WORK PACKAGE ENABLING RESEARCH

2016 scientific/technical report

Deadline: 31 December 2016

<table>
<thead>
<tr>
<th>Project reference number (as in Task Agreement)</th>
<th>Towards demonstration of Inertial Fusion for Energy</th>
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<tbody>
<tr>
<td>Project title (as in Task Agreement)</td>
<td>S. Jacquemot</td>
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<tr>
<td>Principal Investigator</td>
<td>CEA</td>
</tr>
<tr>
<td>Beneficiary of Principal Investigator</td>
<td>AWP15-ENR-01/CEA-02</td>
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Filename should be of the format: WPENR_AWP15_interim_report_Beneficiary-nn where Beneficiary-nn is, for example, ENEA-01.

Purpose and use of report

This compact report is to report the progress on the deliverables, to justify payment. A brief summary of the scientific highlights is also requested. While the report will be available to STAC the performance will be assessed by the PMU unless there are issues which require the advice of STAC. The mid-term evaluation of the project, where relevant, is a separate activity but can refer to these reports.

The reports should be as brief and clear as possible, referring to publications and other information for details. However there should be enough information to support statements that deliverables have been achieved. As an indication the full report should not exceed 4 pages excluding this title page. Please keep to the report format and do not attach additional information. If there are one or two particularly significant figures that are needed to demonstrate the results, these can be included in the tables.
**1. Main scientific output - summary**

In order to keep the report as short as possible, the following section gives the most recent highlights obtained by the ToIFE partners (completing the summary already presented in the MidTerm report). It has been deliberately restricted to activities not presented in section 2. More achievements are given on the project’s website: [http://web.luli.polytechnique.fr/IFE-Kit/ToIFE.htm](http://web.luli.polytechnique.fr/IFE-Kit/ToIFE.htm).

It is important to point out the high number of articles published this year (see section 3).

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**Mission 1. Acquiring new insights into the basics of ignition physics**

*Laser-Plasma Interaction* – A new theoretical study of three-wave interactions has been undertaken at RAL (CCFE) and promising results have been obtained for CBET conditions, complementary to the work done at CPhT (task 1.2.2).

*Plasma atomic physics and radiation sources* – Aluminium opacity in the warm dense regime was modelled and compared to experiments performed at LCLS by IST while modelling of interaction with CF capsule ablator dopants of radiation fields and/or particle beams has started at ULPGC (task 1.1.1). The new opacity code based on the FAC atomic physics package and developed by LIDYL was used for a study of the high-order moments of the spin-orbit energy in a multi-electron configuration [Na2016] (task 1.1.2). ROM high-order harmonics were generated up to the record 100th order on the LWS20 laser facility at MPQ, in collaboration with HAS; a clear dependence of the harmonic spectrum on the carrier-envelope phase of the laser pulse was found which is an important step toward completion of the ToIFE task (1.1.5). Uncertainties in the determination of the plasma parameters (temperature and density) by K-shell spectroscopic methods (often used to infer ICF core conditions) were also analysed by a wide US-Europe collaboration involving ULPGC (task 1.1.4) [Nagayama2016]. High-order harmonics were finally produced with the new (task 4.1) diode-pumped Yb laser at IST; the energy per harmonic pulse is sufficiently high (~5 nJ) to perform single-shot plasma probing experiments (task 1.1.6).

*Hydrodynamics* – A straightforward approach to the description of magnetized nonlocal electron transport, based on the extension of a reduced entropic model, was developed by CELIA and CEA [DelSorbo2016] (task 1.3.3).

**Mission 2. Towards demonstration of shock ignition (SI) on MJ-class laser facilities**

The preliminary experiment performed on the LIL laser facility by a collaborative LULI-CELIA-CEA team, in order to study the bipolar shock ignition scheme, was successfully analysed [publication accepted in Phys. Rev. E]; the influence of the spike laser wavelength, in presence of a well-characterized pre-plasma, was investigated at PALS by an IPPLM-CELIA-IPP.CR-CNR team; competition between 2D effects and laser-to-shock energy transfer efficiency was for instance investigated [Pisarczyk2016]; the effects of hot electrons generated by nonlinear laser-plasma interaction on the dynamics of shock ignition targets were also theoretically and numerically investigated by CELIA [Colaitis2016, LlorAisa2016] (task 2.3). The IST OSIRIS framework platform is now distributed, via an open access procedure based on a standard MoU, with ~20 European academic institutions now routinely using it (including its visualization infrastructure); an open source version will also soon be made available (task 2.2).

