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The HiPER project for inertial confinement fusion and some experimental results on advanced ignition schemes

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Abstract
This paper presents the goals and some of the results of experiments conducted within the Working Package 10 (Fusion Experimental Programme) of the HiPER Project. These experiments concern the study of the physics connected to 'advanced ignition schemes', i.e. the fast ignition and the shock ignition approaches to inertial fusion. Such schemes are aimed at achieving a higher gain, as compared with the classical approach which is used in NIF, as required for future reactors, and make fusion possible with smaller facilities.

In particular, a series of experiments related to fast ignition were performed at the RAL (UK) and LULI (France) Laboratories and studied the propagation of fast electrons (created by a short-pulse ultra-high-intensity beam) in compressed matter, created either by cylindrical implosions or by compression of planar targets by (planar) laser-driven shock waves. A more recent experiment was performed at PALS and investigated the laser–plasma coupling in the 10^{16} W cm^{-2} intensity regime of interest for shock ignition.

(Some figures may appear in colour only in the online journal)

1. Introduction

In 2006 the HiPER Project (European High Power laser Energy Research facility) was included by ESFRI (the European Strategy Forum on Research Infrastructures) in the European roadmap for Research Infrastructures [1–3]. The HiPER Project concerns the study, and the following realization, of a high-energy laser facility for studies on the production of energy via inertial confinement fusion. HiPER will represent a possible follow-up to the National Ignition Facility (NIF) [4–6]. The biggest laser in the world located at the Lawrence Livermore National Lab (LLNL) in the US has recently started the NIC, National Ignition Campaign, aimed at demonstrating the scientific feasibility of nuclear fusion by the end of 2012. This paper presents the goals and some of the results of experiments conducted within the Working Package 10 (Fusion Experimental Programme) of the HiPER Project. These experiments concern the study of the physics connected to 'advanced ignition schemes', i.e. the fast ignition and the shock ignition approaches to inertial fusion. Such schemes are aimed at achieving a higher gain, as compared with the classical approach which is used in NIF. This is required for future reactors and will make fusion possible with smaller facilities.

In particular, a series of experiments related to fast ignition were performed at the RAL (UK) and LULI (France) Laboratories and studied the propagation of fast electrons (produced by a short-pulse ultra-high-intensity beam) in compressed matter, created either by cylindrical implosions or by compression of planar targets by (planar) laser-driven shock waves.

A more recent experiment was performed at PALS and investigated the laser–plasma coupling at intensities of the order of 10^{16} W cm^{-2}, the regime of interest for shock ignition. This studied in particular the role of parametric instabilities in the extended plasma corona, the ability to create strong shocks (in the hundreds of MBar range) and the role of fast electrons produced during the interaction.

2. WP10, the 'Fusion Experimental Programme'

The National Ignition Facility (NIF) has recently started the Ignition Campaign. By the end of 2012 they should demonstrate the scientific feasibility of nuclear fusion.

The goals of the HiPER Project are to study the follow-up to NIF ignition and prepare the way to future fusion reactors. This, of course, includes all the 'more technical' issues such as (i) the study of high-energy high-repetition laser drivers, (ii) the study of target mass production, injection, tracking and position at high-repetition frequency, (iii) studies on chamber design, material resistance, material activation, etc, at high radiation fluxes, etc.

However, fusion does not only involve technological problems. Before that, there is also a very important physical problem: NIF ignition will indeed be based on indirect drive (ID), which does not seem to be compatible with the requirements of future fusion reactors. Indeed ID requires (i) complicated targets, (ii) massive targets injecting a lot of high-Z materials in the chamber, and above all (iii) it is intrinsically a low gain approach due to the intermediate step of x-ray conversion.

In addition, ID poses several 'political' problems connected to proliferation issues and classification.

Therefore we need to investigate the direct drive (DD) approach in order to achieve higher gains and allow for simpler reactor schemes. Unfortunately the scientific problems connected to DD drive are today not solved. Pursuing the DD approach implies studying (i) the hydrodynamics of target implosions and methods for smoothing of non- uniformities, and (ii) the possibility of realizing 'advanced ignition' schemes which may guarantee even higher gains while relaxing the constraints on target and irradiation uniformity (and also make

Table 1. Experiments performed in the European Laser Facility within HiPER time slots.

