Scientific proposal for Enabling Research project

(max 10 pages, excluding title page)

Title	**Advancing shock ignition for direct-drive inertial fusion**
Topic Area	**Inertial Fusion (CfP-FSD-AWP21-ENR-01)**
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Beneficiary	**CEA**
Project duration	**3 years**

Abstract

We aim to study and unlock key issues of the physics of laser direct-drive (DD) inertial fusion, and Shock Ignition (SI) in particular. Indeed, inertial fusion energy (IFE) requires high-gain, hardly compatible with the indirect-drive approach investigated at NIF and other major facilities. Our project would therefore complement the NIF approach by studying the physics of potentially higher-gain DD schemes.

SI is based on separation of compression and ignition. First, the target is compressed and then a high-intensity spike of several-hundred ps launches a strong shock (>300 Mbar) igniting the precompressed fuel. Since compression does not need to create a hot spot, implosion can take place at lower velocity and with thicker targets, reducing the impact of hydro instabilities. SI demonstration is compatible with present-day laser technology and, with some modifications, target areas. In this respect, SI is one of the few IFE schemes that can be tested at ignition-scale within the next decade on facilities like NIF, LMJ, SGIII.

The project is organized in five Work Packages, each including experiments and theory:
WP1: characterization of hot electrons and hot-electron-driven SI;
WP2: hydrodynamic instabilities and mitigation strategies in DD-SI, including use of foams;
WP3: bipolar SI: direct drive compression and bipolar spike irradiation, new ignition concepts;
WP4: parametric instabilities and cross beam energy transfer, and their mitigation using broadband lasers;
WP5: magnetic-field-assisted inertial fusion implosion and ignition.
We emphasize the coupling of theory and experiments, especially the development of theoretically-based simulation tools relevant to DD and SI. In addition to usual radiation-hydrodynamics and nuclear packages, these include self-consistent description of parametric instabilities, hot electron generation, non-local electron transport, magnetic flux compression, etc. State-of-the-art codes, developed by the proponents (CHIC, DUED, IFRIIT) or made available to the proponents (ASTER, FLASH) will be used.

We plan to perform experiments at European laser facilities, in particular PALS, currently the only facility in Europe allowing intensities of 1e16 W/cm2 in a sub-ns pulse, VULCAN, offering the possibility of multi-beam irradiation, and LMJ/PETAL which will allow realizing experiments at full IFE scale. In addition, we will collaborate with overseas groups and Large facilities: Omega (LLE, Rochester), Gekko (Osaka), SG II and III (China).

The present project builds on physics and community building achievements of our previous Enabling Research project ENR-IFE19.CEA-01 “Study of Direct Drive and Shock Ignition for IFE: Theory, Simulations, Experiments, Diagnostics development”. In particular, we will continue the fruitful collaboration with Rochester University, the birthplace of SI. Our objectives are answering key physics issues on SI and DD, consolidating the European community doing DD research, with the longer-term objective of designing and performing SI demonstration on NIF or LMJ.

1. Introduction.

A decade of experiments on the NIF (National Ignition Facility) in the US **has proven that inertial confinement fusion is a credible approach**, with the best performances reaching the α-heating regime (twice more energy from nuclear fusion than the kinetic energy of the imploding shell) [1, 2]. The burning plasma state has yet to be reached, but many of the underlying physics issues have been identified and could be addressed with the existing technology. However, while the demonstration of ignition could be reached on NIF in the few next years, the indirect-drive approach is not suited for high-gain implosions and reliable inertial fusion energy (IFE) because of the intrinsic low laser-fuel coupling efficiency. IFE will most likely have to resort to direct-drive (DD) schemes, which also require simpler targets. Anyway, DD is not free of difficulties, especially its high sensitivity to non-uniformities of laser-irradiation seeding the development of hydrodynamic instabilities.

The difficulty of achieving ignition on NIF, as evidenced by the "National Ignition Campaign" (NIC) [3], is due to many interplaying causes: larger than expected impact of LPI's (laser-plasma instabilities, especially Stimulated Raman Scattering, SRS) in the gas filled holhraum, imperfect mastering of X-ray emission and absorption in the cavity, inaccurate equation-of-state data, target defects seeding Rayleigh-Taylor instability (RTI). In the end, ignition was prevented by lower than expected energy coupling to the fuel, implosion asymmetries, and mixing attributed to RTI.

