MEMORIA CIENTÍFICO-TÉCNICA PROYECTOS INDIVIDUALES

Convocatoria 2024 - «Proyectos de Generación de Conocimiento» y actuaciones para la formación de personal investigador predoctoral asociadas a dichos proyectos.

Tipos A, B y RTA

AVISO IMPORTANTE - La memoria no podrá exceder de 20 páginas. Para rellenar correctamente esta memoria, lea detenidamente las instrucciones disponibles en la web de la convocatoria. Es obligatorio rellenarla en inglés si se solicita 100.000 € o más (en costes directos).

IMPORTANT – The research proposal cannot exceed 20 pages. Instructions to fill this document are available at the website. If the project cost is equal or greater than 100.000 €, this document must be filled in English.

1. PROPOSAL DATA

IP 1: Alfonso de Castro Calles

TÍTULO DEL PROYECTO (ACRÓNIMO): Blindajes de plasma de metal líquido como soluciones de nueva genereación para extracción de potencia en dispositivos de fusión magnética (LIMPLASH)

TITLE OF THE PROJECT (ACRONYM): Liquid Metal Plasma Shields as new generation power exhaust solutions for magnetic fusion devices (LIMPLASH)

2. JUSTIFICATION AND NOVELTY OF THE PROPOSAL

2.1. Adequacy of characteristics and the purpose of selected modality.

Selected modality: Research-oriented Type A. This project aims to participate in solving one of the most critical issues for the development of magnetic fusion energy as a feasible and economically viable clean energy source. This remaining scientific challenge is the development of reactor-relevant power handling scenarios through the selection of adequate and sufficiently resilient Plasma Facing Components (PFCs) able to withstand the extreme heat flux conditions expected in future fusion devices. Herein, we propose to experimentally study Liquid Metal Plasma Shields, generated in front of Liquid Metal (LM) PFCs, as alternative and novel method that can decisively contribute to the power exhaust handling challenge. The development of such reactor-relevant solutions for the expected extremely harsh power exhaust environment is one of the main problems identified in the European Research Roadmap of EUROfusion (European Consortium for the development of fusion energy). The proposal therefore aims at contributing to solve one of the most pressing global challenges of our society, identified in the Horizon Europe, FP9 Frame Program: Generation of Clean, Efficient and Safe Energy for the future. The development of fusion energy is also present in the list of key actions to be prioritized within the strategic line regarding energy transition and de-carbonization included in the Spanish Plan Estatal de Investigación Científica, Técnica y de Innovación 2024-2027 (PEICTI, Annex I group “Energy and Mobility”).

2.2. Justification and expected contribution of the project to the generation of knowledge on the theme of the proposal. Starting hypothesis

Within the magnetic fusion research, one of the key remaining issues for its development is the performance and resilience of the elements in unavoidable contact with the fusion plasma, the so-called Plasma Facing Components (PFCs). In future devices and reactor prototypes, to accomplish the mandatory power exhaust coming from the escaping plasma, they will need to withstand enormous power loads. The divertor elements (where the plasma exhaust is directed) will be exposed to steady state fluxes ≥10 MW/m^2, value that challenge the physical limits of tungsten (W) that is the known solid material with best thermo-physical capacities, the material selected for ITER and the main conservative option considered for future demonstration prototypes (DEMO) [1-2]. Moreover, intrinsic plasma instabilities (Edge Localized Modes -ELMs- and disruptions among others), that characterize the more advanced magnetic fusion devices (tokamaks), produce off-normal transient events whose associated heat fluxes (GW/m^2 range in few ms timescales) can be catastrophic for the integrity of W

PFCs, severely damaging the armor even in just one event. Adding the stringent neutron irradiation expected in real reactor scenarios, up to date there is no currently known solid material that can withstand these off-normal transient thermal loads if an absolute prediction and mitigation strategy for such events is not guaranteed. When scaled and extrapolated to the predicted values for DEMO prototypes, such transient heat loading will provoke deep cracking/mechanical failure in the device armor and fateful effects in the underlying cooling systems [3] all this resulting in unavoidable machine shutdown as well as in major replacement cost. Ultimately, at real fusion reactor scale, these constraints will be derived in insufficient power plant availability and/or impractical economic feasibility, thus dramatically affecting the entire economic and technical viability of the fusion device.