	LULI	RAL	PALS
2008	D Batani Fast-electron transport in shock-compressed targets	M Koenig, D Batani Fast-electron transport in cylindrical targets	J Davies Magnetic field in laser ablation of solids
	P Norreys Dependence of absorption on density scale length		G Tallents Measurements of ablation rates of plastic targets heated in the regime relevant to ICF
2009	P Norreys Characterization of electron source at 2ω	P Norreys, J Davies Laser channelling for fast ignition	L Gizzi Development of a x-ray imaging technique
2010	J Santos Fast-electron transport in 1D counter-propagative-shock compressed targets—Part 2	D Neely, J Wolowski, P Norreys Characterization of proton source for proton driven fast ignition/controlling fast-electron divergence using two laser beams	D Batani Laser coupling in the shock ignition regime
2011	A Morace Study of cone target perturbation by shock and related fast-electron generation and transport in warm dense matter		P Koester, J Badziak Study of laser coupling in the SI-relevant regime. The effect of preformed plasma on a laser-driven shock produced in a planar target under the conditions relevant to shock ignition

fusion possible with smaller facilities). The two advanced ignition schemes, which have been proposed in the recent past, are (1) fast ignition [7] and (2) shock ignition [8, 9].

Within this context, the goals (and the problems) of WP10, as well as of other WPs, have been the following.

(1) To perform experiments addressing relevant questions on the physics related to ICF, taking into account the limitations of existing laser systems in Europe (and also across the world).
(2) To build a scientific community in Europe working not just on 'laser plasmas' but also on ICF-oriented issues. In particular, learn together how to realize lengthy and difficult, programmatic experiments.
(3) To address experimental issues where we have little competencies (or have lost them), i.e. hydrodynamics, instabilities, implosions, etc.
(4) To prepare collaborations with US and Japan, and realize the first collaborative experiments.
(5) To make the European community 'credible' in face of the international community, while maintaining the European leadership where we have it (i.e. ultra-high-intensity laser–plasma interactions).

Several experiments have been performed in the framework of the HiPER programme within 'HiPER slots' at LULI, RAL, PALS, the laser laboratories, which have endorsed the HiPER project. These are listed in table 1 (see also [10, 16]).

Not all the experiments have really followed a programmatic approach (the research conducted by the laser–plasma community in Europe has always mainly been 'curiosity-driven' and therefore sometimes we must 'learn' how to work in a different way). A significant case of more 'programmatic' research has been the series of experiments related to fast-electron transport performed at RAL (UK) and LULI (France), which studied the propagation of fast electrons (produced by a short-pulse ultra-high-intensity beam) in compressed matter, created either by cylindrical implosions or by compression of planar targets by (planar) laser-driven shock waves. These will be described in section 4. Most of the work which has been performed has been relevant for the study of fast ignition, simply because shock ignition is a more recent approach. However, experiments on SI have also started (as described in section 4).

It is also important to note that, apart from experiments performed within HiPER time slots, several other experiments of interest to FI and SI have been performed. In this case the synergy with the National research programmes, and with the EU 'Laserlab' infrastructure has been positive and essential.

3. Experiments on fast-electron propagation in compressed materials

A programmatic effort was performed within WP10 in order to study the propagation of fast electrons in matter. It is indeed clear that fast-electron propagation is a key issue in order to address the feasibility of fast ignition, Indeed the fast electron must travel between n_c and more than $1000n_c$ over 200–300 μm before depositing their energy in the high-density core. The propagation of fast electrons is, of course, influenced by collisional effects (stopping power, a long known effect starting with the works of Bethe and Bloch) but also by the effects of electric and magnetic fields self generated during the propagation itself. Such fields are indeed the main factors governing the dynamics of the fast-electron beam. They depend on the resistivity of the background material, which is very different for targets, which are initially cold, and for compressed plasmas (collisional effects also change with the target state, although to a lesser extent).

Different strategies are possible for studying the fast-electron transport in dense plasmas. Of course, finally we would like to perform spherical compression experiments, which guarantee higher compression factor and higher ρr attainable (here ρ is the density of the material and r the typical target size (target radius in spherical compression experiments)). However, such spherical experiments are intrinsically integrated. Also, they do not provide any privileged axis for diagnostics.

Therefore, we used two alternative and complementary approaches. The first one was based on planar compression. Here a first ns high-energy beam was used to generate a laser-driven shock, which propagated inside the target compressing the material. The ultra-high-intensity beam was focused on the opposite side of the target to generate the fast electrons, which propagated in the compressed material. Two experiments were realized at LULI following this scheme.

The limitation of such an approach is that, as is well known, single-shock compression only allows a compression factor up to 4. Also, basically the total ρr does not change in such kinds of experiments (increased density corresponds indeed to a reduced thickness).

