COST Action
Final Achievement Report

MP1208: Developing the Physics and the Scientific community for Inertial Confinement Fusion at the time of NIF ignition

(15/04/2013 to 31/07/2017)

The Action was approved by the Committee of Senior Officials (CSO) on 21-11-2012 and has the MoU reference COST MP1208-MoU.

This report was submitted on 16-11-2017 by the Action Chair on behalf of the Management Committee in fulfilment of the requirements of the rules for COST Action Management, Monitoring and Final Assessment.

COST Association AISBL | Avenue Louise 149 | 1050 Brussels, Belgium
T +32 (0)2 533 3800 | F +32 (0)2 533 3890 | office@cost.eu | www.cost.eu

Funded by the Horizon 2020 Framework Programme of the European Union

Action leadership and participants

Leadership positions

Position	Name	Contact details	Country of work affiliation
Chair	Prof Dimitri Batani	batani@celia.u-bordeaux1.fr +33540003753	France

Position	Name	Contact details	Country of Nomination
Vice Chair	Prof Biljana Gakovic	biljagak@vin.bg.ac.rs +381113408560	Serbia

Working groups

#	WG Title	# of participants	WG Leader	Country of nomination
1	Study of fast ignition and fast electron transport	50	Prof Javier Honrubia javier.honrubia@upm.es	Spain
2	Study of the shock ignition Approach to ICF	50	Dr John PASLEY john.pasley@york.ac.uk	United Kingdom
3	Study of Plasma and Laser Diagnostics	50	Prof Arie Zigler zigler@vms.huji.ac.il	Israel
4	Complementary aspects: Secondary sources of particles and radiation	50	Prof Jose Manuel Perlado Martin josemanuel.perlado@upm.es	Spain
5	Complementary aspects: Astrophysics in the laboratory	50	Dr Jacob Trier Frederiksen trier@nbi.dk	Denmark

Other key leadership positions

Position	Name	Contact details	Country of work affiliation
STSM Coordinator	Prof Biljana Gakovic	biljagak@vin.bg.ac.rs	Serbia

Participants

COST members having accepted the MoU

BE	07/02/2013	**BG**	06/02/2013	**HR**	08/04/2013	**CZ**	26/02/2013	**DK**	29/11/2012
FR	19/12/2012	**DE**	02/08/2013	**EL**	26/02/2013	**HU**	13/12/2012	**IE**	04/06/2013
IL	20/12/2012	**IT**	27/02/2013	**LT**	15/11/2013	**PL**	17/12/2012	**PT**	29/01/2013
RO	26/03/2013	**RS**	13/12/2012	**ES**	18/01/2013	**CH**	01/03/2013	**UK**	29/11/2012

Other participants

Institution Name	Country
Joint Institute for High Temperatures of the Russian Academy of Sciences	Russian Federation
Geothermal Researches of Dagestan Scientific Centre of Russian Academy of Sciences	Russian Federation
Kharkov National University	Ukraine
Vavilov State Optical Institute	Russian Federation
P.N. Lebedev Physical Institute	Russian Federation
Institute of Laser Engineering	Japan

Summary

Main aim/ objective

The main objective of the Action is to develop the physics and the scientific community for Inertial Confinement Fusion at the time of NIF (National Ignition Facility) ignition.

The Action addressed this as described below

The post NIF physics is a wide area that includes not only alternative ignition and burn up concepts but also the use of lasers for material development, research in materials under extreme conditions and certainly new sources of energy. In this line our COST action has been able to support research and contacts in Optics, First Wall materials including new advances in phenomena appearing now in ion irradiation at the level of IFE systems such as electronic excitation. It also has covered the EOS of H (as the main fuel in IFE) in the initial steps of laser illumination.
Besides giving new knowledge to the large fusion facilities as NIF, the main role of the COST community is to build connections and collaborations in the topics. Also the large facilities mainly carry out “one way plans”, i.e. in the case of NIF and LMJ the study of inertial fusion by indirect-drive. In this context the merit of our COST action has also been to open the study of possible alternatives and, in particular, we have been able to establish the “shock ignition” approach to inertial fusion as the main route to inertial fusion energy by laser direct drive. IFE is at present not a simple engineering topic but requires more researches, therefore keeping alive the academic community (outside of big dedicated labs) and consolidating it. This may finally result in solving the problems though alternative methods to those, which today represent the “standard approach” to inertial fusion.

