

Towards Demonstration of Inertial Fusion for Energy

Introduction and Background

Inertial Fusion Energy research is currently undergoing significant developments. The National Ignition Facility (NIF) at LLNL (USA) was completed in April 2009. Shortly after its dedication, the National Ignition Campaign (NIC) began, conducting shots to first fine-tune the laser performances, then calibrate a whole set of diagnostics and finally implode cryogenic layered targets, making steady progress toward achieving indirectly-driven ignition. Ignition-level radiation temperatures, up to 330 eV, were reported, shock timing was optimized close to specifications, but hotspot densities and pressures were kept lower than predicted. 90% of the predicted implosion velocity was reached but the achieved pressure was insufficient for achieving ignition. Evidence suggested that two key factors are limiting implosion performances. The first one is time-dependent x-ray drive asymmetry, mainly due to laser-plasma interaction (mitigated in part by energy transfer between crossed laser beams) and the second one ablator/fuel mix, induced by Rayleigh-Taylor (RT) instability growth. The NIC formally ended in September 2012 but the effort to achieve ignition on the NIF is further pursued, with very recent encouraging results, namely demonstration of α -particle heating. This so-called “scientific breakeven” was however obtained at high implosion adiabat to reduce RT growth and mix thanks to a smaller in-flight aspect ratio (i.e. to an increased shell thickness during the coasting phase). Such a design, reducing the areal density of the compressed fuel at stagnation, would not lead to high gain values for which low adiabat, maintaining the fuel as close to the Fermi-degenerate state as possible, is mandatory. Therefore, control of parametric and hydrodynamic instabilities remains the major focus of IFE research.

Anticipating a successful demonstration of ignition and gain on NIF and on LMJ (the Laser MégaJoule, which is close to completion, with first light expected end of 2014), scientists and engineers from across Europe have been developing the case for the next generation laser fusion facility: HiPER (High Power Laser Energy Research Facility). Coordinated by the UK Science and Technology Facilities Council (STFC), HiPER is a fully-civilian ESFRI-labeled European project (its Preparatory Phase being officially closed since mid-2013) which gathers 26 partners from 10 European countries, with international links to Russia, Japan, South Korea, China and Canada. It allowed addressing separately all the technological challenges faced on the route to a real laser fusion reactor device. It led to reference designs for the laser beam lines, for the target and finally for the facility itself. It showed that, to be commercially attractive, the fusion cycle must run at a repetition rate of at least 10 Hz and that a “target gain” ($E_{\text{laser}}/E_{\text{fusion}}$) close to 100 is required. Diode-pumped solid-state laser (DPSSL) technology and alternative ignition schemes may fulfill such requirements. These so-called alternative schemes rely on decoupling direct drive target compression from fuel heating - and thus ignition – using an external matchstick, a laser-launched strong shock (for the shock ignition scheme) or a laser-accelerated ultra-fast particle beam (for the fast ignition scheme which has been extensively studied in the past but still requires validation).

Considering the expertise of the European community in the strongly competitive IFE R&D field and its high degree of coordination resulting from the FP7 EURATOM KIT activities and from the HiPER project, as well as a common ambitious long-term goal of demonstrating the viability of laser-driven fusion as an alternative road towards sustainable, clean and secure energy source, the European community has established a roadmap towards IFE for the near future (downloadable from www.ife-kit.eu). The ToIFE proposal, built in the framework of the “Enabling Research” programme, is a first step towards achievement of the required fundamental understanding.

Objectives

The European IFE roadmap aims at:

- conducting a programme of experiments and numerical simulations to understand underlying

obstacles to central hot-spot ignition on MJ-scale laser facilities, to reduce uncertainties that input into all inertial fusion ignition schemes;

- conducting a programme of experiments and numerical simulations culminating in the demonstration of shock ignition on the LMJ circa 2021-2023, followed by a 5-year period of optimisation to achieve gain values required for IFE;

these two programmes will rely on academic access to LMJ-PETAL from 2016 and to existing mid-scale European laser facilities, and possibly to abroad facilities, for underpinning sub-ignition experiments (and associated numerical modelling) to give confidence in the IFE underlying physics; they will involve active collaboration with inertial fusion scientists worldwide and development of innovative laser-based diagnostics and instrumentation;