The second approach is based on cylindrical compression. In this case, a higher ρr is attainable and can also be tuned by varying the energy of the compression laser beams, as well as the initial density ρ_0 of the targets (e.g. using foams inside the cylindrical targets). Also, unlike spherical experiments, here the cylinder axis is naturally privileged for fast-electron transport diagnostics.

The limitation of such an approach is that the high-density region is limited to the central region with only a few tens of μm radius.

Figure 1 shows the different regimes obtained in the various experiments performed within WP10 in a (ρ, T_e) plane. It is clear that while we are still far from the typical conditions of the

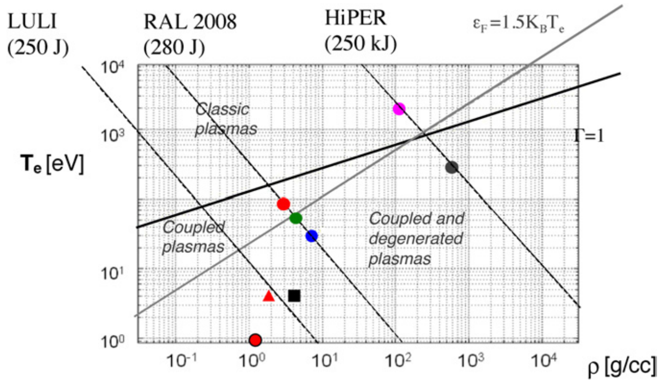

Figure 1. DT HiPER target; hot spot $\rho = 80\,\mathrm{g\,cm^{-3}}$ $T = 2.5\,\mathrm{keV}$, dense fuel shell $\rho = 400\,\mathrm{g\,cm^{-3}}$ $T = 300\,\mathrm{eV}$; RAL 2008 CH cylinders filled with foams of different initial density (at stagnation): $\rho_0 = 0.1\,\mathrm{g\,cm^{-3}}$ $\rho = 3\,\mathrm{g\,cm^{-3}}$ $T = 80\,\mathrm{eV}$, $\rho_0 = 0.3\,\mathrm{g\,cm^{-3}}$ $\rho = 4\,\mathrm{g\,cm^{-3}}$ $T = 45\,\mathrm{eV}$, $\rho_0 = 1\,\mathrm{g\,cm^{-3}}$ $\rho = 7\,\mathrm{g\,cm^{-3}}$ $T = 30\,\mathrm{eV}$; LULI 2008 and 2010 planar shock experiments with foil targets: CH foil $\rho = 2\,\mathrm{g\,cm^{-3}}$ $T = 4\,\mathrm{eV}$, Al foil $\rho = 5\,\mathrm{g\,cm^{-3}}$ $T = 4\,\mathrm{eV}$; initially cold solid target $\rho \approx 1\,\mathrm{g\,cm^{-3}}$ $T \leqslant 1\,\mathrm{eV}$.

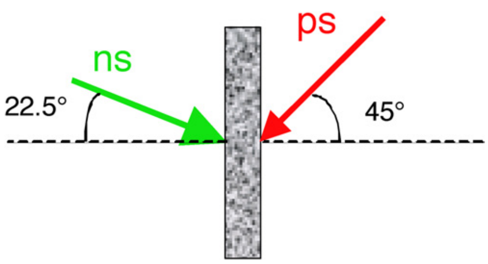

Figure 2. Scheme of the experiment at LULI2000 on fast-electron propagation in shocked targets. The target included a Kα layer to allow the diagnostics of fast-electron transport.

HiPER design, we are undertaking a systematic approach and trying to explore the physics of fast-electron propagation while getting closer and closer to the regime of direct interest for ICF (however, it must also be noted that indeed some parts of the HiPER targets during implosions will be exactly characterized by the parameters obtained in the cylindrical experiment).

The experiment on fast-electron propagation in high-density plasmas created by shock wave compression involved the University of Bordeaux (CELIA), the University of Milano-Bicocca, Italy, the University of Strathclyde, Glasgow, UK, and of course LULI [18]. The in-principle scheme of the experimental set-up and of used targets is shown in figure 2.

A brief summary of experimental results obtained in the experiment performed in 2008 is shown in figure 3. From this experiment we got three expected results and one unexpected result: (1) for the uncompressed target Kα yield is larger for Al than for CH (consistent with the presence of *electric inhibition* of fast-electron propagation in the insulator material); (2) Kα yield is larger for uncompressed Al than for compressed Al, again due to the decrease in electrical conductivity for heated Al (reduced propagation in compressed Al due to resistive effects); (3) Kα yield in compressed Al and CH is comparable (in both cases the target is in a 'warm dense matter' state, with minor differences between the two materials).

