Studying Ignition Schemes on European Laser Facilities

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Abstract. Demonstrating ignition and net energy gain in the near future on MJ-class laser facilities will be a major step towards determining the feasibility of Inertial Fusion Energy (IFE), in Europe as in the United States. The current status of the French Laser MégaJoule (LMJ) programme, from the laser facility construction to the indirectly-driven central ignition target design, will be presented, as well as validating experimental campaigns, conducted on the Ligne d'Intégration Laser and on LULI2000, as part of this programme. However, the viability of the IFE approach strongly depends on our ability to address the salient questions related to efficiency of the target design and laser driver performances. In the overall framework of the European HiPER project, two alternative schemes both relying on decoupling target compression and fuel heating - fast ignition (FI) and shock ignition (SI) - are currently considered. After a brief presentation of the HiPER project's objectives, FI and SI target designs will be discussed. Theoretical analysis and 2D simulations will help understanding the key unresolved issues of the two schemes. The on-going European experimental effort to demonstrate the viability of the two schemes on various laser facilities will finally be described.

1. Introduction

First experiments on the National Ignition Facility (NIF) in the United States have successfully begun in 2009. That major milestone gives confidence in demonstrating ignition and net energy gain within the next two years. Such an achievement will be a major step towards determining the feasibility of Inertial Confinement Fusion (ICF) as an option for a carbon-free and sustainable energy source. The European horizon is then dual: first trustfully demonstrate indirectly-driven laser ignition at the MJ level on the *Laser MégaJoule* in France, thanks to an improved target design and a series of validating experiments, and then coordinate all the efforts, whether theoretical, numerical, experimental or technological, towards IFE, in the framework of the ambitious ESFRI project: HiPER.

2. Current Status of the CEA ICF Programme

2.1. The LMJ laser facility

FIG.1. Views of one of the 2 completed LMJ laser halls (left) and of the target chamber and some of its surrounding mechanical support components.

The LMJ project has been launched in the 90's and is now close to its completion. Located in the Aquitaine region, at CEA/CESTA, the facility has been designed to deliver, in up to 240 laser beams (arranged in 30 bundles), up to 1.8 MJ and 550 TW (for pulse duration of ~3.5 ns) of UV light (0.35µm). The building has been commissioned end of 2008 and half of the four laser bays are now fully equipped. The vacuum chamber (10 m of diameter) has been installed in the target bay and the surrounding mechanical frameworks are currently progressively implemented (see Fig. 1). In parallel, the feasibility of the fusion target fabrication has been demonstrated: the CH capsule met specifications, a cryogenic target assembly prototype is undergoing full characterization and the main equipments (Thermal Shield Positioner and Extractor, Cryogenic Target Positioner and Cryogenic Transfer Unit) have been validated [1].

2.2. The Ignition Target Design

The main approach for achieving ignition on LMJ relies on the *indirect drive* (ID) central ignition scheme. The baseline target design (from which LMJ has been laid-out) has a DT capsule, with an uniformly germanium-doped plastic ablator, in a cylindrical gold cavity, operating at 300 eV, and leads to a net gain G~16 [2]. But, in order to explore the large LMJ parameter space, a variety of ignition targets, linked to different strategies of risk mitigation, have been recently designed. High-yield (20 MJ) fusion targets requiring no more than 1.2 MJ of laser energy (330 TW) have for instance been identified, allowing first attempts to achieve ignition in a 160-beam 2-cone configuration. They take advantage from graded-doped capsules and advanced rugby-shaped cocktail hohlraums. More precisely, the uranium-gold composite which composes these latter, allows improving the hohlraum energetics, by filling in the "holes" of their absorption spectra and thus increasing the mean Rosseland opacity [3], while their prolate-spheroid shape also improves the coupling efficiency by minimizing the cavity wall surface (and thus the wall losses) [4] and furthermore better controlling the radiation drive asymmetry on the capsule with a 2-cone fifty-fifty energy balance. As for the use, for the capsule, of a gradually doped plastic ablator, it leads to a better robustness by enhancing tolerance to initial ablator roughness and consequently reducing sensitivity to Rayleigh-Taylor instabilities [5].

2.3. The Preparatory Experimental Programme

A series of experimental campaigns has been conducted, either in France, at CEA on the *Ligne d'Intégration Laser* (LIL, the LMJ quad prototype) and at Ecole Polytechnique on LULI2000, or in the United States, at LLE on OMEGA, as part of this programme to validate the above-described design and to better ensure success in achieving ignition.