- conducting a programme of numerical simulations and experiments to test the viability of the other alternative ignition schemes, electron- and ion-driven fast ignition or impact ignition, culminating in the design of relevant campaigns on the LMJ/PETAL;

this programme will include massive integrated numerical simulations, from compression to ignition and burn, as well as experimental optimization of laser-driven particle acceleration and transport processes;

- developing key IFE technologies such as laser driver, low-cost targets, advanced materials for fusion chambers, target injector and position sensor;

this programme will also include works on engineering concepts for an IFE reactor, including development of experimental tools to validate innovative materials; it will provide unique opportunities of innovation and transfer to industry.

This roadmap has been distributed for the coming years among the European academic partners. The following section describes the tasks allocated for 2014.

Description

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

Task 1.1. Matter properties

From the theoretical point of view, plasma atomic physics is of first importance for all IFE-relevant experiments which are, and will be, conducted on high-energy laser facilities. Indeed, key compression and implosion diagnostics (from precise measurements of the indirectly-driven soft x-ray power to x-ray emission and backlit imaging of the target core as it ignites) rely on accurate modelling of the radiative properties of multi-charged plasmas. Progress is however still to be done as the statistical approaches that are often required to model these properties for elements of high atomic number, are not yet fully validated. Furthermore, as the laser energy is increasing from a few kJ to hundreds of kJ, new states of matter are reached and improved matter models (based on many-body theories to simultaneously treat electrons and ions) shall be developed to accurately take them into account in equations of state, especially the doped ablator one. From the experimental point of view, innovative high-energy high-brightness radiation and particle sources will be developed to gain valuable insight into highly emissive compressed matter or to contribute, thanks to the sub-ps time resolution they can offer, to benchmark the new generation of numerical tools.

The 2014 task will be centred on:

- validation of a new diagnostic technique to be implemented on LULI2000 and analysis of the near-LTE XUV absorption spectra thus recorded in well-characterized thermodynamic conditions; development of a new detailed opacity code taking into account density effects (CEA/IRAMIS);
- improvement of rad-hydro simulations codes by inclusion of relevant online packages for accurate description of non-LTE radiative properties and equations of state (UPM);

- optimization of high-brightness from soft to hard x-ray sources (high-order harmonics, x-ray lasers, betatron or Thomson sources) as potential plasma diagnostics and study of their interaction with matter (IST, MPQ, UPM);
- development of a x-ray spectroscopic analysis tool to extract time-resolved fuel core densities and temperatures from Ar-doped implosions (UPM, in collaboration with U. Nevada, USA).

Task 1.2. Laser-Plasma Interaction (LPI)

Analysis of the state of art of IFE-relevant LPI physics clearly shows that energy transfer from laser to plasma still remains a major challenge, for theoretical modelling and for experimental demonstration of ignition. One of the most crucial issues is in fact the control of the deleterious parametric instabilities due to the scattering of the incident laser light off plasma waves (namely Stimulated Raman Scattering - SRS - and Stimulated Brillouin Scattering - SBS) inside the low-density gas-filled hohlraum. In recent NIF campaigns, onset of these instabilities and backscattering of a significant fraction of the incident laser energy have actually been evidenced. These energy losses were partially compensated by cross-beam energy transfer but the technique, involving complex microscopic processes, may generate detrimental time-dependent spatially non-uniform irradiation of the pellet, even if leading to 84% absorption. Furthermore, the role of these instabilities has to be carefully revisited for the shock ignition scheme, considering the required intensities, up to 10^{16} W/cm², and the potentially inhomogeneous character, at relatively high temperature, of a directly-driven fusion plasma. Indeed, the present MJ-scale laser facilities were designed to meet requirements dictated by indirectly-driven experiments. It is thus necessary to adjust the spatial distribution of the laser beams for direct drive by redirecting and smoothing them. The focusing systems should be re-designed and re-configured to allow defocusing (the so-called polar direct drive - PDD). Even though, irradiation symmetry may be insufficient. In such a PDD configuration, overlap of laser beams and oblique incidence are unavoidable and cross-beam energy transfer is still an issue. A concerted effort to understand parametric instabilities, their growth and mitigation strategies, is therefore essential for progress in inertial fusion energy.