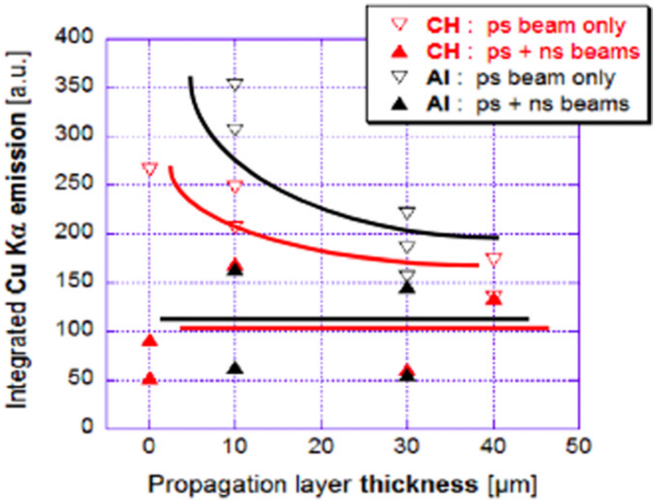

Figure 3. Summary of experimental results. Kα yield from a buried tracer layer versus thickness of the propagation layer in shocked (ps + ns) and cold targets (ps only).

The unexpected result was that Kα yield, was larger for uncompressed CH than for compressed CH. At first, this result does not seem to be compatible with the idea of electric inhibition. Indeed shock-compressed plastic has a larger electrical conductivity as compared with cold plastics, and therefore the return current induced in the material should be larger, implying a significant reduction of collective effects.

A more detailed analysis of the experimental results suggested, however, that results in uncompressed plastics were dominated by electron refluxing, i.e. the different refluxing conditions could explain why the increase in Kα yield is larger for uncompressed CH targets. Electron refluxing takes place at the rear of the targets when the fast electrons escaping in vacuum are pulled back by the strong quasi-electrostatic field created by charge separation. Flowing back into the target, fast electrons produced further Kα emission thereby increasing Kα yield. Indeed, in our experiment, the presence of the ns laser beam creates a longer plasma gradient on the target 'rear' side, thereby limiting the creation of charge separation and electric fields, and reducing, fast-electron refluxing.

In order to experimentally test the idea of refluxing at the rear side, we performed a new experiment at LULI in 2010. Here a flat foil target was shock-compressed using a long pulse (LP) beam with 250 J, 5 ns, 0.53 μm, focused at 3×10^{13} W cm^{-2} in a 400 μm focal spot (flat-top). The fast-electron beam was generated by a short-pulse (SP) beam with ~30 J, 1 ps, 1.06 μm, focused to 5×10^{18} W cm^{-2}, in a Gaussian focal spot of 10 μm (FWHM). To avoid refluxing at the rear side we always shoot the long pulse, but we injected the SP at different times, i.e. either at late times (after the shock had compressed all the target) or at early times, just before the shock entered the Al propagation layer. Preliminary results from the experiment, analysed using hybrid transport simulations (performed by Debayle and Honrubia), confirm the refluxing idea and also evidenced the fact that, under our experimental conditions, changes in resistivity between solid and compressed Al are appreciable for an incident fast-electron current density in the range $10^{10} < j_{\rm hot} < 10^{12}$ A cm^{-2}.

The experiment on fast-electron transport in cylindrically compressed matter was the result of a large collaboration involving LULI, Milano-Bicocca, CELIA, RAL, Bologna, Pisa, Roma, York, UCSD, LLNL and Madrid. It is a first example of a very large European collaboration,

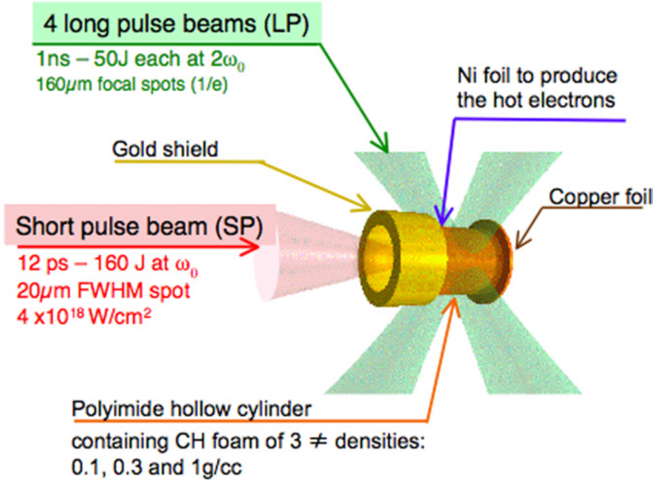

Figure 4. Scheme of the experiment on fast-electron propagation in cylindrically compressed targets done at the Rutherford Lab.