Special attention has first been paid to experiments aiming at characterizing high-energy laser interaction with plasmas to quantify risks linked to parametric instabilities, such as Stimulated Raman Scattering (SRS) and Stimulated Brillouin Scattering (SBS), and to validate the optical smoothing technique (longitudinal SSD) that will be implemented on LMJ. Two specific targets have, for the occasion, been designed: a long open 'tube', to mimic the propagation of the inner laser cone into the homogeneous low-density gas medium (where SRS can developed), and a half-hohlraum, representative of the external cone propagation at the gold-gas interface (where SBS can occur). Measurements performed on LIL with the help of an elliptical Spectralon diffuser exhibit moderate (less than 13%, i.e. within the design margins) SRS and SBS absolute reflectivies (Fig. 2) at LMJ-relevant intensities (~5 10^{14} W/cm^2) and pulse durations. The observed temporal and spectral features, signature of a complex hydrodynamics, have been successfully reproduced by simulations coupling 2D radiative-hydro computations and linear gain calculations.

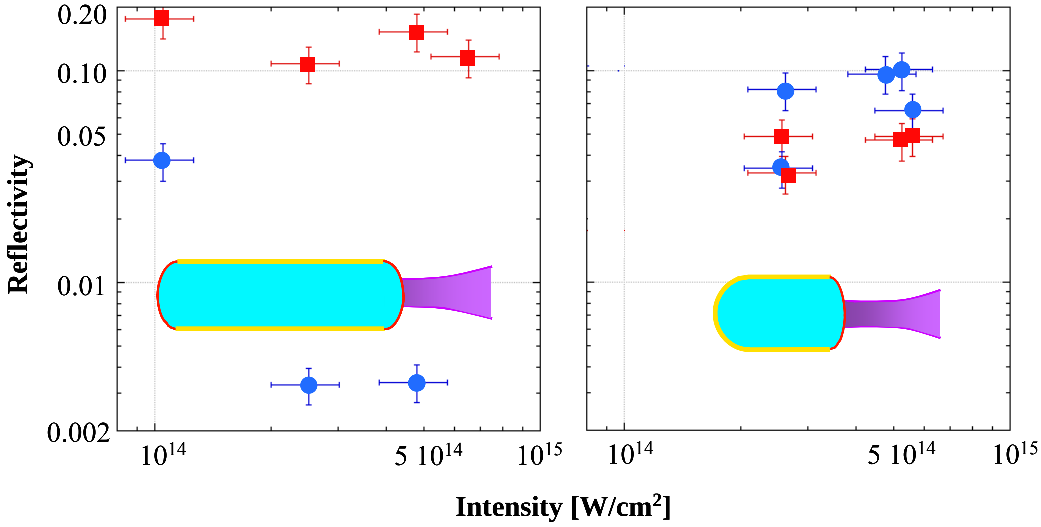

FIG. 2. SBS (right) and SRS (left) absolute reflectivities as a function of laser energy obtained on LIL using half-hohlraum and tube targets and a 14GHz phase modulation.

The concept of rugby-shaped hohlraums to enhance the x-ray drive in indirectly driven capsule implosions has recently been tested in a series of shots on OMEGA in collaboration with LLNL and MIT. When compared to cylindrical hohlraums with equivalent radius and LEH[1] aperture, the rugby-shaped hohlraums exhibit a significant (+18%) increase of the x-ray energy (Fig. 3). Such a high-performance design has led, on DD implosions, to a record neutron yield of 1.5 10^{10} [6].

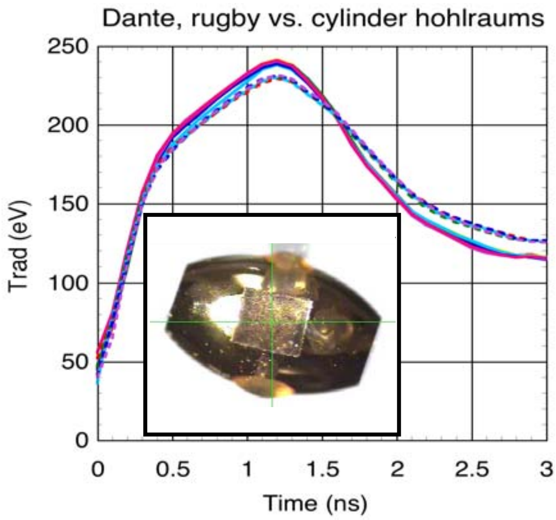

FIG.3. Measured radiation temperature histories for rugby-shaped (solid lines) and cylindrical (dotted lines) hohlraums driven with 40 beams delivering ~20 kJ in 1 ns.