A consortium of internationally recognized European experts, in UK (RAL), France (CPHT) and Portugal (IST), is working on identifying regimes in which these parametric instabilities can be both controlled and harnessed in IFE-relevant plasmas, through modelling and multi-dimensional Particle-in-Cell (PIC) simulations run on national or European supercomputers. It will also contribute to build predictive LPI capabilities. Their objective for 2014 is to (i) investigate thermal effects on SRS and SBS growth rates, as well as on filamentation, (ii) numerically study at full scale interaction of a single or multiple short (a few 10's or 100's of ps) laser pulse with a coronal plasma, (iii) study the onset of SRS in laser speckles and the evolution of this instability in IFE-relevant inhomogeneous plasma density profiles, (iv) study the role of intense laser speckles, with respect to the overall beam, in the energy transfer between crossing laser beams and finally (v) compare numerical results with experimental ones, obtained on LULI and CLF existing facilities.

Task 1.3. 3D hydrodynamics

As mentioned in the introduction, the mix issue is at the core of the poor performances of NIF low-adiabat implosions and shall be seriously tackled. A consortium of UK universities, led by Oxford and York, have been awarded academic-access experimental beamtime on the newly commissioned ORION laser facility to quantify the amount of mix occurring during an implosion thanks to the development of new x-ray instruments and atomic physics diagnostic tools. The CLF will provide support for this experiment, including design, modelling and data analysis, target fabrication and travel/subsistence. In parallel, a target design proposed to reduce the RT instability thanks to a double ablation front (driven respectively by electron conduction and by radiation) will be further studied at UPM, in collaboration with CELIA. Numerical studies on ignition target stability towards hydrodynamic instabilities will also be performed at Univ. Rome "La Sapienza".

Task 1.4. Combustion

Knowing the basic physical properties of warm high-density matter, as ion stopping in hot and dense plasmas, is a central issue for IFE. Not only is the precise description of the equation-of-state of compressed high-pressure matter or ion-plasma interaction important for all ion-based fusion concepts, as heavy-ion fusion or ion-driven fast ignition, but it is also, even more importantly, essential for understanding the α -particle heating mechanisms in the burning DT fuel, that determine the yield of a fusion reaction to a large extent. Two experimental platforms, involving new CVD diamond detectors and a proton microscopy beamline, were developed at GSI. The first one is devoted to measure the energy loss of projectile ions in a hot laser-generated plasma ($\sim 200\text{eV}$) in the velocity region of maximum stopping power ($\sim 0.5\text{MeV/u}$). In that parameter range, discrepancies of up to 30% exist between the various stopping theories and hardly any experimental data are available. The second one will create warm dense matter states by pulsed power techniques and probe them by proton microscopy. Hereby the otherwise hard-to-access density parameter can especially be measured with high precision. Beamtime on the GSI's accelerator has been allocated in 2014 to collect valuable data, in collaboration with CELIA. In parallel, accurate Monte-Carlo schemes for neutron and charged fusion products will be implemented in the DUED fluid code to improve burn simulations (U. Rome "La Sapienza").

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

The SI scheme relies on decoupling target compression from ignition by launching in a nominally compressed pellet a strong shock (~ 300 Mbars, produced by means of an intense - $\sim 10^{16}\text{W/cm}^2$ - laser pulse, or spike, and amplified through convergence effects and collision with compression shocks) precisely timed to reach the imploded core close to stagnation. Ignition is then obtained at low implosion velocities (240-300km/s) which reduce risks of shell break-up during acceleration and allow compression of large fuel masses, thus enabling high target gains, of strong interest for IFE. The two key questions that SI is facing are: (i) is it possible to launch such a high-pressure shock through a large coronal plasma, and (ii) are the parametric instabilities mentioned above not too harmful in terms of energy backscattering and hot electron production? The 2014 task will be three-fold:

- task 2.1: investigating on PALS – thanks to a joint CELIA/U.Rome/INO-CNR/IPPLM/PALS/CTU campaign - the influence of a pre-plasma on the shock strength and on the fast electron beam, generated by interaction of the spike with this corona;
- task 2.2: conducting and analyzing a CELIA-CEA/DIF-LULI experiment on the LIL laser facility (scheduled February 2014) to also investigate pre-plasma effects, but in a more relevant geometry, i.e. with spherical targets, and at conditions closer to those encountered in MJ-class experiments (thanks to the laser energy available and to the pulse shaping capability of the facility);
- task 2.3: performing numerical simulations to further optimize the SI scheme and design future experiments on relevant laser facility (U. Rome "La Sapienza", CELIA, UPM).