Regarding the power exhaust task of steady state heat flux in projected DEMO divertor baselines, to ensure a minimum desirable lifetime for the W elements (1-1.5 years), an extremely uncertain highly radiative, as well as disruption and almost ELM free, power exhaust scenario will be necessary [4]. It will suppose a total radiation fraction of escaping power around 97 % that appears necessary to mitigate the heat flux to the divertor elements up to the established physical limits of W (10 MW/m^2) [4-5]. The commented regimes are intended to be driven by the massive injection of impurities in both plasma edge and core (so-called plasma detachment) [6]. However, these highly radiative scenarios (combined with ELM and disruption-free operational modes) need to be experimentally achieved for sufficiently long pulse operation and, at the same time, demonstrate the envisioned plasma confinement levels with an absolute control of the operational conditions. Such operational scenario will be, in the best case, really constrained and characterized by a very small and risky safety margin in order to avoid the damage to W tiles, the evolution to low confinement mode (that will preclude any thermonuclear gain) or otherwise the plasma radiative collapse.

As the physics/technical feasibility of such conventional W PFC solutions and the mentioned power exhaust scenario do not appear guaranteed or straightforward, active research on novel, advanced and alternative Liquid Metal (LM) PFCs [7] has emerged mainly using Tin (Sn), lithium (Li) and their alloys (SnLi) as candidates. Amid a fusion-relevant heat load irradiation scenario, LM surfaces can act as a sacrifice interface by favoring the creation of LM vapor/plasma clouds in front of it. This happens as a result of the interaction between eroded/evaporated LM atoms and incoming plasma particles/heat fluxes. The process is generally denominated vapor shielding [7-8] and offers an alternative, novel approach to the power exhaust problem. Under control, the mechanism is envisioned to produce partial mitigation of the incoming heat flux with a lower necessity of injecting extrinsic impurities in the plasma. In this way, the power load fraction that utterly reaches the PFC substrate surface/structure can be decreased due to the volumetric dissipation that takes place in the created LM cloud. Therefore, the process allows to enhance the total power exhaust capabilities beyond single conductive transfer that characterizes solid W PFCs (additional vaporization, radiation and convection channels in the LM layer and vapor/plasma cloud) [9].

Last but not least, the liquid surface exposed to plasma possesses self-healing and self-replenishment characteristics that can protect the underlying armor from neutron and plasma exposure [7], being a question especially crucial when facing a destructive transient event, that as previously mentioned, will be fatal for a solid W PFC if no sacrificial layers (i.e. LM surface) are able to mitigate it. Such higher resilience to transients will be necessary in reactor prototypes as the presence of such off-normal episodes is undoubtedly expected. They will decisively affect the economy and technical feasibility of any future fusion power plant [10] being such kind of induced deleterious effects already observed in WEST tokamak (cracking in W PFCs) even under conditions not as stringent as the expected in DEMO future prototypes [11].

The experimental study and data analysis work on the **fundamental characterization of LM enriched plasmoids and their associated thermal shielding regimes** are the main objective of this proposal. This research on LM PFCs and their associated plasmoids attempts to explore an alternative solution that can help to handle the extreme power exhaust scenario in future magnetic fusion devices. The endeavors will be centered in the understanding and characterization of LM plasmoids generated under high heat flux irradiation (such as the shown in Figure 1), also describing and quantifying the thermal shielding regimes associated to it.