In the indirect drive ignition scheme, as in the direct drive one, the central hot spot formation follows an isentropic compression of the capsule due to spherical convergence of accurately

[1] LEH means laser entrance hole.

timed shock waves (4 or 5 shocks, depending on the target design). A preliminary shock timing experiment has been recently conducted on the LIL facility on planar targets. Two VISARs[2] (at 1064 and 532 nm), for shock velocity measurements with a 1% precision, and a rear-surface self-emission 1D time-resolved imaging system have been specifically commissioned. The two first shock dynamics has been correctly reproduced.

3. The HiPER project

The HiPER project, accepted on the European roadmap in October 2006, is a proposed European High Power laser Energy Research facility dedicated to demonstrating the feasibility of laser driven fusion as a future energy source.
During the present preparatory phase (2008-2011), 26 European partners share expertise to address the main scientific issues. The corresponding physics roadmap is describing the experimental, numerical and theoretical studies to be pursued to down-select the most efficient 'alternative' (to contrast with 'nominal' ID) ignition scheme. This important mission is supported by an access program to the large-scale laser facilities currently available inside and outside Europe (USA and Japan), including PETAL, the multi-kJ PW laser facility planned to be coupled with LMJ in a few years.

Once fuel ignition demonstrated, on NIF and then on LMJ, the HiPER strategy will be to address technological bottlenecks to advance on the route to a real high-power fusion reactor device. Mainly linked to operation at high repetition rate (a few Hz), the studies that will be undertaken during this next phase will aim at developing key engineering prototypes, such as a 10 kJ beamline or systems devoted to high-precision target injection, tracking and engagement. The reactor concept itself will also be subject of a detailed analysis dealing with the choice of the chamber materials (able to support large particle and radiation fluxes), remote handling, etc.
The HiPER business case, including the final reactor design and a cost analysis, should be ready by the end of the decade before entering the construction phase. The power-to-grid demonstration is expected at the horizon of 2035-2040 after testing of the key reactor components.

4. The 'alternative' ignition scheme

In the overall framework of the European HiPER project, two 'alternative' schemes - fast ignition (FI) and shock ignition (SI) - are currently considered. They both rely on decoupling *direct drive* target compression from fuel heating (and thus ignition), either a PW-class laser-accelerated fast particle beam or a strong convergent shock. The shared baseline target is an all-DT capsule, of external radius 1044 µm and a shell thickness of 211 µm, irradiated by a shaped sequence of laser pulses: a short intense (~ 3kJ) picket, for low adiabat shaping, a shaped multi-nanosecond ~180kJ pulse, to implode the target at moderate velocity, and a precisely timed, shorter and intense ignition pulse.

A 48-beam (3 rings) irradiation scheme is, for the time being, considered for the direct drive compression phase. As irradiation non-uniformities have to be carefully control to minimize low-mode capsule perturbation they could produce, a specific 3D illumination code has been developed, the resulting mode spectrum being post-processed by 2D multimode simulations to assess the hydrodynamic target stability and the scheme robustness. It has first been shown

[2] Velocity Interferometry System for Any Reflector

that, for a not fully optimized irradiation configuration, the average rms nonuniformity remains close to 1 for moderate power imbalance (σ_{PI}) and laser pointing error (σ_{PE}), leading to a tolerable maximum capsule deformation at the internal interface of ~10 µm from peak to valley. Once the dimensions of the super-Gaussian focal spots carefully optimized, the average nonuniformity can be slightly decreased and the (σ_{PI},σ_{PE}) parameter space noticeably enlarged [7,8].

4.1. Fast ignition studies

The present nominal design assumes production of a fast and energetic electron beam by interaction of a high-energy multi-PW laser pulse with the tip of a re-entrant double gold cone. This cone is mainly used to keep a path free of plasma and allow efficient particle generation close to the compressed core. Though it breaks spherical symmetry, this can be tolerated because ignition will occur through direct particle energy deposition into the fuel, the key issue being then the cone survival.