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

Task 3.1. Electron-driven fast ignition

As for the SI scheme, fast ignition relies on decoupling fuel compression to hot spot heating (and thus ignition). The spark is however in that case quite different. The current electron-driven FI design relies on production of an energetic electron beam by interaction of a high-energy multi-PW (~ 70 kJ / 10-20 ps) laser pulse with the tip of a re-entrant double gold cone (used to keep a path free of plasma and allow efficient particle generation and guiding close to the compressed core). The scheme was widely studied during the past ten years and several issues were identified. Among them, electron transport in a cold and dense (pre-compressed) plasma received particular attention as divergence of the fast electron beam (FEB) has been identified as a key parameter in minimizing the required laser energy. One method recently proposed to force the FEB to remain collimated from the region where the laser is absorbed (and the electrons produced) to the fuel core, over a few hundreds of microns, is to use

magnetic fields, either self-generated or external. An innovative capacitor-coil target was successfully tested on LULI2000 in 2013 in the framework of a collaborative project between 3 French groups (CELIA, CEA/DIF, LULI) and Japanese colleagues (ILE Osaka, Japan). A quasi-stationary magnetic field exceeding 3 kT was measured. The 2014 task will aim to get a clear experimental demonstration of the collimation effect of this B field on fast electron transport in a plasma. Collaboration with TU Darmstadt (Germany) and UPM (Spain) will strengthen the collaboration. New ideas for fast electron collimation will be explored theoretically at the CLF.

Laser peak power required for fast ignition (~5-10PW) will soon be available in Europe, though at much shorter pulse durations (a few tens of fs instead of a few tens of ps), within CALA at MPQ or on APOLLON (LULI) and the ELI laser facilities in Czech Republic, Hungary and Romania. Campaigns there conducted will allow validating FI-relevant concepts at high repetition rate and providing confidence in the corresponding numerical simulations, especially in Particle-in-Cell computations. Preliminary experiments at lower laser power (a few hundreds of TW) will pave the way.

Note that the CLF will host the key scientific meeting on fast ignition physics - the 13th International Workshop on Fast Ignition of Fusion Targets - at the Queens College Oxford in September 2014. It will provide unique opportunities to the European community, especially young researchers, to exchange ideas with colleagues worldwide and enrich its knowledge.

Task 3.2. Ion-driven fast ignition

Laser-accelerated ion beams offer, as fast ignitors, numerous advantages as a stiffer particle transport and a more localized energy deposition, due to Bragg effect, or to be less prone to instabilities. It is estimated however that ion-driven FI for IFE would require a laser-to-ion energy conversion efficiency of, at least, 10%, which remains yet to be achieved. Among the various acceleration schemes that are currently studied (see mission 4), one of the promising candidates is the Laser Induced Cavity Pressure (LICPA) acceleration mechanism - proposed by IPPLM - in which targets are designed in such a way that they allow "recycling" the reflected laser light, thus increasing conversion efficiency. The 2014 task will be devoted to 2D PIC simulations at FI-relevant laser and plasma conditions, to confirm encouraging first 1D computations and prepare a dedicated experimental campaign.

Task 3.3. Impact ignition

The II scheme aims at impacting an accelerated high-velocity macroparticle onto a highly compressed DT target. A crucial milestone is then to demonstrate impact-compressed densities of ~100 g/cm³ in addition to high implosion velocities of ~10⁸ cm/s. In order to validate previous findings at ILE and PALS, UPM will propose experiments to test some of the physical aspects of this scheme, such as the efficiency stability of the plasma acceleration.

