelling.

8.7 Transition from the Ohmic to drag-heating regimes.

In the HiPER facility, the required high-intensity laser energy greatly exceeds the energy available on current laser systems around the world. It is therefore important that to test the understanding of the basic physics of laser-plasma interactions at higher energies before the high-powered laser required by the HiPER project are built.

From a theoretical standpoint, one expects a significant rise in background electron temperature with the move from the currently available lower energy regime into the required higher energy regime. Theoretical modelling and experimental results indicate we are increasingly able to understand the basic physics at lower energies. There the resistivity of the background plasma plays a strong role in determining how the background responds to the fast electron currents because the electric (and hence by induction magnetic) fields produced are heavily dependent on the interplay between background electron motion and the fast electron current. We are able to estimate the background electron temperature and the role of the fields in solid targets [8.36-39], though the modelling is hampered somewhat by the need to include solid-state physics at low temperatures. Experiments have also been performed by propagating the fast electron beam in foam targets [8.40,41]. Here higher background temperatures are expected because of the lower density of the material and indeed in this regime it was found that fast electron penetration showed a scaling in agreement with Spitzer's law for plasma resistivity, thus overcoming the need for including solid state description of resistivity. Such result may give some indication towards scaling to higher material temperatures.

At higher energies, the models predict background plasma temperatures become so high that the electron transport enters a different regime, in which resistivity can no longer lead to significant slowing of the fast electrons [8.42]. It must be stressed that one-dimensional Vlasov-Fokker-Planck simulations now underway indicate that the propagation of the fast electron current is not hindered in this regime, but this study needs to be extended to higher dimensions in this design phase, since beam-plasma instabilities may give rise to anomalous resistivity when the background density approaches the fast electron beam density [8.43]. Equally, it will be important to experimentally determine how the fast electron motion is affected by electromagnetic fields and indeed the interplay between the fields and the beam to complement the numerical modelling.

It is interesting to note that this expected change in propagation distance means that the gold end wall can be thicker than that needed to prevent shock breakout. In the Osaka experiments that thickness was 5 μm in total. This relaxation is fortunate because the total number of electrons in the HiPER ignition beam will exceed the available number in this thickness of gold (assuming a 40 μm focal spot) and the electron beam must be drawn from the return current largely supplied from this plasma. Experiments are needed to confirm the optimisation of the end wall thickness in the baseline design.

8.8 Collective Stopping

Collisional effects are thought to play a secondary role in determining the penetration range and the energy deposition of fast electron with respect to electromagnetic (collective) effects. Nevertheless, they are generally not negligible and should be carefully considered. Until now there is no experimental measurements supporting the theoretical models for stopping power of fast electrons nor in the compressed fuel (very dense and hot mixture of DT) nor for warm dense matter states.

A series of experiments devoted to measuring the stopping power of warm strongly compressed matter (e.g. by using laser-driven shocks) becomes now possible in European laser facilities which couple long (ns) and short laser beams respectively for compression (shock generation) and for the generation of the fast electron beam or proton beams. Such measurements should indeed be done both in the framework of electron-driven fast ignition and for the proton-driven fast ignition approach. The main difference consists in the fact that trajectory of (massive) protons can be assumed to be straight, as opposed to those of (light) electrons which suffer from straggling effect. Such experiments should be performed during the HiPER preparatory phase, in order to validate existing models.

An aspect of particular concern is the correlation effects on the stopping power, i.e. the fact that in a very dense beam the particles interact with each other. Until now there have been a few theoretical works which show that indeed correlation effects may be relevant but they do not allow any definite conclusion. Also there are no experimental measurements to support such models and this needs to be corrected in the detailed design phase.

Most of the work concerns correlation effects in the stopping power of fast ions (and hence protons). Lontano et al. [8.44] studied the stopping power of an ensemble of a large number of fast heavy ions moving in a plasma with a distribution function which has a small spread both in space and in velocity (therefore a much simpler case as compared to the wide energy spectrum of laser-generated protons). Following this work, there was a proposal of for an experimental investigation [8.45] that, until now, has not been performed.

Concerning collective electron stopping effects, Deutsch et al. have studied the problem of collisional stopping power in the framework of EXISTING models for stopping power in dense plasmas [8.46]. The interaction of relativistic electrons produced by ultra-fast lasers in a strongly pre-compressed thermonuclear fuel was analytically modelled. Energy loss to target electrons was treated through binary collisions and Langmuir wave excitation. The authors discuss the possibility of correlation effects playing some role, without really addressing the subject.