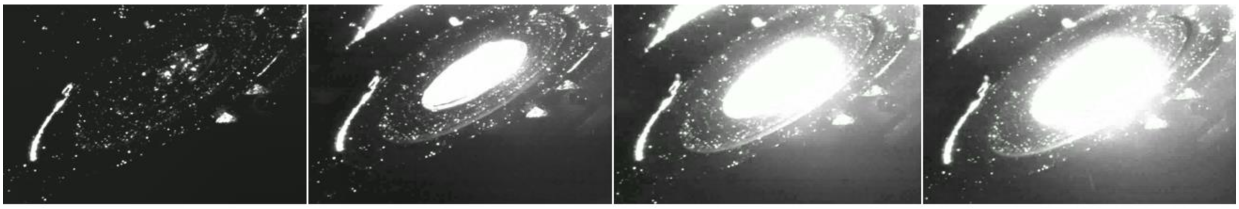


Figure 1. Sequence of images taken with a fast-frame camera showing an example of semispherical Sn plasmoid (developed under 22 MW/m^2 particle beam exposure) expansive behavior. The first interaction of the beam with the target occurs at t=1010 ms (left frame) and beam switch off at t=1100 ms

We propose to experimentally explore these questions by irradiating selected LM targets with fusion relevant heat fluxes. Such power loading will be provided by a H^0/H^0-H^+ particle beam (OLMAT High Heat Flux, -HHF-facility [12]) and a high-energy CW laser, as proxies for the nominal and transient plasma heat fluxes to be expected in a real fusion reactor environment. Both facilities are placed at the Laboratorio Nacional de Fusión (LNF) of CIEMAT. The LM targets will be based on the Capillary Porous System [13-14] basically consisting of a tungsten porous substrate (tens-hundreds micron size) in which a liquid metal is impregnated (Sn and SnLi alloys). The OLMAT HHF facility is a scientific installation annexed to the TJ-II stellarator (infrastructure included in the Spanish map of Unique Science and Technology Infrastructures –ICTS-). It is the only experimental facility in Spain (and among the few in Europe) able to simulate and combine both the transient and nominal power loading conditions expected in the divertor of future fusion devices.

Regarding the protective effect driven by LM clouds, in previous works with Sn targets at the Pilot PSI linear plasma device [15-16], under power densities up to 22 MW/m^2 a partially ionized tin vapor cloud in front of the LM surface (target temperatures oscillating between 1800-2000 K) was found. Similar experiments were performed for liquid lithium targets at Magnum PSI indicating triggering target temperatures for the shielding Li cloud around 1100-1200 K when irradiating at power densities around 9 MW/m^2 [17]. Up to date, however, no relevant thermal shielding regimes have been observed for the case of SnLi alloy prototypes. Despite their relevance, these works did not focus on the local characterization and fundamental understanding of incipient stages, onset, dynamics, and physics evolution of the vapor/plasma clouds within ms time scales and specially in the phases where the non-stationary nature of the system involve clear changes in LM vapor/plasma composition and density. Additionally, no attention was paid to possible effects induced by collisional processes of high energy (20-30 keV) hydrogenic particles. These species are predicted to exist in ITER due to sheath acceleration of pedestal energy H^+ ions (5 keV) up to ≈20 keV during intra-ELM phases [18] and are naturally present in the OLMAT particle beam. All these questions are essential to predict the eventual armor protection capabilities of the partially ionized vapor cloud in the complex environment of a future fusion device divertor region. As better detailed in section 3.3, the IP candidate has developed a **novel diagnosis method**, based on a **Langmuir Probe (LP) directly embedded on the center of the LM target**, that has allowed a deeper and continuous local characterization of generated LM plasmoids with temporal resolution in ms scales [19-21]. Such novel experimental approach provides a powerful tool to advance in the study and understanding of these complex systems as well as to generate relevant knowledge and results within the topic and clearly useful for the future development of LM PFC reactor-scale solutions.