Action website

http://laserfusion.eu/

Achievement of MoU objectives, deliverables and additional outputs/ achievements

MoU objectives

The Action had the following specific objectives:

MoU objective	Level of achievement	Further information (hyperlink or other)
To allow the realization of common experiments (in particular using the mechanism of STSMs) both in Europe and overseas (Japan, US).	76 - 100%	The Action has been completely successful with this objective. The teams working within the Action's framework have coordinated to realize or propose common experiments. Five international experimental campaigns were carried out at PALS laboratory in Prague using the high-energy iodine laser in order to study the physics of laser-target interaction in regime relevant to shock ignition. These experiments have involved: the group of CELIA (University of Bordeaux), the Czech team, IPPLM from Warsaw, the Italian groups (University of Rome "La Sapienza" and Istituto Nazionale di Ottica, INO CNR, Pisa). An experiment to develop the novel diagnostic technique of time-resolved X-ray phase contrast imaging has been done at GSI in Darmstadt using the laser Phelix involving the groups of Bordeaux, GSI Germany, the Swiss team, the Spanish team from university of Salamanca, the University of Rome. Under the framework of the Action, we have submitted several proposals to do experiments on the LMJ/PETAL laser facility, which, as specified in our program, is a key facility for our Action since it is the most energetic laser available in Europe and the only one where full-size experiments on Inertial fusion will be possible. One of such proposals has been selected by the International Scientific Committee and will be performed in Winter 2018. This involves the French teams (Bordeaux and Ecole Politechnique in Palaiseau), INO Pisa, IPPLM Warsaw but also the Japanese groups from University of Osaka and the American group from University of Rochester. Within the framework of the Action we have strengthen the collaboration with the University of Osaka (home of the Gekko/Firex laser facility). This ahs brought to several experiments jointly done during the life span of our Action. Experiments have addressed the feasibility of time-resolved X-ray radiography, the capability of

		creating strong shocks, the study of materials at high pressures. We also have started a collaboration with the University of Rochester (home of the Omega laser facility), which ahs brought to common experiment proposals. Experiments will be jointly realized in 2018 involving the teams from Rochester, Bordeaux, Palaiseau, Warsaw, Pisa and Osaka. Several other smaller experiments have jointly be done by the teams involved in the Action, as apparent from the list of publications. Of particular relevance we should cite the work done on generation and control of EMP (Electromagnetic Pulses) during laser-matter interaction. Experiments have been done for instance at LULI (Ecole Polytechnique), at CELIA, at IPPLM Warsaw. Our Action has played a triggering and pioneering work in attracting the interest of the laser-plasma community in Europe on the topic of EMP. Two one-day workshops devoted to this effect had been organized with the Action support: on March 11, 2016 in Bordeaux, and January 20, 2017 in Warsaw (http://emp2017.ipplm.pl/). This topic is now at the center of several European initiatives. aaa
To catalyze the formation of new scientists competent in this field. In particular, this Action will use a significant part of the budget for the realization of summer schools for Ph.D. and Post Docs.	76 - 100%	Our Action has been completely successful. One of our main goals was to promote excellence via networking, to support research in the field of laser fusion, to encourage mobility of researchers and capacity building via training actions. We both co-organized training activities and supported young scientists and experienced researchers to participate, as external students or lecturers. In particular: The HiPOLIN 2014 Erasmus Intensive Programme, 30th June – 12th July 2014: (http://hipolin.chania.teicrete.gr/): “An Introduction to High Power Light-Matter Interactions”, Rethymno, Greece. *The main objective of the HiPOLIN was to offer high quality training in the field of laser-matter interactions and fusion science and technology.* The 12th Kudowa Summer School, "Towards Fusion Energy", Kudowa Zdrój, Poland, 9-13 June 2014 (http://www.kudowaschool.ipplm.pl). *The school addressed to PhD and Master students from different countries provided courses on fusion energy, plasma experiments and technology.*

The winter school and workshop on Matter in Extreme Conditions: from MATerial science to PLAnetary physics (http://web.luli.polytechnique.fr/MECMATPLA/) Montgenèvre France, February 1-7 2015.