Task 3.4. Aneutronic fusion

Even if conditions required to harness aneutronic fusion are much more extreme than those required for the conventional DT fuel cycle, such alternative scheme would greatly reduce problems associated with neutron radiation and technological requirements. It is then worth studying. The p-B reaction is the most promising one. Preliminary work performed on ABC (ENEA) and at LULI gave interesting results but the α particle production was kept rather low. The 2014 task, performed by ENEA in collaboration with LNS-INFN Catania, IPPLM, University of Texas and LULI, will be focused on (i) optimization of the target design to increase the number of produced particles and improve statistics, and (ii) on full characterization of their spectra. In particular, the LICPA-type targets will be considered to increase the proton current density, and thus α yield.

CLF, LULI, PALS, MPQ and GSI will provide access to their laser facilities for joint experiments in the framework of the three missions described above. A new call for proposals for academic access to the Vulcan laser facility at CLF and the PHELIX laser facility at GSI will be issued shortly for scheduled experiments starting in the second half of 2014. The call for academic access to the LULI laser facilities was

recently closed. Among the 27 proposals received, half a dozen is of direct relevance for IFE. The beamtime will be allocated by an external Program Committee, on scientific quality criteria, before the end of November for the period April 2014-March 2015. The PALS experiment on shock ignition (task 2.2) is already scheduled. A contribution for scientific support, consumables (targets, mechanical adaptation for specific diagnostics) and T&S for the participants in these experiments is requested (task 0). No user fee will be charged.

Mission 4. Developing key IFE technologies

Task 4.1 Laser-driver technologies

To develop high-repetition-rate laser capabilities for IFE, various projects on diode-pumped solid-state laser (DPSSL) technology are conducted in Europe. The most important are LUCIA at LULI (currently delivering 14J at 2Hz and on the way to 30J thanks to development of a 2nd cryogenic amplifying stage based on an innovative, patented, cooling architecture) and DiPOLE at the CLF's Centre for Advanced Laser Technology (CALTA). Their role is to be used as a test facility for future IFE laser systems, at higher energy, and to fuel economic growth through new cutting-edge technologies. R&D projects are also ongoing at IST and MPQ. In 2014, the CLF will support investigations into laser damage thresholds, knowledge of which is a key technical requirement for DiPOLE. The plan is to supply test samples to colleagues in other EU countries who will make tests to help determine the factors that influence laser damage threshold.

However, lasers delivering energies above 1 kJ are still based on glass technology, which currently limits their repetition rate to mostly single shot operation. This shot rate is a strongly limiting factor for IFE experiments and it must be increased dramatically (which motivated works on DPSSLs). GSI has already made first steps in this direction by building a testbed dedicated to the study of birefringence effects and their compensation on the 10-20 Joule level. In 2014, a programme will be started to understand limitations of thermal stress in glass lasers at higher apertures and to implement innovative thermal management scheme that are scalable to MJ-class lasers.

Thanks to its capabilities in producing very uniform target illumination, in zooming to follow the critical surface backward movement during compression and in operating in a deep UV regime at high repetition rate, the KrF laser technology is also a promising driver possibility. The only system in operation in Europe is in Hungary. Some improvements are however needed to allow relevant IFE experiments, especially in terms of contrast. In 2014, the objective will be to decrease the nanosecond pedestal level to less than 10^7 W/cm², in order to get well-defined laser-matter interaction conditions, and to implement a new focusing laser system to reach intensities of $\sim 10^{19}$ W/cm².

Task 4.2 Targets

Apart delivering and characterizing specific micro-targets for the planned ToIFE experimental campaigns, R&D work on novel target designs and micro-assembly techniques, including cryogenic fuel assembly, is ongoing at the CLF's Target Fabrication group, as well in Germany, Spain and Italy: cryogenic hydrogen foils at the Technical University of Darmstadt, ultra-thin plastic foils at the Helmholtz Institute Jena and the Fraunhofer Institute in Stuttgart, diamond-like carbon foils, near-critical density targets using carbon nanotube technology and fully-isolated levitating targets (using Paul traps) at MPQ, agar agar foams at ENEA, in collaboration with the Lebedev Institute of Moscow, or high-density carbon layered targets at UPM.

Note that the developments mentioned above on laser and target technologies are mainly in-kind contribution of the ToIFE consortium.