The novel diagnostic employed in experiments with Sn and SnLi targets has allowed an innovative, sound and original characterization (also combined with spectroscopic measurements) of this type of LM-based plasmoids. The research attempts to delve deeper in the vapor shielding dynamics and to elucidate how they can contribute to the power exhaust regimes envisioned for future fusion devices. These are questions of paramount importance when considering real LM divertor scenarios foreseeing operation with ELM containing regimes. However, so far, the experiments have been concentrated mostly in Sn, showing very encouraging results only within the onset/early deployment phases (the main LM plasmoid state observed in the limited experimentation up to date). Additionally, many open scientific questions remain unclear, as for example:

-Can the LM plasmoid content (and perhaps other associated plasma parameters) affect the sheath potential and the subsequent heat transmission factors (electron/ion channels) to the exposed surface?

-How the pressure balance between the created plasmoid and the incoming heat flux can affect the thermal shielding/heat loading of the exposed surface?

-How the thermal shielding can evolve in further stages if pulse duration is enlarged and if particle beam-laser irradiation is combined?

- What can be the role of high, ELM-like, energy particles colliding with eroded LM atoms in the generation and deployment of these plasmoids?

This research proposal aims to continue this recently open research line, fully extend it to SnLi alloy targets and develop technological upgrades to eventually apply this research to pure lithium PFCs. Additionally, it pursues to answer the previously mentioned scientific fundamental questions and generate basic knowledge to significantly advance in the **comprehension and understanding of LM plasmoids** capable of **contributing** to the major task of **power exhaust in future fusion devices**.

Finally, is important to highlight that this research and the expected generated knowledge appears prone to synergy and can be exported to other emerging, interdisciplinary fields and applications in which novel material solutions are being explored to handle extreme heat fluxes. The fundamental understanding of LMs, their thermal management properties and the associated characteristics of the deployed vapor/plasma clouds may pave the way to revolutionize important cutting edge disciplines and provide new generation scientific/technological solutions. Possible synergetic actions can be encountered for example in electronics (extreme ultraviolet lithography driven by Sn plasmoids [22]) as well as materials for extreme applications in aerospace technology (ablative sacrificial tiles for rocket re-entry or hypersonic devices), biomedicine… [23].

2.3. Justification and expected contribution of the project to solving specific problems linked to the selected thematic priority

Within “Plan Estatal de Investigación Científica, Técnica y de Innovación 2024-2027” (PEICTI) and the corresponding Annex I, the thematic priority in which this proposal fits are: Energy and Mobility, strategic line: Transición Energética y decarbonización.

Worldwide energy demands are expected to considerably increase in the next decades due to the projected economy, population and consumption growth. During the last decades such growing human activity, mostly based on fossil fuel consumption, have made visible the associated anthropogenic effects in greenhouse gasses emission and biosphere modification that are accelerating the climate change and nature degradation trends. To combat this situation, strong actions oriented to economy de-carbonization and green energy transition are claimed in an attempt to lessen and/or mitigate the impact of human activity in the planet. These questions are explicitly considered in the United Nations (UN) Sustainable Development Goals number 7 “Affordable and green Energy” and number 13 “Climate Action”, as well as in the recently Pact for the Future (https://www.un.org/en/summit-of-the-future/pact-for-the-future), adopted by UN Member States in September 2024 that confirms the need to transition away from fossil fuels such as coal, oil and gas in energy systems to limit climate change and preserve a livable planet.

Within these actions, some milestones underlie in reducing the global dependence on fossil fuels and the development of new baseline, large scale and carbon-free energy sources at the same time capable of counteracting the intrinsic temporal intermittency of other well-developed technologies (such as solar and wind power). Such endeavors appear paramount for de-carbonizing the electricity supply and provide affordable and reliable electricity to a growing global population being central to any climate change strategy. The climate and biosphere degradation emergency need such immediate actions, being the next decades crucial to putting the world on such a pathway. This will be mandatory if the exacerbation of climate disasters (with disrupting effects in economies and severe humanitarian consequences especially affecting the poorest and more vulnerable regions) wants to be avoided.