Finally we organized two Summer Schools in Erice (Sicily) in 2015 and in 2017.Each time the duration was 10 days and about 50 students took part. Lessons were given by a team of highly qualified teachers from several research groups in Europe, USA, Japan. We put particular care in realizing a “real” school with a well-structured pedagogical program, at the same time accessible to students and advanced, rather than just proposing a series of seminars.

Our intent for high quality training, met other actions, which already have European dimension. The coordinator of our dissemination activities, M.Tatarakis from Crete coordinated our activities with respect to the organization of European **Master Courses.**

The first one “PLAPA Plasma Physics & Applications” http://plapa.chania.teicrete.gr/ was developed through the Erasmus Curriculum Development Programme. *Partners of the COST MP1208 action were also consortium partners for development of the PLAPA course. Finally, recently, a new project ahs been approved within the ERAMSMUS+ framework, “POWERLAP” including the teams of York, Belfast, Bordeaux, Palaiseau, Salamanca, Crete, Prague*

In addition, several initiatives were possible thanks to our Action. A thesis project on “In-line Phase Contrast Imaging of a shock wave” was allocated in Switzerland with the support of Swiss State Secretary for Education, Research and Innovation (SBFI). In Hungary (Wigner Research Centre for Physics) 2 PhD thesis were done with partial support of MP1208. In the Czech republic a support has been allocated from the Ministry of Education, Youth and Sports for program supporting research by Czech scientists in the frame of existing COST actions, the project number was LD14089 and its title “Rozvoj fyziky pro inerciální fúzi v době jejího zapálení na NIF“ is just Czech translation of the title of our Action.

Finally many STSM have been assigned to young researchers in order to allow them to take part both in training and in research activities.

		In addition to training events, we have organized several scientific workshop and international scientific conferences; for more details see the Action web site http://laserfusion.eu/
To study important physical problems related to ICF.	76 - 100%	Our Action has been completely successful with this respect. We have pioneered the field of “Shock Ignition” approach to inertial fusion and imposed it to the European Fusion agenda. We have established strong links with main research centers in Japan, Russia, and United States. We have obtained several novel very important scientific results, as shown in the list of publications. Our scientific results have been also presented in many International Scientific Conferences. many of these have been organized or co-organized by our Action (we do not report the list since it is readily available from our yearly reports)
Study of matter in extreme conditions (equation of state in the Multimegabar pressure range, radiative properties (opacities), etc.).	76 - 100%	Objective 4 has been fully attained when considered the proposed goals. The energy, deep penetration and time arrival of particles to the first wall and blanket of an Inertial Fusion System without protection, from different target emission after burn up, have been determined considering alternative targets. A comparison of materials under continuous irradiation in magnetic and pulsed in inertial fusion has been performed including the Heat Parameter comparing also with small equivalent experiments. To resist the effect of the ions irradiation in the first wall of an Inertial Fusion Systems we propose the use of nanomaterials. It has been developed and validated nano Tungsten (W) instead of the bulk W that is demonstrated to have a short lifetime. Techniques for manufacturing by HIPMS nano W have been developed with success, including the adhesion to different Structural material layers. Ion Irradiation of nanoW has been performed in FZK Dresden with implantation of H in different conditions and results are compared and published with simulations using Ab initio, Molecular Dynamics and Kinetic MonteCarlo. It is conclude that certainly this nano W proposal can solve the W problems when considering atomistic effects, but being a potential problem the evolution of material because of thermo-mechanical effects. Currently, works do not allow explaining some of the structures present at the solid phase change effect of increased pressure in H. By means of simulation with first principles and Quantum Molecular Dynamics, we compare the structural difference of solid molecular hydrogen pure and solid molecular hydrogen with beryllium, watching beryllium inclusion in solid hydrogen matrix; we obtain several differences in mechanical properties (i.e. elastic constants; in C11 the difference is 37.56 %). This may produce a non-uniform initial compression and decreases efficiency of ignition.