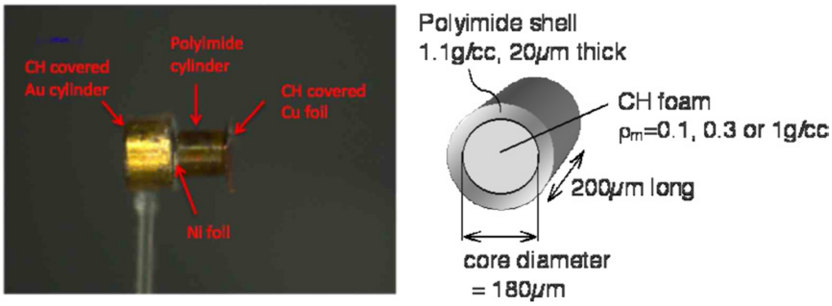

Figure 5. Example of a target used in the experiment (thanks to Ch Spindloe, M Tolley and all the RAL target prep group).

also involving the US, and of good theory/experiment interaction (by which we mean that the experiment was carefully designed in advance, similar to what takes place, e.g., in the US on larger laser facilities). The idea of the experiment is shown in figure 4 and the actual target is shown in figure 5 (produced by the RAL target prep group).

The target consisted in a polyimide shell (1.1 g cm^{-3}, 20 μm thick) filled with an acrylate foam, a plastic containing carbon, oxygen and hydrogen (indicated as 'CH foam' in the following), with density 0.1, 0.3 or 1 g cm^{-3}. The cylinder, 200 μm long and with inner diameter = 180 μm, was closed on one side with a Ni foil to produce the hot electrons, and on the other side with a copper foil producing Kα.

The ns beams were perpendicularly focused on the cylinder to drive the implosion. The ps beam was focused along the cylinder axis onto the Ni foil to generate a fast-electron beam propagating into the compressed cylinder (filled with foam) and finally reaching a plastic-covered Cu foil on the target rear. A Kα imager looking at the Kα emission from this foil was used to evaluate fast-electron propagation in the compressed target.

The experiment was divided into two phases: phase 1: the study of the compression (using proton radiography and x-ray radiography); phase 2: the study of the fast-electron transport at

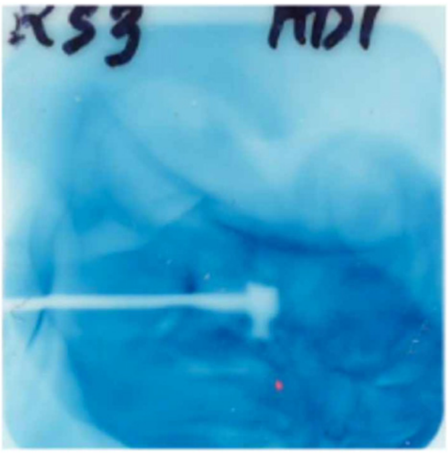

Figure 6. Example of proton radiography image from the RAL cylindrical compression experiment (target with $\rho_0 = 1\,\mathrm{g\,cm^{-3}}$).

different stages of the compression (Cu-Kα back and side imaging, Ni and Cu-Kα spectroscopy, bremsstrahlung cannon).

Figure 6 shows an example of the proton radiography image [19]. This was obtained by focusing another ps laser beam onto a foil target to produce a proton beam propagating through the cylinder. The time between the short-pulse beam producing the protons and the ns-compression beam was changed thus allowing probing of the target at different times. The images formed on RCF films allowed for an evaluation of target compression and allowed us to determine the stagnation time. Cylindrical compression is visible in figure 6 and a stagnation time $\approx$1.8 ns was recovered in agreement with predictions from hydro-simulations for $\rho_o = 1\,\mathrm{g\,cm^{-3}}$.