Under such scenario, nuclear fusion is seen as hopeful option with intrinsic 24/7 availability and tremendously high energy density potential. It plans to use raw materials inexhaustible in the human time scale and not geographically concentrated, being the power generation theoretically free of long-lived radioactive wastes and inherently safe (no danger of runaway reaction or explosions unlike fission energy). Furthermore, research on fusion energy is being boosted in the last years due to the positive concurrence of private-public collaboration and advances in multidisciplinary cutting-edge disciplines (new generation materials, high performance computation, artificial intelligence…). However, nuclear fusion is not available yet, being at scientific/experimental phase and consequently significant investment, basic research and technological advances are needed to bring it to the grid. ITER device (under construction in Cadarache, France) aims to experimentally demonstrate the achievement of breakeven conditions (where more energy is released through deuterium-tritium fusion reactions than the amount necessary to heat the plasma). For the posterior steps towards commercial viability, Demonstration Power Plant (DEMO) projects are programmed. Both major milestones face really stringent physical and technological challenges. As outlined in the previous sections one of the most important is the power exhaust handling (mandatory in any magnetic fusion prototype) where this proposal aims to contribute throughout an original and novel approach.

The application of this project to the modality of oriented research projects in the main thematic area of "Physics Science", secondary thematic subarea of "Particle Physics and Nuclear Physics" within PEICTI thematic priority "Climate, Energy and Mobility" seems natural and adequate.

3. OBJECTIVES, METHODOLOGY AND WORK PLAN

3.1. General and specific objectives.

General objective: Investigate the physics and advance in the understanding of LM plasmoids (Sn, SnLi and/or Li). Explore their heat flux mitigation potential capacities to be harnessed in power exhaust scenarios of future fusion devices. This main research goal is divided in the following specific objectives:

Objective 1.1: Preparation of new LM filled targets for the experimentation with particle beam and laser exposure. Wetting with Sn and SnLi as well as thermal calibration in the Plasma Surface Interaction laboratory of CIEMAT

Objective 1.2: Experimental testing of LM filled targets (Sn and SnLi) at CIEMAT and possibly in Magnum-PSI. Upgrading of LP and spectroscopy diagnosis to extend the characterization of LM plasmoids

Objective 1.3: Data analysis of the results obtained with the different targets (Sn, SnLi) and electrical probe/spectroscopy diagnosis configurations

Objective 1.4: Preparation of the experimental facilities to extend the research to pure Li PFCs (when accomplished technical upgrades allow)

Objective 1.5: Dissemination of the results

3.2. Description of the methodology.

A proactive, progressive and multidisciplinary methodology will be used in an attempt to optimize the research and the results to be obtained. Sn and SnLi alloy filled targets will be prepared and thermally calibrated in the Plasma Surface Interaction Laboratory of CIEMAT. Then, they will be exposed to combined particle beam/laser irradiation as proxies of the heat flux scenario expected in future fusion devices (both steady state and transient loads). This will aim to explore the LM plasmoids behavior in longer timescales also exploring multi-pulse laser operation that will try to mimic the effects of highly-repetitive (tens Hz), ELM transient loading to be expected at relevant fusion devices.

This experimentation will cover Sn and SnLi alloy targets, also testing different configurations for the LP and spectroscopy diagnostics trying to find more resilient probes and an optimized spatially distributed diagnosis of the LM clouds. After the experimental testing, the temporal evolution of the generated LM plasmoids, the physical mechanisms below their generation and their heat flux mitigation capabilities will be studied. For this purpose, a deep analysis work will be conducted to characterize such vapor/plasma clouds characterizing them in terms of parameters as: electron temperature and density, sheath and plasma potential as well as ionic/neutral composition, by using different versions of LP and spectroscopic configurations. Other parameters as the surface LM distribution/coverage, the thickness of the LM layer and the derived post-mortem erosion/surface damage rates (than can be preferential depending on Li/Sn thickness) will be also taken into account. The thermal response of the target will be determined by pyrometry, and visualization tools (fast-frame cameras) will be used to observe the expanding dynamics of such clouds.