A set of inter-connected 2D numerical (Eulerian hydrodynamic, PIC and transport) codes has been developed to properly describe such a scheme. It has exhibited the influence of the radial velocity of the fast electron beam on its magnetic collimation [9]. Unacceptable high divergence (up to 55°) has been then deduced which should be strongly improved (down to, at least, 35°) by means of optimized designs of the cone and of the spatial-temporal laser profiles (Fig. 4).

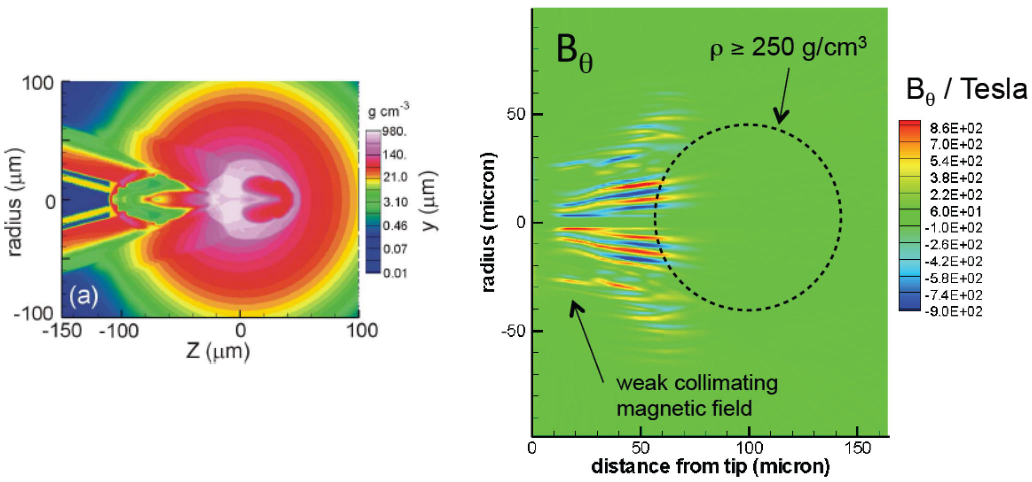

FIG.4. Density profile at the time of peak areal density (a) exhibiting cone tip damaging and (b) self-generated azimuthal magnetic field at the end of the laser pulse.

On the experimental point of view, two collaborative campaigns have been conducted on LULI2000 and on VULCAN at the Rutherford Appleton Laboratory (RAL) to study fast electron transport.

The first experiment aimed at studying the dependence of the laser energy absorption and of the electron beam divergence on plasma density scalelengths. Laser pulses (40 J in 1 ps at ω or 25 J at 2ω) were focused - with a 45° incidence angle - onto solid foils by a f /4 off-axis parabola, leading to peak irradiance on target close to 4 10^{19} Wcm^{-2} relevant for FI studies. The targets consisted of a 5 µm thick ablation (plastic) layer coated onto a propagation layer (from 10 to 50 µm of aluminium) and two fluorescence layers (10 µm of copper and 1 µm of aluminium) at the rear. Different plasma scalelengths, have been produced by either varying the duration of the laser ASE pedestal (which led to with energy contrast ranging from 3 10^{-3}, at best, to 10^{-2}, at worst) or frequency doubling. Fast electron energy transport was monitored with the help of a rather complete set of plasma diagnostics, including, at rear, an optical fibre bundle / streak camera - HISAC - and a gated optical imager - GOI - in the visible range, as well as, in the x-ray range, a well-characterized Cu Kα imager and Kα (Al & Cu) spectrometers. Transverse interferometry (using a frequency-doubled probe beam delivering a few mJ) visualized the plasma expansion and provided an estimate of the plasma scalelength. A decrease of the electron beam divergence has been clearly observed when the plasma gradients steepened (Fig. 5).