Task 4.3 IFE materials and reactor technologies

Task 4.3.1 Virtual Reactor Modelling

In 2012, a CEA/RAL/UPM reactor working group was formed within the HiPER project to connect the various sub-systems of an IFE Power Plant. It was named Virtual Reactor Modelling. STFC and UPM will maintain this new capability by, for instance, providing updates to ToIFE partners. The current HiPER reactor designs will thus be refined, with special focus on tritium loops.

A reliable tool for coupled radiation transport (MCNP) and activation (ACAB) calculations will be developed at UPM; based on a rigorous (R2S) two-step approach, it will allow accurate shutdown dose rate (SDR) calculations. Combined with uncertainty calculations, it will contribute to improve the integral HiPER reactor design, especially in terms of radioactive inventory or any aspect related to radiation: damage, shielding, etc.

Task 4.3.2 Reproducing fusion ion bursts in the lab

One of the main concerns in the development of laser fusion technology is the effect of fusion ion bursts on the inner components of the reactor, especially in the case of dry walls or of the final optics. Those bursts of very energetic ions coming from the ablation of the capsule and the fusion reaction itself are known to severely damage the materials of the first wall as they deposit tens of kJm^{-2} and implant more than 10^{18} particles per m^2 in a few microseconds at high repetition rates. Their thermo-mechanical and atomistic impact on current and novel radiation-resistant first wall materials should then be properly quantified, theoretically and experimentally under realistic flux conditions.

The use of ultra-intense lasers was proposed to recreate such conditions as they can generate, directly or indirectly, very short and energetic ion pulses (protons and neutrons) with controllable spectral distributions and high fluxes, identical to those of fusion ion bursts. However, the basic phenomena at play during the ion acceleration process remain poorly understood. For particles accelerated at moderate laser energies (below 10^{20} W/cm^2), the mechanism of target normal sheath acceleration (TNSA) is dominating but the many hopes to reach very high particle energies based on scaling laws and numerical predictions have not been fulfilled. For mechanisms at play at higher intensities (above 10^{21} W/cm^2), there is still a lack of experimental and theoretical studies. Various studies dedicated to understanding the TNSA mechanism and its limitations will be conducted in 2014 by the ToIFE partners (GSI, in collaboration with the Technical University of Darmstadt and the Helmholtz Institutes of Jena and Dresden-Rossendorf, and UPM, in collaboration with RAL and Japanese colleagues); novel acceleration schemes will also be explored, including break-out afterburner acceleration or ponderomotive acceleration of plasma blocks (HAS). In addition, to harvest the unique high-flux feature of sub-ps intense laser-accelerated ion bunches, MPQ will develop a reliable ion source to be used at high repetition rate for, for instance, material studies.

Task 4.3.3 Ion-matter interaction

Laser-accelerated ion beams are proven to be suitable, thanks to their unique parameters in terms of brightness and spectral distribution, to validate fusion materials or to investigate the barely known propagation of fusion ion bursts through background plasmas/gases potentially filling the reactor chamber.

UPM, in collaboration with LULI and others, will for instance develop numerical tools to design an IFE-relevant experiment investigating the interaction of a laser-accelerated ion beam with a low-density medium, especially the occurrence of two-stream instabilities.

Task 4.3.4 Advanced materials

The properties of innovative materials under irradiation will in addition be studied, experimentally and numerically. UPM is for instance proposing to design nano-structured tungsten alloys, as potential first wall materials, or to evaluate the possibility to use plasmonic nano-particles embedded in dielectric matrices instead of silica as final optics material. Irradiation tests will be done at the Helmholtz Centre of Dresden-Rossendorf (Germany) and at its home experimental facility (HIPIMS) as well as on ultra-short laser facilities.

New developments of structural and functional materials based on numerical simulations will be done; they will emphasize the need for these materials to support, for IFE, high repetitive operation and not simply continuous irradiation as for MFE.

Note that spin-offs of these IFE-driven material studies are expected in MFE.

In addition to these technical and scientific missions, the ToIFE project must contribute to build a strong Fusion community. Actions to train PhD students and post-doctoral researchers are then strongly encouraged. The CLF's Christmas meeting of the High Power Laser Science Community, held every December, is for instance providing a supportive and attentive audience for young researchers to present work conducted on the EU's high power laser facilities, and supporting simulations/theory, in the past calendar year. Training courses to introduce young researchers to the Prism Computational Science Inc. software suite and to the 3D radiation hydrodynamics suite FLASH or to laser, target and diagnostic operations will also be run by CLF (task 5).