		A quantum kinetic approach based on the Boltzmann equation is developed to describe the response of dielectric and semiconductor materials to high electronic excitation induced by laser irradiation. The formalism describes from the initial photo-ionization inter-band processes through free carrier absorption inducing additional impact ionization to the final heat up by electron–phonon coupling. Swift thermalization through electron–electron scattering, Auger recombination and formation of free excitons, their self-trapping and subsequent non-radiative decay are included. As a result of our calculations the electron energy distribution function, average kinetic energy of the electron system and electron density are obtained as a function of laser intensity, laser photon energy and laser pulse duration. Neutron and Radiation effects in optics have also been analyzed with a solution for aberrations and non-transparency of Silica through a new method of lenses heating. Irradiation of Silica with ions of 0.1 MeV/u leads to the generation of nanometer-sized tracks around the ion trajectory. We have developed and validated an atomistic model able to quantitatively explain the experimental results. The elongation of silver nanoparticles embedded in silica a irradiated with 40 MeV Bromine ions has been understood and published by means of in situ optical measurements and molecular dynamics models. Key importance because of their filter /shielding role to selected emission lines.
Development of so-called "secondary" sources of radiation (X-rays) and particles (energetic electrons and proton beams) and applications in medicine and biology (i.e. tumor therapy by protons etc.).	76 - 100%	We have done a very significant work in this field (again as shown by the list of publications from the groups taking part in the Action). A particular effort has been dedicated to development of novel sources in the X-ray domain for backlighting diagnostics. These could be the main approach to diagnostics for future experiments on laser-plasma interaction and inertial fusion in the regime of laser intensities relevant for shock ignition. In particular we perfume experiments at LULI and Gekko to optimize time-resolved X-ray radiography (in 1D and 2D) and to develop phase contrast time-resolved X-ray imaging. A significant effort ahs been done also on development of proton sources (and for the diagnostic of emitted protons) which will be useful as a diagnostics of laser plasma allowing to obtain proton radiographies which can either measure the density of compressed sample or measure the intense magnetic and electric field self-generated

		during the interaction. We (in particular the group of Wigner Research Centre in Budapest) have investigated the use of noble gas clusters as efficient sources for high harmonic generation. It was shown that besides providing a tunable source in the EUV, the observed frequency shifts reveal the presence of nanoplasmas inside the clusters serving in the same time as a diagnostic of it. The effects of free electrons outside the clusters and electrons inside the nanoplasmas were compared.
Development of novel diagnostics techniques for plasma physics experiments and for laser systems.	76 - 100%	The Action has been completely successful in this respect. In particular our groups have been at the core of the project PETAL+ for the development of novel diagnostics for the Academic European Community on the LMJ/PETAL laser facility. PETAL+ is a special project (EquipEx) funded by the National Research Agency (ANR) with a budget of 9.3 M€ and coordinated by the University of Bordeaux. Among other initiatives, we may recall again the study of very high electromagnetic pulses, which may be generated when high-energy high-intensity laser pulses are focused on targets. Their electric fields may reach hundreds of kV/m in vicinity of the target. Such pulses pose very serious problems for a reliable operation – or even survival – of diagnostic devices relying on electronics, therefore their impact for “diagnostics” is clear. At the same time, EP itself can be sued a novel diagnostics of laser-matter interactions (in particular for hot electrons and return currents) We also have studied new diagnostics for measuring the magnetic fields self-generated during laser-matter interaction. The group at CELAI ahs made a significant work on time-resolved imaging polarimetry and on using proton radiography. The group in Prague has developed algorithms for reconstruction of density and magnetic fields from complex interferograms enabling precise reconstruction of fields even for low-quality diagnostic beams. Diagnostics for KrF lasers as alternative possible drivers for ICF have been studied in particular by the Hungarian group. Due to the low gains the beams have long passes, thus the developed active beam stabilization method has a considerable significance. The short pulses for fast ignition require high contrast. It was demonstrated that even for UV laser a highly efficient plasma mirror is possible on the 248 nm wavelength. At the Lebedev Physical Institute of