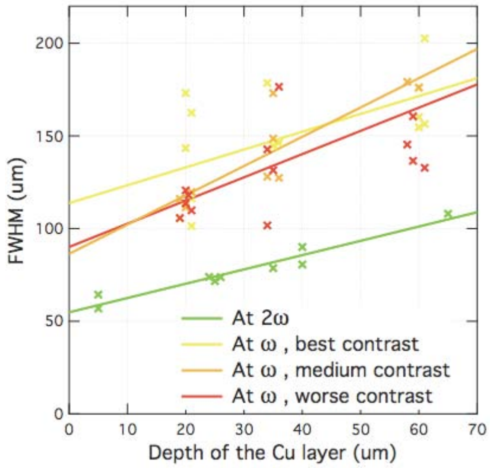

FIG. 5. Fast electron beam size - from Cu Kα imaging - as a function of the emitter depth (or the electron propagation length) for various plasma density scalelengths (or laser contrast ratios) in the LULI2000 experiment.

The RAL experiment, which provided valuable information to benchmark numerical codes, was the first European one devoted to fast electron transport in non-solid dense matter. Four long-pulse 70 J laser beams were used to cylindrically compress a plastic tube in which fast electrons, generated by an other 10 ps/160 J laser beam, propagated (Fig. 6) [10]. Hybrid simulations revealed for instance a complex interaction between the electrons and the self-induced magnetic fields. It was shown that, before stagnation, the presence of resistivity gradients leads to collimation of the fast electron beam, while, at stagnation, they disappear which allows the electron beam to diverge.

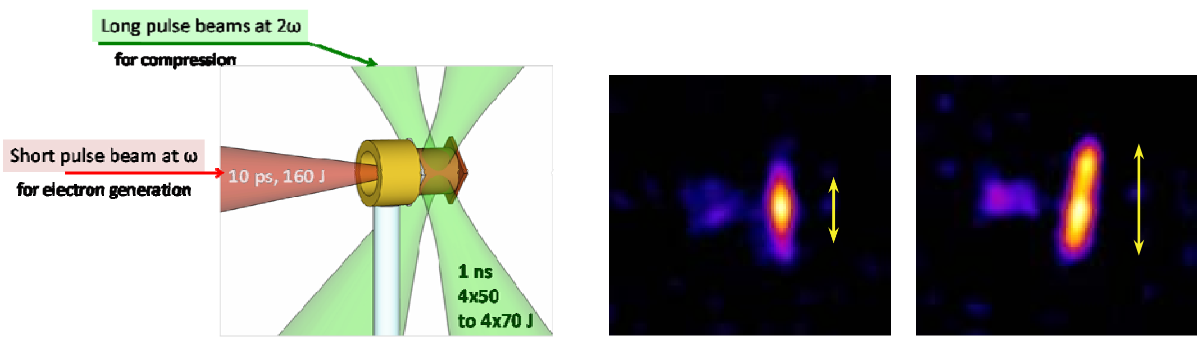

FIG. 6. Sketch of the VULCAN experimental set-up (left) and Cu Kα images showing the electron beam spreading (yellow arrows) before stagnation (center) and at the time of maximum compression (right).

4.2. Shock ignition studies

In the case of shock ignition, a properly timed strong shock is launched by a laser spike with duration of a few thousands of picoseconds. Once amplified thanks to spherical convergence and collision with an outward directed rebound shock, it can lead to high central pressures and hot spot formation. Such a situation corresponds to a nonisobaric fuel assembly which requires less energy to ignite that does the isobaric conventional central ignition one.

Theoretical modelling of the shock ignition gain curves and of the relationship between the intensity of the required laser spike and the implosion velocity has been recently conducted [11].