**Mission 3. Testing the feasibility of fast ignition (FI), impact ignition or other alternative schemes**

According to extensive PIC simulations performed by IPPLM, the protons expected to be accelerated from thin foils by target normal sheath acceleration are more energetic at short laser wavelengths. The HAS KrF laser facility, operating in the UV, was thus upgraded – especially in terms of peak intensity and contrast (thanks to nonlinear Fourier filtering and plasma mirror) – to validate this hypothesis (task 3.2.3) [Szatmari2016, Glicze2016].

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1 Update of the website is scheduled to mid-February.
### Mission 4. Developing key IFE technologies

**Diagnostics** – Thanks to an ENEA-CELIA collaboration, a careful calibration of Imaging Plates, a widely used diagnostic, has been performed [Ingenito2016, Curcio2016] (task 4.3). Absolute calibration of newly developed EBT3 and HDv2 radiochromic films from Gafchromatic™, commonly used in dosimetry, was also performed by LULI [Chen2016] (task 4.3).

**IFE materials and reactor technologies** – Femtosecond laser ablation – a simpler, faster and cleaner process than chemical synthesis – was used by UPM to produce highly concentrated silver colloidal nanoparticle solutions (task 4.4.1) while the influence of grain boundaries on radiation-induced defect evolution and on H retention at 300 K, was studied numerically and experimentally by comparing implantation of H and C ions in coarse-grained tungsten and nanostructured tungsten samples [Valles2017] (task 4.4.3). A systematic study of the thermomechanical response of a W first wall to realistic irradiation conditions (as defined in the different HiPER scenarios) was finally conducted and limitations to the use of this material for a full-scale reactor determined [Garoz2016] (task 4.4.5).

### 2. Project deliverables

Fifteen deliverables (42%) were supposed to be completed at T0+ 18 months (task 1.2.3) or at the end of 2016; 2/3 are achieved. Changes to deliverables 3.1.2 and 4.4.4 were discussed in the MidTerm report. Postponed completions are mainly due to experimental contingencies (including late scheduling and facility breakdowns) and to delays in subsequent analysis.