		the Russian Academy of Sciences, the GARPUN-MTW laser facility was used to demonstrate the effective suppression of small-scale multiple filamentation of UV radiation with a peak power of terawatt (four orders of magnitude exceeding the critical power self-focusing in air) during the propagation of UV radiation in xenon This allows reducing the loss of energy in KrF amplification, to increase the output energy and radiation power, and also to reduce the beam divergence and focal spot on a target.

Deliverables

The Action reported the following deliverables:

Deliverable	Timing of deliverable	Further information (hyperlink or other)
The deliverables are contained in the document "Monitoring_Progress_Report_MP1208_Batani" of 1/11/2015: 1) Reports from the 5 WGs 2) Preparation and realization of experiments on large-laser facilities 3) Preparation of pedagogical material on ICF science. 4) Preparation of final document on “Science with High-Energy Lasers and pathway to Shock Ignition on LMJ/PETAL”	Delivered	http://laserfusion.eu/

Additional outputs/ achievements

N/A

Projects

N/A

Other outputs / achievements

N/A

Impacts

The Action reported the following impact(s):

Description of the impact, i.e. what will change, and for whom, as a result of what the Action achieved	Type of impact	Timing of impact
the merit of our COST action has also been to open the study of possible alternative paths to Inertial Confinement Fusion and, in particular, we have been able to establish the “shock ignition” approach to inertial fusion as the main route to inertial fusion energy by laser direct drive.	• Scientific / Technological	Achieved
we have established an international scientific prize to commemorate one of the founders of the directly driven Inertial Confinement Fusion for Energy studies in Europe. It is rewarding active researchers at mid-career (within 15 years of the doctoral degree) working on ICF-related topics. In 2017 the co-chairs of the International Conference on Inertial Fusion Sciences and Applications (IFSA), the most important international scientific conference in the field, have decided to endorse the Edouard Fabre prize therefore continuing it beyond the life of our Action.	• Scientific / Technological	Achieved
we have identified the following issue for future European collaboration projects, and we have started to build the community on this topic (which may results in submission of proposals for new COST Actions): impact of Electromagnetic Pulse generation (EMP) on diagnostics. This topic is not only relevant for laser installations but also for many other experiments working in a "harsh environment"	• Scientific / Technological	Foreseen within two years
we have identified the following issue for future European collaboration projects, and we have started to build the community on this topic (which may results in submission of proposals for new COST Actions): development of techniques for target fabrication and target characterization. An interdisciplinary field covering many kind of laser facilities (laser but also synchrotrons, etc.) and implying important development in material sciences and diagnostics	• Scientific / Technological	Foreseen within two years

Dissemination and exploitation of Action results

Dissemination and exploitation approach of the Action

The Action's dissemination and exploitation approach as well as all activities undertaken to ensure dissemination and exploitation of Action results and the outcomes of these activities are described below.