The results of this experimentation and data analysis will be reviewed in order to select the optimal target configurations (in terms of substrate, LM type surface and diagnostic configuration). The more promising/relevant LM targets and diagnostic configurations will be selected with the goal of exposing them at Magnum PSI linear plasma device that can reproduce conditions even more relevant when compared to the expected at a real fusion device divertor. Finally, the first conceptual design endeavors and technical efforts to adapt/upgrade the HHF facilities for liquid lithium PFC testing will be carried out. As part of this methodology, the following activities are proposed:

Objective 1.1 Preparation of new LM filled targets for the experimentation with particle beam and laser exposure.

Task 1.1.1. Different W-based target substrates will be selected to be exposed to high heat fluxes (both particle beam/laser and also combining them). The selection of W substrates will be done taking into account existent ones and new generation W substrates (most likely fabricated by 3D printing, additive manufacturing, thanks to an ongoing collaboration with a private company, AENIUM).

Task 1.1.2. For every substrate the preparation endeavors will include wetting processes with the LM candidate (Sn, SnLi alloy). Regarding the wetting process, as liquid metals pose high values of surface tension, the adequate pattern (homogeneous substrate surface coverage by the LM) is not trivial and may require very high temperatures (up to 1100ºC for Sn). Moreover, it needs to be achieved at temperatures compatible with the material vapor pressure and available operational conditions. At this respect is important to highlight that for the more challenging case (pure Sn) the research group has developed a laboratory method to decrease this required wetting temperature considerably (up to around 500ºC) by using an atmosphere with presence of hydrogen radicals [24]. In the case of SnLi alloy, it is important to mention that the group has a stored amount of the alloy under inert Argon conditions that can be used for starting the experimentation, although the synthesis/procurement of another alloy amounts may be necessary. The IP candidate has previous experimental experience on SnLi alloy synthesis and wetting on selected substrates [25]. Additionally, some specific characterization on the homogeneity and composition of the LM coverage may be done by means of surface techniques as SEM/EDX as well as SIMS.

Task 1.1.3. Specific thermal calibration works necessary for the absolute determination of the surface temperature values and its evolution during the experiments. The response of the IR pyrometry sensor depends on the emissivity of the exposed LM surfaces and vary with Sn/Li composition, hence these works will be especially important for the case of SnLi targets where such LM surface content will vary during the experimentation as surface erosion evolves. Calibration of different surfaces varying in the Sn/Li composition (from pure Li to pure Sn) may be necessary.

Milestones: Complete preparation of suitable new targets wetted with Sn and SnLi alloys **(M1).**

Deliverables: Sn and SnLi targets properly wetted with corresponding thermal calibration characteristics **(D1).**

Objective 1.2 Experimental testing of LM filled targets (Sn and SnLi) at CIEMAT under both particle beam and laser irradiation. Upgrading and further testing with LP and spectroscopy to extend the characterization of LM plasmoids. If time and funding allow the optimal LM PFC and electrical probing/spectroscopy configurations will be selected to be utterly tested at MAGNUM-PSI.

Task 1.2.1. Extend the previously performed characterization with Sn to further phases of the shielding regime also exploring laser operation (single pulse and utterly multi-pulse) combined with particle beam irradiation to simulate simultaneous exposition to nominal and ELM-like transient loading at reactor scale. Exportation of this experimentation to SnLi alloy targets. Operation with laser pre-heating (continuous mode) followed by particle beam irradiation will be also explored, attempting to achieve deeper and denser stages of the LM plasmoids at eventually larger surface temperatures. Weight loss/gain experiments with witness samples to infer LM re-deposition/erosion can be also carried out.