In a way, the unexpected impact of symmetry and stability issues on the NIC has re-opened interest in DD. Furthermore, recently there have been important steps in improving DD implosion quality and controlling the onset of hydro instabilities. In addition to optical smoothing, introduced in the 80's and 90's [4, 5, 6], new approaches have been considered (including using foams) to improve thermal smoothing in the conduction region of the targets [7,8]. Finally, recent experiments at Omega have shown a substantial improvement in the ability to control DD implosions and predict neutron yields, using novel approaches based on deep learning techniques [9]. A further advantage of DD schemes is that they have no direct military relevance, while indirect drive is considered potentially proliferating [10].

"Shock Ignition" (SI), initially proposed at Rochester University [11], represents an alternative to the indirect-drive approach and could strongly improve the performance of DD . SI relies on the separation of the phases of target compression and ignition. Compression is achieved as in the conventional approach (but with lower implosion velocity) with lasers at intensity of a few times 10^{14} W/cm^2 and duration ≈ 10 ns with temporal shaping. Ignition is triggered by a high intensity laser spike (≈10^{16} W/cm^2, with several 100 ps duration) launching a very strong shock (≥ 0.3 GBar at the ablation front). The convergence of the shock at the target center heats the compressed fuel creating the ignition hot spot. With respect to hydro instabilities, SI offers definite advantages ([12, 13]). The reduced implosion velocity results in lower susceptibility to RTI. Additional mechanisms (competition of RT and Richtmyer-Meshkov instabilities, radiation smoothing at the bang time, etc.) may also decrease sensitivity to non-uniformities. Finally, the final fuel assembly is non-isobaric, which results in higher gain than ignition from a conventional isobaric configuration [12, 13].
With respect to other advanced approaches to IFE (e.g. Fast Ignition [14]), SI has the advantage of being compatible with present-day laser technology. SI using the so-called "Polar Direct Drive" (PDD) [15] and, in case, "bipolar illumination" for the final spike [16] could even be compatible with present-day target areas built for indirect-drive. SI could in principle be tested at ignition-scale within the next decade. Indeed, with the opening of the French LMJ/PETAL facility to academic civilian research, full-scale IFE experiments could be performed in Europe by cooperating European groups.
The emphasis of our proposed project is to complement the NIF approach by addressing the specific physical issues associated to higher-gain DD SI. The project leverages on physics and community-building made possible by our previous Enabling Research projects CfP-AWP17-IFE-CEA-01 "Preparation and Realization of European Shock Ignition Experiments, AWP17-ENR-IFE-CEA-02 "StarkZee – Towards a universal Stark-Zeeman code for spectroscopic diagnostics and for integration in transport codes", and ENR-IFE19.CEA-01 "Study of Direct Drive and Shock Ignition for IFE: Theory, Simulations, Experiments, Diagnostics development". We will continue this work and bring in new research teams, also to explore ideas that emerged over the last two years. As for the previous projects, we will benefit from a fruitful collaboration with Rochester University. Within this project, we plan to perform experiments in Europe (accessing PALS, Vulcan, Phelix and LMJ/PETAL) and overseas (using Omega at Rochester, Gekko at University of Osaka, Japan, and Shen Guang II and III, China). We will also collaborate with research institutes in Russia (Lebedev, JIHT).

We have deliberately chosen to focus on fundamental physics issues of DD and SI rather than addressing all the issues related to IFE. Indeed, we want to consolidate a community by having the most active research teams working together on specific physics objectives. A final goal of the project is proceeding towards SI demonstration experiments to be performed on NIF or LMJ within the next decade.
The project is organized in five Work Packages, each addressing a key open and/or emerging question in DD and SI. Each WP will include a coordinated effort in theory, simulations, experiments, and development of diagnostics. We will stress the role of theory in guiding/interpreting experiments, and of well diagnosed experiments in validating theory-based numerical codes. **Stefano Atzeni** from University of Rome "La Sapienza" will coordinate the theoretical efforts within the project. Finally, we will continue the work on commonality of plasma diagnostics with magnetic confinement fusion.

2. Objectives and expected outcomes.

Our project aims at different scientific and community-building goals. As for community building, we aim at strengthening the collaboration between research groups in Europe focusing on the physics of DD SI. Although competences in Europe on this subject are sparse, nevertheless there are excellences, both at the experimental and at the theoretical/numerical level, which can be integrated to provide a critical mass. We also aim at strengthening the existing collaboration between our groups and University of Rochester, the birth-place of SI. Within our previous Enabling Research projects, the EUROFusion support has allowed us to buy shot days on Rochester's Omega laser. We stress that within our projects we concentrated resources on specific goals shared by all teams (i.e. acquiring laser time on Omega) rather than dispersing them among. This has both strengthened the collaboration among participants and allowed to create a preferential collaboration with Rochester. For instance, with a joint work on hot electron (HE's) generation in spherical implosions we evidenced, for the first time, the direct impact of HE's on implosion performance [17].