<table>
<thead>
<tr>
<th>Deliverable (2016 deliverables as specified in the Task Agreement)</th>
<th>Achieved: Fully/Partly/Not</th>
<th>Evidence for achievement, brief reason for partial or non-achievement</th>
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<tr>
<td>Task 1.2.3: demonstration of the relevance of isolated µm-scale targets for PIC code validation [IPP/MPQ]</td>
<td>fully</td>
<td>Single truly isolated spherical targets, levitating thanks to the Paul trap developed at LMU, were irradiated at GSI and at the Texas laser facility. The importance of full dimensionality in theoretical models was underlined [Pauw2016] and experimental laser-to-proton energy conversion efficiencies remarkably reproduced by 3D3V PIC simulations [Ostermayr2016].</td>
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<td>Task 1.2.4: comprehensive study of kinetic effects in IFE-relevant plasmas [CPhT, LULI]</td>
<td>partly additional experimental run scheduled</td>
<td>Kinetic effects are omnipresent in IFE-relevant plasmas and play a significant role in the saturation process of the laser-plasma Stimulated Raman and Brillouin Scattering instabilities. For SRS, a model, which allows modelling phenomena arising from such kinetic effects, was developed by CPhT and benchmarked against 2D PIC simulations. It can be incorporated in multi-dimensional fluid-type codes and allows computations over mm-size volumes [G. Tran et al., in preparation]. A series of bi-speckle experiments on ELFIE (LULI) demonstrated the influence of collective effects and the role of the hot electrons on the SRS threshold [Rousseaux2016]. The ELFIE (LULI) experimental campaign on “Study of anomalous electron heating produced by kinetic saturation processes of LPI’s in picosecond time scale”, scheduled in July 2016, suffered from a series of incidents (including a fire in the capacitor bank cave) and could not be completed; additional shots are scheduled in July 2017.</td>
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<td>Task 1.3.1: comprehensive study of foam smoothing effects [CELIA]</td>
<td>fully</td>
<td>A multi-scale model was developed by CELIA and CTU to simulate laser absorption in porous materials; it was</td>
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<td><strong>Task 1.4.1</strong>: comprehensive study of ion energy loss in hot plasmas</td>
<td>partly additional experimental runs required</td>
<td>implemented in the ALE hydro code PALE and validated in terms of ionization front velocity against GEKKO-XII experiments [Velechovsky 2016]. Laser energy absorption in foam plasmas, as well as induced x-ray emission, was studied by ENEA. Finally, a mitigation effect of a foam coating on the development of the Rayleigh-Taylor instability was experimentally evidenced in planar geometry on the OMEGA laser facility by a CELIA-led collaboration. PARAX and CHIC simulations demonstrated a significant laser imprint reduction, due to parametric instabilities in the foam plasma, and a consequent delay in the instability growing [Delorme2016].</td>
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<td><strong>Task 2.1</strong>: SI-dedicated proposal to apply for access on LMJ [LULI, CELIA, CCFE]</td>
<td>fully</td>
<td>A new experimental platform was developed at GSI, at the Z6 station, to measure, in hot laser-generated plasmas, energy loss of UNILAC projectile ions at velocities close to the plasma electron velocity, where the stopping power is maximum and where strong discrepancies exist between perturbative and non-perturbative stopping theories. Analysis of results from the 1st run, performed in collaboration with CELIA, indicates that a detailed treatment of strong ion-electron collisions is required to tentatively reproduce ion energy deposition. Unfortunately, even if the 2nd run confirmed this observation, a higher-than-anticipated background noise due to EMP did not allow improving the measurements' precision. However, a better in-depth knowledge of proton stopping powers in warm dense plasmas was gained thanks to the complementary experiments conducted by LULI on the ELFIE and TITAN (US) laser facilities; analysis performed in collaboration with U. Rome showed that the developed experimental platform is fully adequate to benchmark simulations in a range of temperatures (a few hundreds of eV) where theoretical approaches agree [publication pending]; regimes where theories differ (at lower temperatures) and where ion charges play a significant role (using helium ions for instance) shall be now explored. Finally, effects of partial electron degeneracy on plasma stopping powers were theoretically investigated at IPPLM [paper under preparation]. The proposal Strong shock generation by laser plasma interaction in presence or not of laser smoothing (SSD) in the context of shock ignition studies on LMJ-PETAL facility, led by LULI and CELIA, in collaboration with CNR, and Rochester University, was accepted on the LMJ-PETAL facility following the 1st call for academic access. The kick-off meeting was held the 14th of December and the 1st shots scheduled late 2018. Advanced 2D rad.-hydro simulations are ongoing; they will help improving the experimental set-up (target and laser pulse) in order to maximize the effects that the collaboration intends to maximize.</td>
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<td>Task 3.1.1: full validation of the capacitor-coil target concept for electron guiding [CELIA, LULI]</td>
<td>fully</td>
<td>Reproducible quasi-static B-field generation by laser interaction with capacitor-coil targets was demonstrated by CELIA on LULI2000, typically with a few ns duration and a 1 mm²-volume, yielding peak strengths of several hundreds of Tesla, depending on the target material. Thanks to this platform, laser-accelerated relativistic electron beam guiding was thus attempted and efficiently demonstrated for the first time in planar geometry. The concept was ultimately validated in spherical geometry at ILE (Japan); Cu-doped small beads were compressed by 6 GEKKO-XII laser beams up to 8 g/cc before being overheated by the LFEX PW laser beam to 3 keV (according to an spectroscopic analysis) only in the presence of an external B field.</td>