Our Action ahs done three main dissemination activities. First, we have realized a web site http://laserfusion.eu to give information on our Activities and on laser driven inertial fusion research in general. Recently, the Action website laserfusion.eu was moved to a server belonging to IPPLM in Warsaw. The website will be maintained beyond the lifetime of the Action to service the needs of the ICF community for as long as it takes. In particular it will serve as web site of the EUROFUSION "enabling research" project on "Preparation and Realization of European Shock Ignition Experiments" Second, we realized movie on laser fusion and our COST action, which has been spread and widely sued, in our initiatives. The movie "Fusion Energy – a solar power plant on earth" is available on our web site at http://laserfusion.eu/about Third, in 2014, we have established an international scientific prize to commemorate one of the founders of the directly driven Inertial Confinement Fusion for Energy studies in Europe. It is rewarding active researchers at mid-career (within 15 years of the doctoral degree) working on ICF-related topics. In 2017 the co-chairs of the International Conference on Inertial Fusion Sciences and Applications (IFSA), the most important international scientific conference in the field, have decided to endorse the Edouard Fabre prize therefore continuing it beyond the life of our Action. The prize will be chosen by an international selection committee comprised of the chair of the COST MP1208 action, 6 members nominated by the IFSA co-chairs (2 from Europe, 2 from Asia and 2 from America) and the last 2 winners. The committee members are not eligible for the prize. The Past winners of the prize in historical order are: 2014: Gianluca Gregori (U. Oxford) and Stéphane Sebban (LOA), 215: Pierre Michel (LLNL), 2016: Jérôme Faure (LOA), 2017: Alexis Casner (CEA) and Felicie Albert (LLNL).

Dissemination meetings funded by the Action

The Action did not fund any Dissemination Meetings

Other dissemination activities

The Action also undertook the following dissemination activities:

Activity	Our Action ahs done three main dissemination activities. First, we have realized a web site http://laserfusion.eu to give information on our Activities and on laser driven inertial fusion research in general. Recently, the Action website laserfusion.eu was moved to a server belonging to IPPLM in Warsaw. The website will be maintained beyond the lifetime of the Action to service the needs of the ICF community for as long as it takes. In particular it will serve as web site of the EUROFUSION "enabling research" project on "Preparation and Realization of European Shock Ignition Experiments" Second, we realized movie on laser fusion and our COST action, which has been spread and widely sued, in our initiatives. The movie "Fusion Energy – a solar power plant on earth" is available on our web site at http://laserfusion.eu/about Third, in 2014, we have established an international scientific prize to commemorate one of the founders of the directly driven Inertial Confinement Fusion for Energy studies in Europe. It is rewarding active researchers at mid-career (within 15 years of the doctoral degree) working on ICF-related topics. In 2017 the co-chairs of the International Conference on Inertial Fusion Sciences and Applications (IFSA), the most important international scientific conference in the field, have decided to endorse the Edouard Fabre prize therefore continuing it beyond the life of our Action. The prize will be chosen by an international selection committee comprised of the chair of the COST MP1208 action, 6 members nominated by the IFSA co-chairs (2 from Europe, 2 from Asia and 2 from America) and the last 2 winners. The committee members are not eligible for the prize. The Past winners of the prize in historical order are: 2014: Gianluca Gregori (U. Oxford) and Stéphane Sebban (LOA), 215: Pierre Michel (LLNL), 2016: Jérôme Faure (LOA), 2017: Alexis Casner (CEA) and Felicie Albert (LLNL).
Target	General Public and Scientific community
Outcome	Very good
Link	http://laserfusion.eu/

Exploitation activities

The Action undertook the following activities to ensure exploitation (use, in particular in a commercial context) of the Action's achievements:

No input provided by the Action

Action Success(es)

The Action’s two most significant successes were the following:

- We have more than 2 main success: Being the seed of the new EUROFUSION project including collaboration with the University of Rochester and the University of Osaka. Establishing the Prize Fabre Creating many summer school and Erasmus Master projects Preparing a joint proposal for the LMJ/PETAL laser facility Realizing the movie on fusion

Action Expenditure

The table below shows the budget allocated to the Action for each Grant Period:

#	Grant Period	Start Date	End Date	Budget allocated to Action (EUR)
1	MP1208-20130522	2-6-2013	1-6-2014	118,000.00 (EUR)
2	MP1208-2	2-6-2014	31-5-2015	134,000.00 (EUR)
3	CGA-MP1208-3	1-6-2015	30-4-2016	121,993.74 (EUR)
4	AGA-MP1208-4	1-5-2016	30-4-2017	105,000.75 (EUR)
5	AGA-MP1208-5	1-5-2017	31-7-2017	25,250.00 (EUR)