Within this new project, we also aim at accessing laser facilities and strengthening collaboration in Asia (laser Gekko at Osaka University; lasers Shen Guang II and III in China). At ILE (Univ. Osaka), it is just thanks to the joint experiments with our group [18] that a specific research line addressing SI has started. Concerning China, a common "letter of interest" has been signed in September 2019 between our EUROFusion ER network and the Institute of Optics and Fine Mechanics (SIOM) in Shanghai, home of the SG II and SG II UP laser facilities. A joint experiment on the SG II UP facility is scheduled in 2021.

Our project will be organized in the following five Work Packages each addressing relevant questions in DD and SI, and each including theory, simulations, experiments, and development of diagnostics:

- WP1: characterization of hot electrons and hot-electron-driven SI;
- WP2: hydrodynamic instabilities and mitigation strategies in DD-SI, including use of foams;
- WP3: bipolar SI: direct drive compression and bipolar spike irradiation, new ignition concepts;
- WP4: parametric instabilities and cross beam energy transfer, mitigation using broadband lasers;
- WP5: magnetic-field-assisted inertial fusion implosion and ignition.

These WP's, the methodological approach, the main WP responsible, will be presented in the next section.
We emphasize that since there are no ignition-scale laser facilities configured for DD, experiments in the past few years focused on understanding the physics of DD and SI at reduced scales, utilizing small- to medium-scale facilities in Europe (PALS, ORION, LIL) [19, 20, 21], Japan (GEKKO) and the US (Omega) [22]. With this respect, the objectives of our present project are answering key physics issues on SI and DD, consolidating the European community doing DD research, with the longer-term objective of designing and performing SI demonstration on NIF or LMJ. We will also pursue the goal of demonstrating the need and feasibility of construction of an international DD laser facility.
Finally, again as a long-term goal, there is a good opportunity to revisit implosion schemes considered in the past, using the new tools available for studying ICF implosions (which will be partly developed within our project). One such a scheme concerns the use of solid spheres [23] (rather than hollow shells), with significant potential advantages in terms of manufacturing, costs and robustness

3. Description and methodology.

Our project aims at different scientific goals which reflect in distinct experiments to be realized on laser facilities worldwide. Some of these experiments have already been approved and will be performed in 2021-22, with PI's from the present project. Other experiments will be proposed by our consortium for 2022-23.

In some cases, we will get laser time through international access programs (e.g. LASERLAB). In other cases, facility access will be possible only thanks to EUROFusion funding. For this, we will use part of funding to buy laser access (e.g. on Omega), as we did within our previous projects.
A few experiments will be performed at PALS, currently the only facility in Europe reaching an intensity of 10^{16} W/cm^2 in sub-ns laser pulse in a large focal spot, and VULCAN, which allows for multi-beam irradiation. Also chirped high-energy lasers (e.g. PHELIX, LULI, ELI-BL, ...) will be used for studies related to reducing LPI's. As already mentioned, as in our current project, we will again collaborate with overseas groups and perform experiments at laser facilities in the US, Japan and China, which provide spherical geometry and/or offer a combination of long-pulse and high-intensity beams mimicking the condition of SI DD experiments.

The experimental work will be guided by theory/simulations and, in turn, will serve to validate simulation models. The objective is to include a detailed kinetic transport of HE's, self-consistent treatment of LPI including SBS and adjusting SRS/TPD saturation levels, improved description of laser speckles, effects of magnetic fields, etc.

The design of ICF targets has long relied on 1D and 2D radiation-hydrodynamic simulations takin into account the multi-scale physics at play. In particular, our consortium relies on systematic use of the hydrodynamic codes CHIC [24] and DUED [25]. In addition, it makes use of the 3D code IFRIIT [26] for laser-plasma interaction and of PIC codes. In this project, we aim at substantial improvements both on physics models and geometry. We also plan to use the 3D codes ASTER [27] (developed at Rochester) and FLASH [28] (U. Chicago), which are required given the intrinsically 3D nature of some physical processes and target features. The final goals will be to make advanced hydro codes available to the whole community, and to propose robust ignition schemes designed through advanced and robust simulation tools.

In addition to experimental and numerical/ theoretical tasks, we will continue the work on diagnostics commonality in MFE/IFE. The goal will be to study the possible use in IFE of diagnostics typical of MFE research. Some of these diagnostics could be implemented in the experiments which we plan to perform on very large facilities like Omega or SG II UP.

We now describe the five WP's.