Scientific and technical deliverables

Task #	2014 deliverables	Lab in charge
0	up to 15 beamtime weeks provided on ToIFE laser facilities for joint experiments	GSI, LULI, PALS & RAL
1.1	assessment of the relevance of the proposed diagnostic technique for future IFE-relevant campaigns on LMJ-class laser facilities; first opacity calculation with density effects set-up of a pulsed multi-keV x-ray source (based on electron acceleration) more than 10^7 photons per pulse first rad-hydro simulation with non-LTE atomic physics; conceptual design of a CPA x-ray laser	CEA/IRAMIS & LULI MPQ UPM
1.2	limits of validity, in time and as function of the pump laser intensity, of the fluid-type modelling of SRS-driven Langmuir waves via a phenomenological amplitude-dependent non-linear frequency shift in inhomogeneous plasmas; identification of the role of intense speckles in energy transfer between multiple crossing laser beams identification of plasma thermal effects on SRS, SBS and filamentation instability growth rates; comparison with VULCAN experimental data	CPHT RAL & IST
1.3	support to the Oxford-York experiment on the ORION laser facility analytical weakly non-linear stability analysis of double-ablation-front targets	RAL UPM & CELIA
1.4	plot showing ion stopping power in laser-generated plasmas at low energy as a function of time first DUED simulation integrating MC transport of neutrons and charged fusion products	GSI & CELIA U. Rome
2.1	plots showing (i) shock pressure versus laser intensity with and without pre-plasma and (ii) fast electron beam characteristics (cut-off energy, divergence) as a function of the pre-plasma parameters, at ω and 3ω , in planar geometry	IPPLM & U. Rome
2.2	first pressure measurement with spherical targets	LULI
2.3	set of optimal laser-target parameters for the SI scheme	CELIA, U. Rome & UPM
3.1	plots confirming the kT magnitude of the magnetic field reached in the LULI experiment and showing its effect on the propagation of a relativistic electron beam; related numerical simulations formulation of new concepts for fast electron beam divergence control	CELIA & UPM RAL

3.2	plot showing FI-relevant average ion energy & ion beam intensity versus laser intensity for realistic cavity parameters	IPPLM
3.3	evaluation of the II scheme efficiency	UPM
3.4	determination of p-B fusion rates in plasmas	ENEA & IPPLM
4.3.1	provision of updates to ToIFE partners first SDR calculations with uncertainty assessment	RAL & UPM UPM
4.3.2	determination of the influence of a temporal pulse pedestal on TNSA experimental demonstration of ponderomotive acceleration of plasma blocks by clean KrF pulses (with a 10^{11} contrast) proof-of-principle of TNSA for IFE material irradiation set-up and test of a rep-rated ion beamline on ATLAS300	GSI HAS UPM MPO
4.3.3	design of an IFE-relevant ion-gas interaction experiment	UPM & LULI
4.3.4	first irradiation of plasmonic nano-particles embedded in dielectric matrices, of nanostructured W alloys and of HDC targets	UPM
5	up to 4 training weeks of PhD students and post-doctoral researchers	RAL

Management

The EURATOM IFE KIT activity having been very successfully in enabling a collaborative research programme to be fruitfully developed across national approaches, the national representatives have decided to build the ToIFE consortium to capitalize on this integration and significantly contribute to the global understanding of IFE, acting as national coordinators (and not as scientific partners). The management structure is thus ensured by the ToIFE representatives first at the national level and then at the European level. Tools have been defined to help monitoring the project and report on the defined deliverables: (i) meetings will be held on a semester basis, the first one (early summer) during the annual EPS Plasma Physics conference to allow identifying any risk not to fulfil the consortium's commitments and strengthening links with the MFE community, the second one (early November) either at the PI lab or at any facility where a joint experiment will be ongoing; (ii) the current www.ife-kit.eu website will be upgraded to reflect the transition from keep-in-touch or watching activities to more programmatic tasks. Finally, as the IFE roadmap has been drawn within Horizon2020, it could be foreseen that ToIFE will ask for additional support in the following years, for continued or totally new tasks, but a PI turnover may be reasonably envisaged.