However, the measured cylinder diameter was much bigger than hydro-predictions. This was due to the fact that our low-energy protons (the maximum obtained proton energy was $\sim$7 MeV) slow down considerably and suffer multiply scattered in the dense core. Also plasma effects (variation of stopping power with respect to cold matter) needed to be taken into account. In conclusion, proton radiography allowed the recovery of the stagnation time but, in order to allow for an evaluation of compression, detailed simulations are needed which we performed using the Monte Carlo code (MCNPX).

A x-ray radiography [20] was also used as a diagnostics of implosions using a Kα source emitting at $h\nu \approx 4.5$ keV. Again the time between the short-pulse beam producing the x-rays and the ns-compression beam was changed thus allowing probing of the target at different times. The obtained images showed cylindrical compression and also the diameter of the x-ray transmission profiles was in fair agreement with predictions from hydro-simulations. For $\rho_o = 0.1\,\mathrm{g\,cm^{-3}}$ a stagnation time $\approx$2.5 ns was obtained, again in agreement with predictions from hydro-simulations

During the second phase of the experiment [21], the ps laser beam was shot on the Ni entrance foil, along the cylinder axis, to study the propagation of fast electrons in the compressed material. Figure 7 shows typical experimental results obtained from the Kα imager looking perpendicularly to the cylinder target (Cu-Kα fluorescence from $\rho_0 = 1\,\mathrm{g\,cm^{-3}}$ targets).

In this case, the foam was also doped by adding nano-clusters of Cu inside (CH foams with 10% mass of Cu doping). This allowed fast-electron propagation to be seen not only at

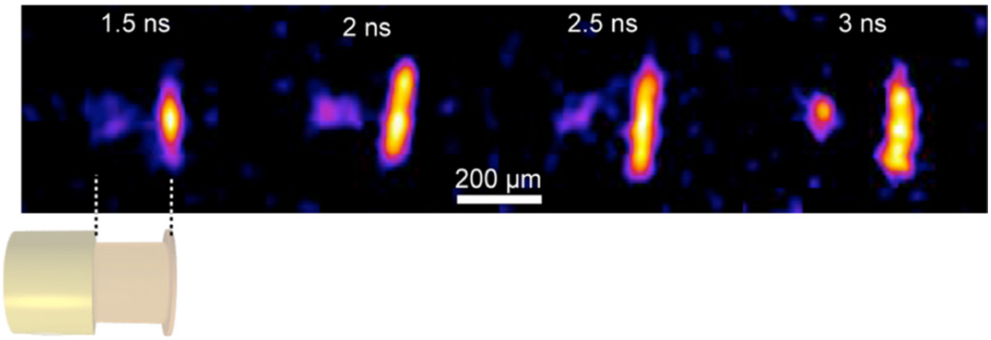

Figure 7. Typical results from the rear side Kα images (target with $\rho_0 = 1\,\mathrm{g\,cm^{-3}}$).

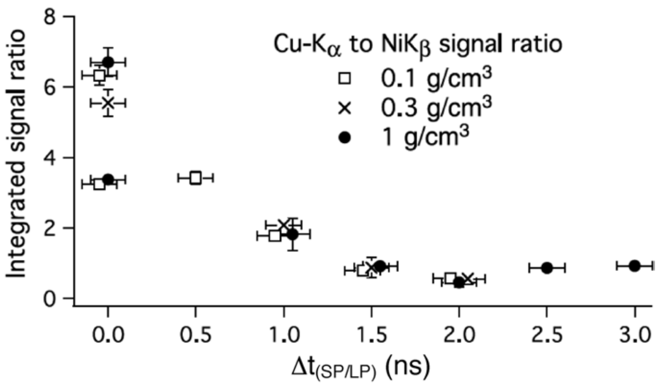

Figure 8. Experimental Kα yield versus the delay between the ns lasers (LP) and the ps beam (SP).

the Cu foil on the target rear, but also inside the compressed target. Also, in this way Cu doping of the foam allowed an independent diagnostics of implosions (the size of the compressed core corresponding to the size of the emitting region).

From figure 7, it is clear that for an initial foam density of $1\,\mathrm{g\,cm^{-3}}$ the size of the fast-electron beam measured at the rear side foil (through the Kα diagnostic) becomes larger: compression makes the beam diverge. Instead, we observed that for an initial density $0.1\,\mathrm{g\,cm^{-3}}$ compression makes the beam converge.