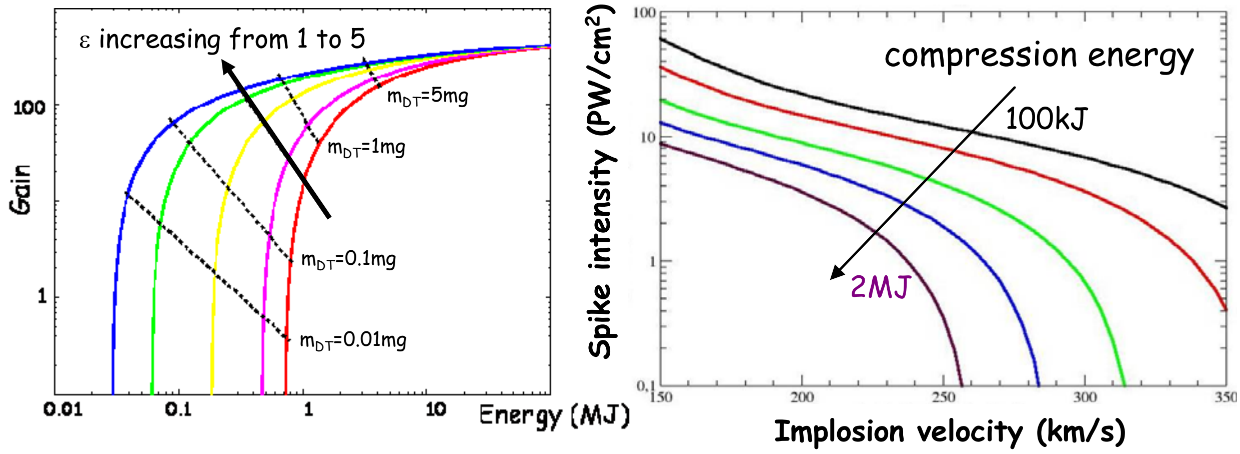

FIG. 7. (left) Fuel mass curves depending on laser energy for different values of the ratio hot spot pressure / cold shell pressure; (right) Required intensity of the ignition spike (PW/cm^2) as a function of the implosion velocity (km/s) for laser compression energies between 0.1 and 2 MJ.

The conditions for non-isobaric ignition have been revisited by using the Rosen-Lindl gain model. The gain curves are shown in the figure above (Fig. 7). The ignition threshold may be lowered when the pressure ratio increases. Gains close to 100-150 are expected at 1 MJ of laser energy and of 50-75 at 200 kJ. This provides a strong incentive for IFE demonstrators as HiPER. The ignition conditions have been shown to depend both on the spike intensity and on the implosion velocity, as this quantity is a key parameter for the rebound shock. Figure 7 presents the required spike intensity as a function of the implosion velocity for different values of the target mass and of the laser energy. These curves define a SI operating domain, limited by the hydrodynamic instabilities at high velocities and by the parametric instabilities at high intensities.

The conceptual design of shock ignition has to be confronted to experiments. Planar collaborative experiments have been conducted at PALS and on LULI2000. The second one is still under analysis. The first one has studied shock formation and laser-plasma interaction in well-characterized preformed plasmas under laser intensities in the 10^{15}-10^{16} W/cm^2 range. Shock pressures in the 10 Mbar range (lowered by 2D effects and a lack of shock sustainability, as the PALS laser pulse only lasts 300 ps) were measured

Two important issues are the susceptibility of shock ignition to the Rayleigh-Taylor instability (RTI) that may strongly perturb the shell-hot spot interface during the shell deceleration and

subsequent stagnation, and to parametric instabilities. They have been addressed through numerical simulations.
The growth of perturbations seeded by a non-isotropic compression has, for instance, been studied. Despite a strong observed RTI growth, the target ignites and produces 20 MJ of thermonuclear energy. In fact, once the ignition shock has crossed the dense shell, it converges, rebounds at target centre and diverges with a spherical shape; it then interacts, for the second time, with the dense perturbed shell and the perturbation phase gets reversed, which strongly mitigates RTI [12].
In parallel, 1D large-scale plasma fully kinetic simulations of laser-plasma interaction under SI conditions have been performed. The results demonstrate that, after a short initial burst of backscattering, a significant part of the incident laser radiation is absorbed and that the energy is transported to the dense part of the plasma by 30 keV electrons which indicate rather favourable conditions for the SI scenario [13]. The low level of the calculated reflectivities is compatible with the one observed during the PALS experiment (< 5%).

The shock ignition presents then overwhelming advantages: it does not require any complex cone-in-a-shell target nor high power CPA lasers, and its physics (laser-driven hydrodynamics) is well-known and widely experimented. Furthermore, the scheme appears much more robust than initially expected and rather efficient at moderate laser energy, which makes it very attractive for high repetition rate operation.

5. Conclusion

Current experiments and target design improvements give confidence in demonstrating indirectly-driven ignition at ~1 MJ on NIF and then LMJ. It will be a major step towards determining the feasibility of ICF as an energy source.
Europe has launched coordinated studies in the framework of the EURATOM keep-in-touch & HiPER programmes to (*i*) choose the most suitable ignition scheme, thanks to innovative experiments and 2D numerical simulations, (*ii*) improve diode-pumped solid-state laser driver and target technologies and (*iii*) design an appropriate IFE reactor. It is currently one of the most interesting places to study ICF thanks to its laser continuum and to these federating activities.

6. Acknowledgements

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7. References

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