<u>WP 1 - Characterization of hot electrons and hot-electron-driven SI</u> (researchers in charge: D.Batani, R.Scott).
Unlike in conventional "central hot spot ignition", in SI hot electrons may either be beneficial or detrimental. Indeed, the presence of a very extended plasma corona during the ignition spike acts to reduce the shock pressure produced by the ablation process [29]. HE penetration is instead practically insensitive to the plasma corona length (being determined by the total crossed areal density <ρr> only). HE will therefore cross the corona to deposit their energy in the compressed shell, increasing the pressure there. Typically, electrons with energies <100 keV will be unable to overcome the shell <ρr> and will therefore play a positive role. Higher energy electrons instead will be dangerous, producing undesired fuel preheating. Therefore, it is important to study HE generation, energy distribution, and their influence on shock wave strength. Such a study will allow to evaluate to what extent HE are needed for reaching shock pressures above 300 Mbar, as recently proposed in [30, 31, 32] (so-called hot-electron-driven SI).
The work on HE is intrinsically connected to the study of LPI in DD and in SI, since HE's are produced by TPD and SRS with different characteristics. We also plan experiments to measure the time-correlation between HE and LPI, and the angular divergence and energy spectra of electrons produced by TPD and SRS respectively. These are essential ingredients needed for the validation of advanced simulations codes.

The work takes advantage of the experimental and modelling activities carried out in the previous ER project, as summarized in [33], and also of results of more recent experiments, performed at Vulcan and LMJ again within our previous ER project, where we tried to achieve conditions more directly relevant for SI, i.e. high intensity and long density scalelength [34].
We will also continue the work for characterization of HE's at different laser wavelengths [30]. We aim at a more complete description of the parameter space of LPI. This includes assessing the potential of Nd: glass second harmonic irradiation (rather than the usual third harmonic). The advantage would also consist in increasing laser energy and reducing damage to the optics, as compared to "traditional" 3ω irradiation.

Specific work on diagnostics

- Accurate characterization of high-energy HE tail. Optimization of bremsstrahlung spectroscopy (BSC) through Monte Carlo simulations (e.g. GEANT). Simultaneous use of diagnostics (K-α spectroscopy, K-α imaging, electron spectrometry) to constrain the parameters of HE distribution function.
- Time resolved measurements (using K-α or BSC) to define the correlation with LPI.
- Optimization of time resolved X-ray radiography, X-ray Phase Contrast Imaging (XPCI), and shock chronometry to characterize shock strength
- Defining the limit of applicability of VISARs.

Specific work on theory/modeling

We will continue current work on development of numerical tools for generation and transport of HE in large scale hydrodynamic models (using the codes IFRIIT and LPSE). The goal will be to perform realistic studies of the hydrodynamics driven by the SI spike, as well as to assess the effect of HE's on SI in 3D..

WP2 - hydrodynamic instabilities and mitigation strategies in DD-SI, including use of foams (researchers in charge: A.Casner, M.Cipriani). Rayleigh-Taylor (RT) instability plays a crucial role in inertial fusion. RT may cause perturbations at accelerated interfaces to grow causing shell break-up or material mixing. In laser-DD, RT seeds come from imprinting of the laser speckles onto the target resulting in mass-density and velocity perturbations [35], or from target defects. Imprint features should be minimized [36, 37], either based on optical smoothing techniques [38] or novel physical mitigation mechanisms based on appropriate target design [39, 40, 41].
One possibility is represented by the use of a foam layer around the target. This "foam buffered target" scheme was proposed several years ago and is of renewed interest in DD. The groups of our project have a large experience in working with foams [42, 43, 44, 45, 46]. A preliminary experiment on using medium-Z doped foam has been realized on laser SGIIIP within our previous ER EUROFusion project.

Concerning SI, the impact of hydrodynamic instabilities and the required laser uniformity needs have not yet been the object of a complete study. Reduced implosion velocity results in lower expected RTI growth, and additional mechanisms (competition of Rayleigh-Taylor and Richtmyer-Meshkov instabilities [47], radiation smoothing at the bang time, etc.) may also act stabilizing effects. However all this has not yet been investigated further experimentally, nor there has been a systematic simulation study.
Finally, recent experimental results [48] underlined that attention must be paid to the very early phase of laser matter interaction, before ionization and plasma formation. The velocity fluctuations measured with optical high-resolution spectrometer (OHRV) on OMEGA exceed any simulated ones [48].

Specific work on diagnostics

- We will develop advanced imaging diagnostics, X-ray Phase Contrast Imaging (XPCI), capable of detecting small details with high spatial resolution. XPCI is potentially more sensitive than X-ray radiography, in particular to the presence of edges and discontinuities in the plasma. A series of preliminary experiments have been already conducted by our groups [49, 50, 51].
- Optimizing XUV measurements (wave front sensor for extreme ultraviolet spectral range) [52, 53] to study the initial phase of solid-to-plasma transition.
- Diagnostics of laser interaction with foams: a) time-resolved characterization of reflected and transmitted laser light from foam samples with different parameters (pore size, density, thickness...); b) characterization of the foam ability to increase the ablation loading on solid materials. In the case of thin foils covered by foams, the acceleration will be measured through time-resolved optically-streaked shadowgraphy.