Figure 8 summarizes instead the graph of the experimental Kα yield versus the delay between the ns laser beams (driving the compression of the cylindrical targets) and the ps laser beam, producing the fast-electron beam. A correction of the shot-to-shot variations of the fluorescence yield from Cu (rear side tracer) was done using the signal from the Ni-Kα yields. Figure 8 clearly shows a minimum in fast-electron propagation to the rear Cu foil, i.e. the number of electrons reaching the target rear surface decreases during compression for densities, with no clear dependence on the initial foam density.

Concerning the variation of the observed size, the hybrid simulations show that the observed different behaviour is due to magnetic fields. For instance, in the case of $1\,\mathrm{g\,cm^{-3}}$, before the full compression, the density is not perturbed at the centre and the temperature is low. This produces a central high resistivity channel which, following Faraday's law, produces a collimating magnetic field that focuses the electrons towards high resistivity regions. Instead after the shock has converged the density is maximum at the centre but also the temperature. Hence there is a low resistivity on the cylinder axis and no resistive collimating magnetic field is present and the fast-electron beam diverges. The behaviour of targets with 0.1 g cm^{-3} foam is different and the collimating magnetic field is present after stagnation.

Therefore, the cylindrical compression experiment has shown that the electron beam is guided for some plasma conditions. Naturally the question arises as to whether it is possible to extend such a magnetic (resistive) collimation effect to 'real' ICF targets

4. Experiments on shock ignition

Following the novel approach of SI, WP10 dedicated its efforts to studying the physics of laser–matter interaction and laser–target coupling in an intensity regime of direct relevance to SI, which is emerging as a credible approach to fast ignition.

The first HiPER experiment was realized in 2010 (with a follow-up in 2011) and was done at PALS, which allowing one to reach intensities on target of the order of 10^{16} W cm^{-2} in a single high-energy laser beam seems to be an optimal candidate for these kinds of experiments among European laser facilities (also the laser duration at PALS indeed exactly matches that required for SI).

Several activities have been undertaken in order to prepare a proposal for an experiment to be performed at PALS on shock ignition. The idea of the experiment was to create a preplasma using the auxiliary beam at PALS (2×10^{13} W cm^{-2} for 300 ps) followed by a high intensity pulse at 2×10^{15}, 4×10^{15} or 10×10^{15} W cm^{-2}. The goal was to study the coupling of the high intensity laser through the plasma, how much light is reflected, how much couples into the target, what is the shock pressure we are able to create under such conditions. Let us note that this regime has not been much studied in the past because it was specifically avoided being known to be optimal for the growth of parametric instabilities and filamentation.

Therefore, we first characterized the preplasma (density and temperature measurement) and second we studied the interaction with the high intensity pulse (to measure backscattered light and shock pressure). Of course the characteristics of the preplasma are not identical to those produced by the implosion of a real ICF target (we would need a kJ ns laser beam with much longer duration for this) and also the shock pressure is not maintained in time since, due to the SP, a relaxation wave quickly follows.

We used two-layer targets (CH and Al). The CH layer mimics the low-Z target used for ICF pellets. The Al layer will be used since it is a standard witness for shock velocity and shock pressure measurements. Figure 9 shows a hydro-simulations (performed by Schurtz using the code CHIC) concerning the propagation of the first and the second shock in the target. It also shows the results obtained from the shock breakout diagnostics (shock chronometry) consisting in a streak camera looking at the target rear side and recording the emissivity of the shocked targets.

At the RAL cylindrical experiment, there were two different phases: (1) characterization of the preplasma and (2) the study of laser–plasma coupling (shock creation, back reflected light). In the first phase, we also used the XRL beam of PALS for diagnostics of density through XRL deflectometry [22]. We also used the energy-encoded pinhole camera (EEPHC [23]), which showed a size of the hot plasma (corresponding to the main beam) $\approx$100 μm and provided the evidence of hot electron generation.

In order to detect hot electrons we also placed a thin Cu layer between the plastic and the Al layers in the stepped targets. We also shot on the Ti/Cu layer. Observing Kα emission from the Cu layer thereby implied electrons with energy large enough to cross the Cu or Ti layer, from which we inferred an energy of about 30–50 keV.

