Accompanying Document

Proposal Title	*Advancing shock ignition for direct-drive inertial fusion*
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- Coherence with the EUROfusion programme and complementarity to the main Work Packages:
  - How distinct from work in the main work programme either in subject area, or in the approach

Our project aims at different scientific and community-building goals. The scientific goals, study of direct-drive (DD) inertial confinement and of "shock ignition" (SI) are clearly coherent with the keep-in-touch activity on Inertial Fusion Energy (IFE) of the EUROfusion programme and distinct from the main Work Packages. As for community building, we aim at strengthening a collaboration among research groups in Europe, which is really focused on the physics of DD and SI. Although competences in Europe are sparse, nevertheless there is a certain number of excellences, both in experiments and theory / simulations, which can be integrated to provide a critical mass. We also aim at strengthening the existing collaboration between our groups and overseas teams, in particular the University of Rochester, the birth-place of SI.

  - Path to exploitation of the work or tools developed within the main work packages

We believe that our program will substantially advance the field and that , fulfilling our program will create new capabilities in the IFE community.
Our scientific goals address the main open issues of DD and SI and will improve our understanding of related physics. The technical goals are related to development of advanced diagnostics (i.e. high-resolution X-ray radiography and spectroscopy, X-ray Phase Contrast Imaging), allowing diagnosing SI experiments in realistic inertial fusion conditions. Also, we will study the possible use for DD and SI of diagnostics from MCF (in particular neutron and gamma-ray spectroscopy). In this respect, it is of particular importance the collaboration with groups which are well established in the field of MCF. These include the research group in Milano (Nocente, Gorini, Croci) and the research group at ENEA (Pacella, Claps, Cordella, etc).

In collaboration with the first group, we want to develop and test a detector based on the Cherenkov effect for measurements of high energy gamma-rays born from fusion reactions in plasmas. The measurement of 17 MeV gamma-rays born from the D+T -> ^{5}He+ γ reaction is being proposed as an alternative method to determine the fusion power in magnetically confined fusion (MCF) plasmas. The reaction occurs together with the main D+T -> ^{4}He+n fusion reaction in deuterium-tritium plasmas, but with a comparatively much lower probability, at a level between 10^{-4} and 10^{-5} depending on the plasma conditions. In inertially confined fusion plasmas, the 17 MeV emission is one of the preferential methods to determine the time resolved yield from high gain implosions as, unlike 14 MeV neutrons, 17 MeV gamma-rays do not experience scattering in the dense plasma medium and their yield is thus representative of the fusion reaction rate. The successful test of this detector will be of relevance for MCF, too.
In collaboration with the group at ENEA, we plan to study the use of LiF X-ray detectors. There is a great interest on the use of LiF detectors for X-ray imaging and spectroscopy at very high spatial resolution in ICF experiments. The incoming X-ray radiation produces volumetric absorption effects on the detector, and this offers the very interesting opportunity of obtaining spectrally-dependent X-ray images on the same detector. Preliminary tests were performed in the past project ENR-IFE19.CEA-01 "Study of Direct Drive and Shock Ignition for IFE: Theory, Simulations, Experiments, Diagnostics development" on the use of LiF crystal detectors in laser-matter experiments in regimes of ICF, using the ABC laser at ENEA-Centro Ricerche Frascati. Further investigations are proposed at the ABC laser within the present proposal. The goal is the assessment of actual potential of these detectors for applications relevant to ICF, as well as possible full application to Magnetic Confinement Fusion diagnostics.
Also, in the previous Enabling Research 2018-2019, new diagnostics for laser produced plasmas have been developed as a byproduct of previous developments in the field of MCF. In particular two innovative techniques were tested, one for gamma rays (Timepix3) and one for soft-X rays

imaging/spectroscopy (Gempix). In particular, preliminary experiments using GEM-pix have been done on the lasers Eclipse (Bordeaux), Vega (Salamanca) and Gekko XII (Osaka), while Timepix3 has been used to monitor of hard-X / gamma rays in experiments at Vega. In the present project, we plan to continue this activity, acquiring more experience and confidence in the use of such diagnostics, in particular by arranging them for 2-D imaging and for 1-D measurement of SXR emissivity coupled with an estimation of the spectral distribution (1-D spectral imaging).