Following this work, in 1999 Deutsch and Fromy published a paper specifically devoted to correlation effects [8.47]. They investigated the stopping of intense and relativistic electron beams (REB) from short-pulse lasers interacting with a pre-compressed deuterium-tritium fuel. They used the Bohr–Fermi formalism with a large impact parameter. Dynamical intrabeam correlation was treated through long-range collision with target electrons. In some cases, this was shown to be quantitatively significant and affecting the overall REB penetration in the DT fuel leading to shorter stopping ranges (although the authors conclude that this yields an easier access to fuel ignition through hot spot production, in reality the effect may either be positive or negative depending on the specific parameters).

Finally, in 2001, Mima and Lontano also addressed the problem of correlation effects in fast electron stopping power [8.48] using a simple model which neglects straggling and relativistic effects. It is clear that the theoretical studies presented in the literature do not allow any conclusions to be drawn, not only on the relevance of correlation effects, but also on whether play an important role or not.

It must also be stressed that, apart from the occurrence of straggling, another main difference between a relativistic fast electron beam and a beam of energetic protons arises from the fact that the divergence, the energy spread (and the mutual Coulomb repulsion) of the particles introduces a finite decorrelation time, thereby limiting the importance of correlation effects in the stopping power. However such decorrelation is much less important for electrons because, due to the relativistic time effect, the real interaction time for electrons will be expanded with respect to (non-relativistic) ion beams. Therefore correlation effects may be much more important for electrons. However they might be fairly important for protons too due to the very high brightness (large number, short duration, laminar flow) of laser-generated proton beams.

8.9 Whole beam self-focusing.

Whole beam self focusing of the incident high-intensity laser beam has been studied at Osaka University in experiments using a 50 TW laser pulse interacting with a 100 μm scale-length preformed plasma [8.4]. Three separate propagation modes were identified: (a) filamentation that occurred when the laser pulse was focused onto the original target surface position (b) whole beam self focusing that occurred when the focus was placed at the critical surface and (c) stimulated Raman forward scatter that occurred when the laser pulse was focused into the coronal plasma.

The interesting feature of the whole beam self-focusing channel mode is that it forms a natural "cone" shape in the preformed plasma, as illustrated in Figure 8.2. One potential difficulty is that the leading edge of the laser pulse itself self-focuses to a much higher $I\lambda^2$, thereby generating electrons with a larger kinetic energy than required for fast ignition. On the other hand, preliminary evidence from Osaka University is that electron spectrum (measured at the chamber wall) does not change when this process occurs – suggesting that the laser pulse interacts primarily with the channel walls [8.49].

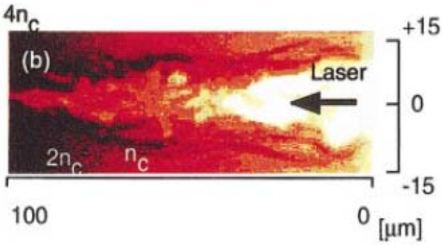

Figure 8.2. Ion density map at 1.1 ps after the start of the laser pulse from a 2D PIC simulation, indicating whole beam self-focusing into overdense regions close to the target surface. From reference [8.4].

The experiments need to compare energy transport results obtained for solid density targets with those generated through the whole beam self-focusing effect with the preformed plasma. These experiments can be performed on Vulcan, LULI 2000 and PETAL. They will be the first investigation of fast ignition relevant conditions for this process, i.e. the correct $I\lambda^2$ and pulse duration. The experiments will allow the characterisation of both the properties of the electron beam (whether self-focusing of the laser pulse allows the intensity to become too high) as well as its subsequent propagation in the solid density plasma (i.e. conversion efficiency and collimation). It will also help determine if cavitation of the channel becomes important (since ion motion can occur on this timescale) and whether beam pointing via the hosing instability becomes an issue.

8.10 Colour and Z scaling.

The colour of the PW heating pulse for HiPER is a real constraint on the final design of the laser system. Estimates from the ponderomotive scaling of the laser pulse indicate that the laser pulse may have to be frequency converted to second harmonic in order to reduce the kinetic energy of the fast electrons so as to be within the stopping range of the dense DT fuel in the hot spot [8.9] (although it is clear that the modelling did not take into account the whole complexity of fast electron transport and may therefore be not quantitatively correct).