Specific work on theory/modeling

- Development of new microphysics models and their inclusion in hydrocodes to describe the solid-to plasma transition [54]
- Modellisation of foams [55]
- Systematic study of RT impact in SI implosions (2D simulations)

WP 3 - Bipolar SI: direct drive compression and bipolar spike irradiation; new ignition concepts (researchers in charge A.Colaitis, S.Atzeni). While SI is compatible with present-day laser technology (in terms of pulse energy and power), the largest facilities have been designed for indirect drive. In these installations, the laser irradiation is concentrated at the two poles of the target. Can such facilities be used for SI?

i) A very good degree of irradiation uniformity is still required during the compression phase. Indirect-drive facilities could then be used in the PDD mode [56], with the beams re-pointed and defocused to allow for uniform illumination of the target. Uniform illumination can be guaranteed at the beginning of the implosion but the configuration will degrade as the target shrinks. Should nonuniformities become too large, a possible solution would be to steer the laser beams to follow the implosion, e.g. using chirped beams which, focused by gratings (as it is the case of LMJ) would "automatically" steer in time (dynamic repointing [57]). Another solution would be to pre-compensate the deformation, using a shaped target designed [58].
ii) Concerning the final spike, the uniformity requirement can probably be relaxed. The large conductivity at late times (in presence of extended hot plasma) can produce a strong homogenization of the applied pressure even if the irradiation is initially not uniform. At the extreme, one can even think of a "bipolar" illumination in which the ignition spike is produced by two sets of oppositely directed laser beams [59]. This would be a natural fit to the indirect-drive configuration of LMJ, NIF and SG-III. Also this configuration would be extremely useful in the context of magnetic-aided fusion since the symmetry created by magnetic coils naturally matches the beam configuration of indirect-drive machines.
While realistic experiments on PDD need to be performed in MJ facilities [60, 61] (or at least facilities like Omega) we can contribute to this topic by experiments on smaller facilities by studying advanced steering techniques and capsule shaping. The final part of this work will be designing bi-polar experiments on LMJ.
Finally as a long-term goal, there is a good opportunity to revisit implosion schemes considered in the past, using the new tools available for studying ICF implosions (which will be partly developed within our project). One such a scheme concerns the use of solid spheres [62] (rather than hollow shells), with significant potential advantages in terms of manufacturing, costs and robustness. We will also address more futuristic approaches to inertial fusion, like using hydrogen-boron fuel.

Specific work on diagnostics
Most of the diagnostics tools required for evaluating the uniformity are already available at large facilities. The development of XPCI (as described in WP2) will also be important in this context.

Specific work on theory/modeling
Using 2D tools with 3D laser-plasma irradiation (CHIC and DUED) and 3D tools (ASTER + IFRIIT), we will study the feasibility to ignite a DD target using PPD compression and two colliding polar shocks in an indirect-drive-machine. We will assess the bi-polar irradiation scheme as an alternative to ignite the target with lower anticipated CBET levels [63].

WP4: parametric instabilities and cross beam energy transfer, and their mitigation using broadband lasers (researchers in charge: G.Cristoforetti, Jiri Limpouch). Due to the high intensity of the laser spike ($\sim 10^{16}$ W/cm^2) interacting with a long-scale corona, a major issue of SI is the outburst of LPI. Reaching a detailed understanding of laser-plasma interaction in this regime is important, because a fraction of laser energy can be diverted out of the plasma via scattered light (SBS and SRS), and SRS and TPD result in HE generation.
Experiments reveal the onset of both SRS and TPD. The quantification of TPD, which is expected to produce the highest energy electrons, is however experimentally tricky. Experiments at PALS at laser intensity $\approx 10^{16}$ W/cm^2 and plasma scalelength of ≈100 µm, carried out in the framework of our previous ER project, suggest that TPD is driven at early times of interaction, while it is successively damped [64, 65]. In experiments at Vulcan laser and at LMJ, also carried out within our previous project, at intensities close to 10^{16} W/cm^2 and density scalelength larger than 400-500µm, TPD was not observed and SRS was driven at very low densities, well below the classical Landau limit $k\lambda>0.3$, where SRS would be prohibited according to linear theory. Clearly more experiments are needed to resolve these issues.