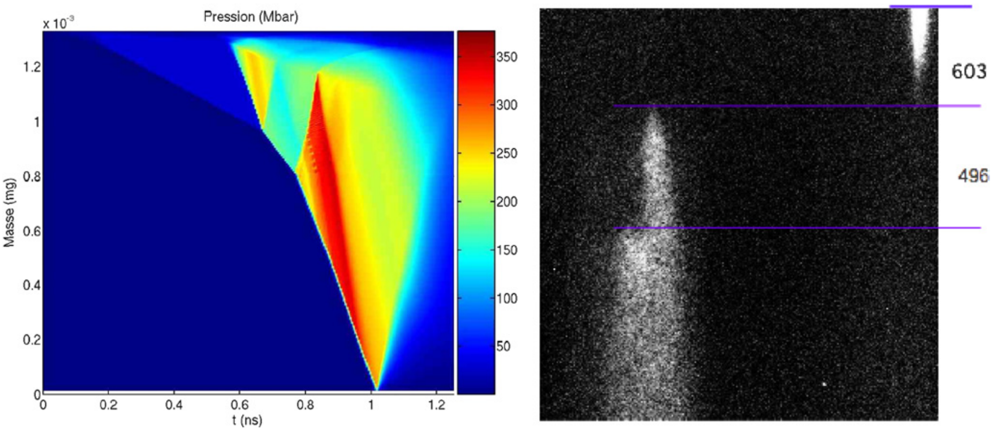

Figure 9. Left: simulation of high-pressure shock propagation under PALS conditions. Right: shock breakout from a stepped targets (on the right edge the delay between laser fiducial and the shock breakout on the target base, and the delay between shock breakout on base and on step). The shot corresponds to $E(3\omega) = 245$ J, E auxiliary beam $= 29$ J, delay 500 ps.

We also measured the backscattered light (through parametric instabilities) and obtained a low back scattering level: $\leqslant 5\%$ in all cases, which is in sharp contrast to what was measured in experiments on the Omega laser.

The pressure inferred from shock chronometry is quite low (of the order of ≈ 10 Mbar) [24]. However, 2D hydro-simulations show that the low-measured values of P corresponds to a much higher value of shock pressure at the target front. Indeed in our experiment, shock pressure undergoes a rapid decrease due to (1) 2D effects during shock propagation and (2) relaxation waves from the front side when the laser turns off.

2D simulations done with the codes CHIC and DUED show that a final pressure ≈ 10 Mbar corresponds to an initial pressure ≈ 90 Mbar. However, they also show that such a value of pressure was obtained using a beam at $I \approx 2 \times 10^{15}$ W cm^{-2} and a focal spot diameter $\approx 100\ \mu$m instead of the 'nominal' value of 10^{16} W cm^{-2}.

Due to the low level of light scattered by parametric instabilities, the two values are absolutely non-compatible with each other. Although there is still a need for an accurate characterization of absorbed laser energy, the first SI related experiments seem to suggest that in the SI intensity regime the transport mechanisms may be substantially different from those of the 'classical' ns regime used in ICF (10^{14} W cm^{-2}) with a possible large role played by hot electrons, delocalized absorption and transport, magnetic fields, etc.

5. Conclusions

Research from the WP10 groups has addressed many important topics related to FI and are beginning to address SI issues. Often, we have given a significant contribution to several subjects.

The series of experiments on fast-electron propagation in compressed materials is a particularly good example of how we should proceed in addressing physical questions connected to ICF. Indeed (1) it is programmatic (three experiments in a series: showing the capability of performing systematic studies), (2) well designed and analysed showing good interaction of experimentalists with numerical/theoretical groups, (3) it is a large collaboration (involving also US groups), and finally, (4) the work has also been useful to develop/optimize new diagnostics tools.

In Europe we now have a unique possibility to perform a full series of experiments on SI and FI, progressing from small to big lasers:

(1) experiments for 'basic physics' (and developing diagnostics) at PALS, Vulcan, LULI2000,
(2) 'directly relevant' experiments on LIL (in planar geometry) and Orion,
(3) full scale experiments on LMJ/PETAL.

In parallel we need to establish strong collaborations with the US and Japan and perform collaborative experiments on Omega/OmgaEP and Gekko/Firex.

Concerning shock ignition, this is promising but the main issues are to study the basic physics (first of all we must show that we can create a 300 Mbar shock) and study the polar direct drive option (PDD) designing a polar direct drive options for LMJ/PETAL and finally performing shock ignition demonstration experiments

Physics experiments will be needed to characterize the physics and benchmark simulation codes, possibly introducing new physical issues.

We also need to continue to study fast ignition approaching the regime of real interest for ICF as much as possible. The non-scalability of collective effects is probably one of the main issues here, which implies the need for big laser systems (ILE, Omega EP and, on a relatively short-time scale, PETAL).

In parallel, since both FI and SI imply the use of DD, we should begin to perform serious experimental work on smoothing of non-uniformities, hydro-instabilities and mitigation of instabilities.

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