Apart from the interest of the scientific results, and of diagnostics development, our action will open the way to stronger presence of European researchers in international IFE programs (and facilities) in the US and in Asia. Also, our action (and our experiments and experimental proposals) will contribute to consolidate the "academic opening" of the LMJ/PETAL laser facility, therefore consolidating the possibilities for "European" IFE research.

Finally, codes and diagnostics developed within our programme will remain as open and permanent contributions and tools. In particular, as written in the project, we aim at making "advanced" hydro codes with self-consistent treatment of parametric instabilities and hot electrons available to the whole community.

- Scientific motivation for the use of external facilities, e.g. test facilities, experiments or computing resources not part of EUROfusion programme.

  In the framework of the previous Enabling Research project CfP-AWP17-IFE-CEA-01 "Preparation and Realization of European Shock Ignition Experiments", the EUROFusion support allowed us to buy one shot day on Omega, while other shot days were obtained within the LBS (Laser-Based Science) access program at Omega. In other words, we opted for concentrating available economic resources with a single goal shared by all teams (i.e. acquiring laser time on very large facilities) rather than dispersing it among all groups with little final effect. This has both strengthened the internal collaboration among participating groups and allowed to create a real preferential collaboration with Rochester University.

  Within the new project, we want to strengthen our collaborations with the main research centers and laser facilities world-wide:

  Japan: our groups have long standing collaboration with ILE at University of Osaka, home of the Gekko/LFEX facility. However, it is only thanks to the interaction with our groups that a specific research line addressing SI has started at ILE (Univ. Osaka) with the realization of several joint experiments in the period 2019/20 [1]. Additional joint experiments are already scheduled for 2021.

  China: a first joint experiment on the use of medium-Z doped foam for increasing uniformity of laser energy deposition was realized on the Chinese laser SGIIIP within our previous ER EUROFusion project ENR-IFE19.CEA-01 "Study of Direct Drive and Shock Ignition for IFE: Theory, Simulations, Experiments, Diagnostics development". Also, a "letter of interest" has been signed at the IFSA conference 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 is in preparation on the SG II UP facility, scheduled in the first semester of 2021.

  United States: Our main objective is continuing the close collaboration with LLE, Rochester University, home of the Omega laser facility. We are currently analyzing the results of several experiments conducted together, which have been possible thanks to the EUROFusion support. Also, concerning the topic of magnetized inertial fusion (our WP5), two experiments have already been granted for end 2020 and for 2021. In these experiments, implosions will be conducted at Omega adopting a cylindrical implosion geometry with imposed laser-driven seed B-fields. Let's notice that in 2020 Riccardo Betti and Wolfgang Theobald from LLE Rochester and Alexis Casner and Xavier Ribeyre from CELIA have been awarded the joint APS-EPS Landau-Spitzer prize "for major advancements of the shock ignition concept through collaborative experimental and simulation efforts in inertial confinement fusion research". At the moment, we are trying to hire Wolfgang Theobald with a permanent position at CELIA.