In parallel, we will investigate LPI mitigation strategies. It is well known that in a homogenous plasma the growth rate γ of LPI is reduced by a factor $\gamma/\Delta\omega$ for bandwidth values $\Delta\omega >> \gamma$. In inhomogeneous plasmas, as those occurring in ICF, the effect of bandwidth requires detailed studies. The effect of bandwidth on the absolute SRS and TPD instabilities can be relevant and already visible for values of $\Delta\omega/\omega_0$ of a small fraction of a percent, as shown in preliminary experimental and theoretical works [66, 67, 68]. The suppression of absolute instabilities in ICF can be an outstanding result, since they are expected to generate most of the hotter electrons, which may lead to a preheating of the precompressed fuel.

An additional related topic is the possibility of tuning or suppressing LPI by using chirped laser pulses.
Indeed, at high laser intensity, the growth can be limited by the frequency detuning of plasma waves due to non-linear terms. Detuning leads the interaction out of resonance and results in a rapid suppression of the instability. Chirped pulses have the potentiality of compensating or, at the opposite, of increasing frequency detuning. This process is well-known and deeply investigated in the physics of SRS plasma amplification, where SRS is used to compress and amplify a seed pulse to get laser intensities well beyond the limits of present CPA systems [69]. We plan to carry on detailed measurements of SRS and TPD growth in ICF conditions, by using chirped pulses with different, positive and negative, chirp rates and compare the results with non-chirped pulses. Relevant laser facilities for this work are Vulcan at CLF, Phelix at GSI, Omega EP at LLE, Titan at JLF featuring high-energy broadband lasers. Smaller energy ultrashort laser facilities like the GEMINI at CLF, VEGA at CLPU, ECLIPSE at CELIA, or the ILIL-PW laser at CNR-INO could also be used for preliminary exploration of the interaction of a broadband/chirped laser with a moderate temperature plasmas (100's of eV at most).

Similar to LPI, the Cross beam Energy Transfer (CBET) is particularly dangerous because, by transferring energy from one beam to another, it can completely alter the uniformity of irradiation. Although CBET has been analyzed in experiments at Omega and NIF [70, 71], where multiple beams simultaneously interact with each other, our understanding is still incomplete. We plan to perform relevant experiments using facilities like Vulcan, using some beams to create a plasma with pre-defined conditions and then studying the CBET taking place between two additional laser beams fired at later times.

CBET could be reduced by detuning the wavelength of the laser beams, as already investigated on Omega and NIF. Preliminary designs of ignition-relevant PDD targets [62,72] show the possibility of increasing absorption and reducing scattered-light losses caused by CBET by adopting a wavelength-detuning strategy. We plan to perform basic experiments on this topic, too.

Specific work on diagnostics
Use of time-resolved visible and X-ray spectroscopy to characterize LPI and study the correlation with HE.

Specific work on theory/modeling
Assess the effect of Cross-Beam Energy Transfer (CBET) on the compression and ignition stages of the interaction. Quantify, for the first time, the effect of CBET on SI using 3D online calculations (ASTER+IFRIIT).

WP5 - Magnetic-field-assisted implosion and ignition (researchers in charge: J.Santos, N.Woolsey). Strong magnetic fields reduce cross-field energy transport, hence both cross-field electron thermal conductivity and cross-field fusion alpha-particle transport. Fields of 20-100 kT lower hot spot ignition thresholds and can increase fusion yields [73, 74,73]. Implosions in magnetized conditions may also be less vulnerable to hydro instabilities [75]. Regarding specifically SI, B-fields can also impact LPI growth, the associated generation of HE and their trajectories. Including B-fields in implosion design will provide new degrees of freedom to control LPI, including the possibility to tailor the deposition profile of HE [76].
The issue remains of how to generate and transport these fields to the hotspot. The baseline method is to impose an external magnetic field at the beginning of the implosion, let it permeate into the target, and compress it during implosion. B-fields of around 100 Tesla can be amplified up to tens of kT during laser-driven compression [77]. The magnetic fields generated by coils (or laser-driven coils [78]) are axi-symmetric, matching the symmetry of bipolar illumination.

The work-package will be centered on the design of new experiments for the study of kinetic and hydrodynamic processes in magnetized high energy-density (HED) plasmas such as the electronic heat transport and the compression of magnetic flux. We will build upon novel laser-based platforms capable of generating high-energy-density plasmas embedded in strong magnetic fields (B-fields), by means of either intense laser-induced discharges (>100 T, few ns, mm^3) [76] or capacitor-bank pulsed discharges (>20 T, 100 µs, cm^3) [79]. We aim in particular to assess performance enhancement that can be achieved in ICF implosion experiments via magnetization, particularly if energy transport therein is optimized or mitigated. Our first implosion experiments will be done at Omega adopting a cylindrical geometry with imposed laser-driven seed B-fields (two experiments already granted for 2020 and 2021). These integrated studies will be complemented by smaller-scale experiments (at LULI, PALS, Gekko …) devoted to characterize heat transport in plasmas in the presence of a controlled external B-field, for a broad range of collisionality and magnetization.