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<td>Task 3.1.2: validation at low energy of the Inverse Conical Taper concept [CCFE]</td>
<td>partly</td>
<td>An experiment was undertaken on the Vulcan PW laser facility (CCFE) to test the ICT concept. Analysis is still in progress.</td>
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<td>Task 3.2.1: proof of principle of laser-to-ion conversion efficiencies above 10% [IPPLM, IPP.CR, CCFE, IPP/MPQ]</td>
<td>fully</td>
<td>Conversion efficiencies as high as ~5% were measured by MPQ at the Texas PW laser facility with isolated spherical targets. The PIC code designed to numerically investigate the LICPA approach at IPPLM was upgraded to allow for advanced cavity geometries; preliminary simulations indicate instantaneous conversion efficiencies as high as 16% [publication to be submitted]. Proton acceleration from H-ice plasmas was successfully performed on ELFIE (LULI), in collaboration with HZDR, where were achieved proton energies higher than the ones obtained from solid targets of equivalent thickness, and at PALS (IPP.CR), in collaboration with IPPLM, where a collimated 30J/1mC proton beam was generated. Double-pulse irradiation of thin foils on the VULCAN PW laser facilities (CCFE) also exhibited very high (~15%) conversion efficiencies. Finally, a novel mechanism – low-density shock acceleration – which allows delivering beams with a better collimation than TNSA ², thus a higher fluence, was recently demonstrated by LULI on the ELFIE and TITAN laser facilities.</td>
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<td>Task 3.3: demonstrating macro-particle velocities above 100km/s [IPPLM, IPP.CR]</td>
<td>fully</td>
<td>Using the LICPA scheme proposed by IPPLM, Al macro-particle (of several µg) were accelerated at PALS (IPP.CR) to velocities of ~135 km/s with an efficiency of ~22%, for laser energy of only ~200J (published in 2015).</td>
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<td>Task 3.4: clear evidence of p-B fusion reactions [ENEA, IPPLM, LULI, IPP.CR]</td>
<td>partly</td>
<td>α particles from p-B reactions (up to 10⁹ per steradian) have been evidenced by different approaches on various facilities [ABC, PALS, ELFIE and ECLIPSE] thanks to an important collaborative effort, involving ENEA, IPP.CR, LULI, CELIA and IPPLM [publication under preparation].</td>
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² Target Normal Sheath Acceleration
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<tr>
<td>Task 4.1: demonstrating ultra-short capabilities of the OPCPA technology [IST]</td>
<td>partly completion of the task was delayed to test the capabilities of the pump source to produce high-order harmonics (task 1.1.6)</td>
<td>All the key elements for an ultra-broadband OPCPA have been developed at IST; the pump - a diode-pumped 2-stage amplifier - was successfully tested at 1 Hz and is currently upgraded to 100 mJ / 10 Hz; the seed - a white-light continuum - was demonstrated and characterized [Imran2016]; its bandwidth was shown to support ~10 fs pulses; parametric amplification over the 700-900 nm range was finally obtained with good spectral quality.</td>
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<td>Task 4.2: improved DT EOS with inclusion of phase transitions [CIEMAT]</td>
<td>fully</td>
<td>A new model was implemented by UPM in the ab initio molecular dynamics SIESTA code to allow studying the mechanical properties of the cryogenic fuel. Systems composed of H, D, T and/or Be (a mixture that could happen if the target ablator is entering the fuel due to hydro. instabilities) were studied; phase transitions below a few GPa were for instance shown to induce variations in the bulk modulus and sound velocity [Guerrero2016].</td>
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<tr>
<td>Task 4.3: quantification of electromagnetic pulses produced by laser-matter interaction [ENEA, IPP.CR]</td>
<td>fully even if analysis of the latest run on VULCAN (using levitated targets) will only be completed next year</td>
<td>EMP measurements have been done on ABC (ENEA), PALS (IPP.CR) and VULCAN (CCFE) by use of antennas, electric field sensors, polaro-interferometry or electro-optic probes [Consoli2016]. Correlations with laser-target parameters were investigated, the analysis being supported by PIC simulations. A 3D multi-scale multi-physics suite of numerical codes was developed by a CELIA-CEA team to identify the EMP generation mechanisms and to define new mitigation concepts. Experimental campaigns dedicated to validation of these concepts were conducted on EQUINOX (CEA) in the fs regime and on LULI2000 in the ps one. Finally, a one-day workshop on “laser-driven electromagnetic pulses” was held in March 2016 in Bordeaux and gathered various European laboratories, including ToiFE partners: CELIA, IPPLM, ENEA and IPP.CR; a follow-up workshop will be organized in January 2017 in Warsaw.</td>
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<td>Task 4.4.2: reproducing fusion ion bursts in the lab [IPP.GSI, IPPLM, LULI]</td>
<td>fully</td>
<td>Efficient neutron production (up to 3 (10^6) n/J, with energies up to 16 MeV) was shown to be feasible at PALS (IPP.CR) thanks to a pitcher-catcher scheme [Krasa2016]. TNSA experiments at GSI, using sub-(\mu)m thin foils and ultra-high temporal contrast laser pulses, have yielded ion beams with record energies, up to 85 MeV [Wagner2016]. Ion energy distributions – as obtained on mid-scale laser facilities – allow thus mimicking ion-matter interactions in fusion-relevant conditions and 1st experiments have been done. The propagation of MeV ions through a rarefied, magnetized or not, plasma (representative of the background atmosphere of a fusion vessel) was studied at LULI; significant energy losses were observed due to</td>
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WPENR_AWP2016 – interim report form
3. Publications/presentations