However, recent particle-in-cell simulations have indicated that the fast electron energy in multiple ps-duration laser pulses can be lower than the ponderomotive potential energy of the laser pulse by a significant fraction [8.50]. This is caused by the acceleration of the electron bunch occurring in a time-dependent manner – hole-boring in preformed plasma with initial large density scalelength occurs very quickly such that after a short period of time (half a picosecond) the scalelength is less than the wavelength of the laser pulse. The acceleration distance is reduced by the relativistic increase in the electron mass. The kinetic energy that the electrons acquire is then reduced by a factor $(\gamma n_c / n_s)^{1/2}$, where $\gamma = (1+a^2/2)^{1/2}$, a is the normalised vector potential, n_c is the critical density and n_s is the density in the skin depth.

The effect may be good news for fast ignition – the PW laser pulse interacts with the Au end wall. Detailed studies of energy transport in high Z materials with 5-ps duration PW laser pulses are needed to confirm this new prediction. Again the effect of prepulse and plasma scalelength in front of the Au foil is an issue which needs to be addressed.

8.11 Proton / ion driven FI scaling experiments.

The production of collimated multi-MeV proton and ion beams from solid targets irradiated by ultraintense lasers has continued to attract considerable interest since the pioneering work done on both the VULCAN and the Nova PW laser facilities. The possibility of using such a proton beam as a ignitor beam (i.e. Proton Fast Ignition (PFI)) was first suggested by Roth *et al.* [8.51], and the same authors have also published a more extensive article on this matter [8.52].

There are a number of issues which affect the feasibility of PFI. Firstly, and foremost, there is the matter of energetics. The most detailed theoretical study of the heating of the compressed fuel by a proton beam was done by Temporal *et al.* [8.53]. Their reference case suggested that a minimum of 26 kJ of proton energy was required for ignition. The highest conversion efficiency observed experimentally is 12% [8.54]. On this basis around 200 kJ of short-pulse laser energy is required. This estimate makes it unlikely that PFI ignition experiments are possible on HIPER with a specification of 70 kJ of short-pulse laser energy.

However it is not inconceivable that the ignition energy could be revised downward, and that the conversion efficiency might be revised upward. In the study of Temporal *et al.*, it was noted that if the proton energy spectrum could be controlled then the proton energy required for ignition could be reduced to 10 kJ. Considerable progress has been made in the field of spectral control [8.55,56], and improving conversion efficiency [8.57]. Given the rapid progress being made in the field of ultra-intense laser-plasma interactions, the factor of two improvements required to change the prospects of PFI on HIPER are very much possible.

Other issues include the focussing of the proton beam, and the survival of the proton source during fuel compression. A great deal of experimental and theoretical work has been done on the focussing of the proton beam, and it seems quite likely that it will be possible to focus down to spot sizes of 10μm (currently 50 μm has been demonstrated experimentally). Simulations have also shown that a protective shield can be used to keep the source foil intact despite the intense flux of x-ray radiation that is produced during fuel compression.

In summary, current estimates suggest that PFI ignition experiments on HIPER are unlikely with 70-100 kJ of short-pulse laser energy. However, this estimate could change completely over the next few years. Conversion efficiency and ignition energy requirements need to be studied more extensively. Even if PFI is eventually regarded as not being a primary objective of HIPER, it should still be recognized that HIPER could be invaluable to PFI research.

8.12 Two stream instability – ion heating.

High ion temperatures (that exceed the background electron temperatures) have been observed in PW laser-solid interaction with deuterated plastic targets, as observed by neutron spectroscopy [8.58]. The heated layer were confined to a small region close to the front of the target and this was confirmed by placing thin layers of ordinary plastic of increasing thickness over the target and observing a reduction in both neutron yield and signal width (which are both related to the ion temperature). While the amount of energy transferred to the ion population was small (~1%) it does suggest the development of a new plasma instability that cascades the laser energy to the ion population without significantly heating the background plasma. Further measurements since then have confirmed that this process is highly non-linear and the experiments were just on the intensity threshold for the observation of this effect.