Specific work on diagnostics

- We will develop diagnostics based on atomic physics models on X-ray emission from HED plasmas under the effects of strong magnetic fields.
- We will optimize diagnostic approaches already used for the measurements of strong B-fields (Faraday rotation, Complex interferometry, Proton radiography, etc.)

Specific work on theory/modeling

- Leveraging on existing code already including an MHD package (DUED, FLASH), develop and validate full MHD/transport packages, including all main MHD effects (field compression and diffusion, Nernst effect) and effects on plasma thermal species and fast fusion products..
- Magnetized implosion will be studied in 2D geometry with DUED (already suitable for magnetized ICF implosions) and in 3D geometry with the IFRIIT+ASTER codes for the implosion stage and FLASH code for the ignitor spike stage [28]. Since FLASH is not suited to ICF implosions for its lack of spherical grids, we will initialize the hydrodynamics of converged targets in FLASH from outputs from ASTER.
- Develop models and codes for magnetized atomic physics, radiation transfer, and structural and dynamical plasma properties in magnetized conditions.

The outcomes will be a robust physics background for magnetized HED experiments at a MJoule energy-scale. Our approach bridges a gap between ICF and MCF regarding in particular atomic physics, nonlocal heat transport and magneto hydrodynamics.

4. Work plan

The following gantt chart, organized in trimesters, proposes a timeline of the proposed work including tentative dates for milestones and deliverables. All WP will run in parallel and will cover the full duration of the project (3 years). Unless specified milestones and deliverables are intended at trimester beginning.

year	*Year 1*				*Year 2*				*Year 3*			
trimester	*J-M*	*A-J*	*J-S*	*O-D*	*J-M*	*A-J*	*J-S*	*O-D*	*J-M*	*A-J*	*J-S*	*O-D*
Web Meetings	*V1*	*V2*	*V3*	*V4*	*V5*	*V6*	*V7*	*V8*	*V9*	*V10*	*V11*	*V12*
General Meetings		*G1*				*G2*				*G3*		*G4*
WP1 – HE & SI			*M1.1*		*M1.2*	*D1.1*	*M1.3*	*M1.4*	*D1.2*	*M1.5*	*M1.6*	*D1.3*
WP2 – hydro & unifor.		*M2.1*	*M2.2*	*D2.1*	*M2.3*	*M2.4*	*M2.5*	*D2.2* *M2.7*	*M2.6*	*D2.3*	*M2.8*	*D2.4*
WP3 – bipolar SI					*M3.1*			*M3.2*		*M.3.3*	*D3.1*	
WP4 – LPI & CBET				*M4.1*			*M4.2*		*M4.3*	*D4.1*		
WP5 – magnetized fus.		*M5.1*	*M5.2*	*M5.3*	*D5.1*		*M5.4*	*M5.5*		*M5.6*	*D5.2*	

The critical milestones and deliverables are indicated in the tables below. The results of some experiments represent of course milestones for some following experiments. Indeed, some ideas tested in preliminary experiments will/will not be implemented in following ones depending on the obtained results.

List of Milestones

V1, .. V12 on-line meetings at beginning of trimesters of group leaders and WP leaders
G1, G2, G3 General meetings of the researchers of the project on months 6, 18 and 29.
G4 Closing meeting on month 35 or 36.
M1.1 Characterizing HE from TPD/SRS at 3ω including angular distribution and time correlation (WP1 & WP4)
M1.2 Characterization of HE from TPD/SRS at different irradiation wavelengths (PALS) (WP1 & WP4)
M1.3 Characterization of shock wave dynamics in SI conditions using XPCI (SGII UP, Omega) (WP1)
M1.4 Experiments in planar geometry on HE penetration in the fuel (the large ρr close to stagnation will be mimicked by using high-Z dense layers embedded in the target) (WP1)