Note that, considering the low level of funding, none of the activities carried out in the framework of the ToIFE is “substantially” supported by EUROfusion. However, the following 2016 publications acknowledge the programme, among others.

[17] Ingenito F. et al., Comparative calibration of IP scanning equipment, JINST 11, C05012 (2016)
4. Managerial aspects (optional)

Reply to STAC comments/recommendations after MidTerm reviewing

“It is often unclear what was achieved as a result of the EUROfusion funding since it is generally, and overall, a minority fraction of the funding needed to achieve the research. The role of EUROfusion funds should be made clear in any proposal for extension.” The ToIFE collaboration was of great importance to get additional funding (from local institutions – LiDyL – or at the national level: “funds” for HAS and IPPLM) and to be included in national roadmaps of research infrastructures (IST) as its objectives are aligned with a number of national strategic priorities. Apart from this leverage aspect, it was also a strong case for convincing Selection Panels to provide access to highly competitive laser infrastructures (LULI2000, VULCAN, LMJ-PETAL) and was essential for financing target manufacturing (usually supported by the users, not by the facilities) and other consumables, as well as travel and subsistence abroad (to the USA or to Japan).

“There are several areas where at least some discussion with EUROfusion workpackages leaders should be undertaken as this overlaps, perhaps heavily, with similar work done within MFE, and duplication needs to be avoided, e.g. when developing tools such as R2S.” It is assumed that this

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[18] Krasa J. et al., Generation of fast neutrons through deuteron acceleration at the PALS laser facility, JINST 11, C03050 (2016)
[19] Llor Aisa E. et al., The preplasma effect on the properties of the shock wave driven by a fast electron beam, Phys. Plasmas 23, 082702 (2016)
Comment relates to Spanish studies under mission 4; these activities are of course dual but are not doubly supported at the European level. The UPM partner would like to state that IFE systems have indeed been modelled thanks to R2S tools, *inter alia*, but that the required developments have been done consistently; for that matter, the Spanish team at UNED/UPM was used to discuss R2S developments and EUROfusion missions, including the IFE-oriented ones, with MFE scientists. Communication within EUROfusion is of course a key element of success for both the MFE and the IFE communities. But, even if some studies are of common interest (for instance on the first wall materials), the operational conditions are quite different and shall be recognized as such; different behaviours under stress and irradiation may be expected and experimental and computational solutions defined and validated independently for the MFE approach and the IFE one. In any event, the EUROfusion management can directly contact UPM (Prof. Perlado) if the outputs of the ToIFE project are judged important to be incorporated/linked in one of the IPHD projects.

Call CfP-AWP17-IFE
Some adjustments in the ToIFE tasks and in the beneficiaries’ list may be necessary for 2017 and possibly 2018 – if extension granted – to avoid double backing and optimize EUROfusion funding.