It has been proposed that the preferential heating of the ions observed in the original experiment is caused by two coupled instabilities, as described by Mendonça et al. [8.59]. First, the two-stream instability occurs between the electrons accelerated into the target by the fast electrons induced by the laser-plasma interaction and the electron return current provided by the background electrons in the target. This drives up large amplitude electrostatic waves that themselves become modulationally unstable, decaying resonantly into ion-acoustic waves. These ion acoustic waves are heavily damped, leading to ion heating without significant electron heating (because the electrons support high frequency plasma oscillations that are not significantly affected by collisions). The measurements have been reproduced using hybrid-PIC simulations, but some caution is needed in interpreting these results due to numerical heating effects in the code.

The experiments do suggest an alternative approach to hot spark formation in fast ignition where one relies on this instability to heat the core rather than collisions. This might be achieved by using a higher intensity picosecond laser pulse, providing that this is compatible with the growth rate of the coupled instability in the deuterium-tritium fuel.

Indeed, Mendonça et al. have proposed this mechanism as an explanation for the coupling to the ion population in the Osaka University cone-shell implosion experiments [8.59]. They suggest that this mechanism is responsible for the heating on the edge of the compressed core in those experiments, where the lower plasma density matched the growth rate of the instability. Since it is of the utmost importance to identify the underlying plasma physics processes responsible for ion heating in these implosions, additional shots need to be undertaken on Vulcan PW (where the neutron spectrometer is located) in the detailed design phase to further elucidate the physics of this mechanism. If successful, they should inform experiments on higher energy PW facilities (e.g. PETAL) as a precursor to HiPER experiments. Their aim needs to be to confirm whether the HiPER PW beamlines should have the capability of higher intensity (i.e. shorter ps) pulse durations to target for hot spark formation.

8.13 Hole boring.

Much of this risk reduction exercise has concentrated on energy transport experiments relevant to cone-shell implosions, as these targets appear to circumvent many of the plasma physics problems associated with hole-boring in a long underdense coronal plasma (as suggested in the original fast ignition paper). These problems appear formidable – both the fire-hose and filamentation instabilities have been observed with electron beam propagation in plasmas whose background density is comparable to the beam density [8.60].

Nevertheless, one should not rule out this possibility, particularly given the knowledge base of assembling high quality DT ice layers in full spherically symmetric capsules. Experiments can be envisaged on Vulcan, LULI and PETAL to test the integrated approach. It should be noted that the OMEGA laser facility in the United States plan to use a combination of high intensity laser pulses for their integrated fast ignition experimental campaign to study this effect. If this approach is found to be practical on the OMEGA facility, then the HiPER facility design should have the capability of combining a spherical symmetry irradiation with the delivery of 100 ps / 10 ps hole boring / ignition pulses to target.

8.14 Alternative geometries

The first cone-guided compression experiment for fast ignition was conducted by a UK-Japan team on the Vulcan laser facility in 1999 [8.61]. In that experiment a plastic foil, containing a deuterated plastic signature layer, was driven down the inside of the cone by the nanosecond duration laser pulse. At stagnation, the short pulse was fired into the apex of the cone and an increased neutron signal was observed for the first time. That particular closed geometry was chosen by the team because the Vulcan laser was not able to deliver sufficient energy to target to generate compressed densities above a few gcm^{-3}.

Since then, extensive numerical design work has been carried out at Sandia National Laboratory on hemispherical target designs using a gold glide plane. A summary of that work is given by Slutz et al. [8.62]. The experimental work started with the Z machine and were indirectly driven by X-rays generated in a wire array Z-pinch. The Z machine stores 11.5 MJ of electric energy in its capacitor banks and was able to generate more than 2 MJ of soft X-rays. The capsule implosions were backlit using 6.7 keV iron backlighting target foil. Remarkably good agreement between a series of radiographs of the implosions and synthetic images generated from the radiation hydrodynamics code. The simulations have indicated that compressed densities of 130 gcm^{-3} and areal densities of 0.84 gcm^{-2} can be achieved. The simulations confirm that a wide parameter space is available to optimise the compressed density in hemispherical and “ice-cream” cone-guided compression geometries.

One notices immediately that the LIL-PETAL laser facility has a 4-beam cluster available for hydrodynamics experiments with a total drive energy of 40 kJ of UV light. That is equivalent to the full specification of HiPER over the full 2π. This provides a unique facility to test the hydrodynamics of the HiPER baseline implosions and allows the interesting possibility to be asked as to whether the HiPER facility could or should be reconfigured at a later stage into a single sided cluster arrangement to drive implosions equivalent to 3 MJ of direct drive energy. That is a truly exciting possibility.

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