M1.5 Experiment on HE generation and penetration in spherical geometry using a moderate convergence and tracer layer within solid sphere targets (pre-irradiated to produce the desired plasma scalelength) (WP1)
M1.6 Development and availability of advanced hydro codes taking into LPI instabilities and HE self-consistently (WP1 & WP4)
M2.1 Implementation of XPCI in planar experiments to study RT growth from imprint seeds (Omega) (WP2)
M2.2 Implementation of XUV diagnostics (wave front sensor for extreme ultraviolet spectral range) for measuring the impact of imprint during the initial phase of solid-to-plasma transition (WP2)
M2.3 Experiments on RT growth from laser imprints in SI conditions using XPCI, planar geometry (WP2)
M2.4 Experiment on characterization of shock velocity in foam (to validate theoretical models) (WP2)
M2.5 Evaluation of impact of hydro instabilities (simulations) in compression phase for SI conditions (WP2)
M2.6 Mitigation of imprints using intermediate-Z overcritical foams, planar geometry (WP2
M2.7 Experiments of reflected and transmitted laser light from foam targets, and on ablation loading on layered foam targets.
M2.8 Development of 3D hydrocodes for studying hydro instabilities (WP2)
M3.1 Experiment on bipolar collision of shocks in preformed plasma in planar conditions (WP3)
M3.2 Experiment on bipolar collision of shocks in spherical targets (either pellets or solid spheres) (WP3)
M3.3 Developing 3D tools to study the feasibility to ignite a directly-driven target using two colliding polar shocks in an indirect-drive-machine 3D geometry (WP3)
M4.1 Realization of experiment on CBET with two beams in preformed plasma (e.g. Vulcan) (WP4)
M4.2 Development of an experimental plan to investigate mitigation of LPI with Chirped laser pulses (WP4)
M4.3 Develop numerical tools to describe, possibly in 3D, laser absorption (collisional and resonant), LPI and CBET. Quantify the effect of CBET on SI in 3D inline calculations (WP4)
M5.1 Optimization of diagnostic approaches already used for the measurements of strong B-fields (Faraday rotation, Complex interferometry, Proton radiography, etc.) (WP5)
M5.2 Develop diagnostics based on atomic physics for HED plasmas under the effects of strong magnetic fields. Acquisition of X-ray spectra from HED plasmas affected by strong B-fields (WP5)
M5.3 Generation of 100 T uniform B-field over mm-scale length as seed for implosion experiments (WP5)
M5.4 Magnetized Implosions (Omega) (WP5)
M5.5 Realization of heat transport measurements at solid density (WP5)
M5.6 Develop numerical tools for kinetic and MHD simulations to model electronic transport and B-field diffusion. Benchmark to data from heat transport experiments (WP5)

List of Deliverables

D1.1 Report on measurements of HE distribution and HE tail in SI conditions. Optimization of bremsstrahlung cannon, correlation among different diagnostics (WP1)
D1.2 Report on HE effects in SI-designed targets (WP1)
D1.3 Report on advanced hydro codes taking into LPI instabilities and HE self-consistently (WP1 & WP4)
D2.1 Report on the evaluation of imprints effects during the initial solid-to-plasma transition (WP2)
D2.2 Report on the evaluation on the impact of RT for SI-designed targets (WP2)
D2.3 Report on using foams to mitigate hydro instabilities growth (WP2)
D2.4 Report on advances in 3D hydrocodes for studying hydro instabilities (WP2)
D3.1 Report on feasibility of bipolar shock ignition and proposal for experiments on LMJ/NIF (WP3)
D4.1 Report on LPI and CBET in SI conditions (WP4)
D5.1 Design of a magnetized implosion experiment at MJ scale at LMJ or NIF (WP5)
D5.2 Report on the characterization of magnetized HED plasmas over the implosion and at stagnation (WP5)

The experimental program is very intense with experiments in many facilities worldwide (as it is the accompanying numerical/theoretical work). This reflects the increasing interest in SI and DD over the last few years, as well as the impact of our previous ER IFE projects within the European community. Hence, the large experimental program is coherent with the number of groups and researchers taking part in the project, and justifies the large support requested to EUROFusion to allow for the challenge of joining together the European research groups working on SI and DD in a coordinated and focused project.

5. Organization of the project and research groups involved

The project is based on an extended network of collaborations, including the groups, which in Europe have already contributed to DD and SI research. The coordination of the work will be assured through the constant contact of the project PI and the leaders of the groups, and through the organization of “internet” meetings involving group leaders and WP leaders (one every 3 months, duration half a day). Specific “physical” workshops of 2-3 days on selected important topics will be organized whenever needed (these workshops may for instance address topics like code validation, development of diagnostics, final analysis of experimental results, final editing of proposals for experiments). General meetings of the researchers involved in the project will be organized on months 6, 18 and 29. A closing meeting will be organized on month 35 or 36. This will also include the discussion about future continuation of the work.
The groups involved in the present project are listed in the attached document “List of Consortium Members”. This include the group leaders, individuals, and the main effort realized by each group.

The document also include research groups from other countries (USA, China, Russia, India) with whom we will collaborate and which have explicitly asked to be listed as international collaborators of our research project (confirmation emails available if needed)

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