  The use of the different laser facilities is in each case justified by the characteristic of the facility itself. In particular, we will use the support from EUROFusion to acquire laser time at Gekko and Omega, while laser-time in the remaining facilities will be granted through existing access programs (e.g. LASERLAB) or through bilateral collaborations. Facilities like Omega, Gekko, SG II and III are particularly important for our project because (at a different level of laser energy), they allow for experiments in spherical geometry and/or offer a combination of long pulse and high intensity laser beams, which allows *mimicking the condition of SI DD experiments. Access to Gekko and Omega is important also because these are the only facilities today working in the DD configuration. In addition, Omega is the only facility where the available laser energy allows for a realistic preparation of experiments to be later proposed and realized on full-scale "ignition" facilities (NIF, LMJ, SGIII).*

- Justification for large total projects in terms of manpower, number of individuals and/or budget.
  Our experimental program is very intense (as it is the accompanying numerical/theoretical work) and includes a large number of groups and researches. This justifies, but also implies, the need for the large support requested to EUROFusion. The research teams of the project are listed below:

  1) CELIA, Université de Bordeaux, Talence - Group Leader: Dimitri Batani, 11 researchers
  2) PIIM, Université de Marseille, Marseille - Group Leader: Sandrine Ferri, 4 researchers
  3) LULI, Ecole Polytechnique, Palaiseau - Group Leader: Bruno Albertazzi, 1 researcher
  4) University of Rome "La Sapienza", Rome - Group Leader: Stefano Atzeni, 2 researchers
  5) Politecnico di Milano, Milano - Group Leader: Matteo Passoni, 1 researcher
  6) INO, CNR, Pisa - Group Leader: Gabriele Cristoforetti, 3 researchers
  7) Università di Milano Bicocca, Milano - Group Leader: Massimo Nocente, 3 researchers
  8) ENEA - Centro Ricerche Frascati, Frascati - Group Leader: Mattia Cipriani, 8 researchers
  9) Universidad de Las Palmas de Gran Canaria (ULPGC) - Group Leader: Ricardo Florido, 1 res
  10) USAL Salamanca - Group Leader: Luca Volpe, 1 researcher
  11) Polytechnic University of Madrid - Group Leader: Javier Honrubia, 3 researchers
  12) University of Valladolid - Group Leader: Marco Gigosos, 1 researcher
  13) Instituto Fusión Nuclear "Guillermo Velarde" - Group Leader: Antonio Rivera, 2 researchers
  14) Czech Technical University, Prague - Group Leader: Jiri Limpouch, 4 researchers
  15) PALS, IPP.CR, Prague - Group Leader: Oldrich Renner, 4 researchers
  16) University of York - Group Leader: Nigel Woolsey, 5 researchers
  17) Central Laser Facility, Rutherford Appleton Laboratory - Group Leader: Robbie Scott, 2 researchers
  18) Imperial College, London - Group Leader: Jeremy Chittenden, 3 researchers
  19) University of Warwick - Group Leader: Tony Arber, 6 researchers
  20) University of Strathclyde - Group Leader: Zheng-Ming Sheng, 3 researchers
  21) Queen's University Belfast , Group Leader: Daniele Margarone, 1 researcher
  22) Wigner RCP, Budapest - group leader: István Földes, 3 researchers
  23) IPPLM, Warsaw - Group Leader: Tadeusz Pisarczyk, 8 researchers
  24) IST, Lisbon, Portugal - Group Leader: Marta Fajardo, 4 researchers
  25) Hellenic Mediterranean University of Crete - Group Leader: Michael Tatarakis, 6 researchers
  26) Kharkov Institute of Physics & Technology - Group Leader: Vasyl Maslov, 5 researchers

  This makes total of 26 groups and 95 researchers involved in the project (we notice that many of them contribute "in kind" to the project). Our project takes the challenge of bringing together these European research groups in a coordinated project focused on SI and DD. There are many open scientific questions concerning the physics of DD and SI, which require a large number of experiments (and considerable theoretical and numerical work). But the step of "achieving a critical mass" requires adequate economical support.

[1] K.Shigemori, T.Kawashima, Y.Hironaka, S.Lee, T.Ueda, H.Nagamoto, D.Batani, J.Trela, Ph.Nicolai et al. "Ultrahigh pressure generation with laser-produced hot electrons" Talk presented at IFSA Conference, St. Malo, France, September 2017