Task 1.2.2. Explore and develop upgraded diagnosis of the LM plasmoids. The previous LP characterization has been successful up to power densities of 35-40 MW/m^2 and pulse durations up to 150 ms but has shown problems related to the deterioration of the insulator elements (alumina ceramics) at temperatures of 1500-1600ºC when they were directly embedded on the target center. For this reason, new ceramic insulators will be explored and different probe configurations (lateral ones) will be tested and combined with the existent ones trying to find more resilient probes with an optimized and spatially distributed diagnosis of the plasmoids. In terms of spectroscopy, the employment of specific optical systems (based on focusing lenses) is also envisioned to separately explore different regions of the plasmoid (core-edge).

Task 1.2.3. Selection of the best LM PFC and electrical probing/spectroscopy configurations to be utterly (if time and funding allow) tested at MAGNUM-PSI.

Milestones: Exposition of Sn and SnLi targets to simultaneous/sequential particle beam+laser exposure under different diagnosis (LP and spectroscopy configurations) scenarios **(M2).**

Deliverables: Experimental data regarding the electrostatic (LP) and spectroscopic characteristics of the generated plasmoids, the surface temperature evolution of the target, and the geometry of the generated clouds **(D2).**

<u>Objective 1.3</u> Data analysis of the results obtained with the different targets (Sn, SnLi) and electrical probe/spectroscopy diagnosis configurations.

Task 1.3.1. Determination of the temporal dynamics of the Sn/Li LM plasmoids and specific analysis on the role of LM content/composition on plasma sheath potential that can be related to the heat flux transmission factors and possibly to power mitigation metrics. Investigation on the fundamental atomic processes behind the creation of these plasmoids and possible role of the ELM-energy hydrogenic species coming from the particle beam. Complementary characterization of the surface damage/protection effect driven by the LM plasmoids on the targets and possible comparison to LM uncovered W matrix.

Task 1.3.2. For the SnLi alloy targets, specific analysis on the role of Sn/Li surface content and the derived erosion rates (than can be preferential depending on Li/Sn thickness) in the nature, composition and density of the plasmoids.

Task 1.3.3. Thermal analysis (including evaporation, thermal sputtering and radiative contributions) to determine power dissipation characteristics and estimate heat flux mitigation by the LM clouds within the most relevant LM plasmoids developed. Specific additional modelling works with engineering/multiphysics tools (such as ANSYS) may be incorporated here for benchmarking if time and human resources allows.

Milestones: Development of analysis methods to accurately characterize the LM plasmoids evolution and the atomic physics phenomena behind their deployment in the case of Sn/Li species after exposition to combined particle beam/laser irradiation at LNF and ideally under linear plasma exposure at MAGNUM-PSI **(M3).**

Deliverables: Experimental results (mostly from LNF experiments but ideally from MAGNUM-PSI as well) containing the evolution of parameters as: electron temperature and density, floating, plasma and sheath potential, plasmoid ionic/neutral composition depending on time and surface temperature. Radiative, evaporative and thermal sputtering contributions within the heat dissipation metrics. Power load shielding conditions in terms of densities and plasmoid compositional thresholds **(D3).**

Objective 1.4. Preparation of the experimental facilities to extend/adapt the research to pure liquid Li PFCs.

They offer advantages in terms of compatibility with plasma, more benign liquid surface behaviour and benefits in plasma confinement/performance at fusion device scale that should not be ignored. However, due to the larger values of vapour pressure of Li in the expected temperature operational window, the necessary final research with lithium will ultimately imply upgrades in the systems (crucial target active cooling with translation capabilities). These global strategic actions are considered as a future major milestone for the research team but its completion most likely exceeds the time duration of this proposal. Crucially, the IP candidate has a previous broad research experience with liquid lithium PFCs [26-27] at the University of Illinois (institution that leads the worldwide efforts to bring actively cooled liquid Li PFCs to future fusion reactors) and maintain continuous support/collaboration with his previous advisors (Professors D. Ruzic and D. Andruczyk). Such experience places the IP candidate at a privileged and optimal position to go ahead within the duration of this proposal with the first actions for eventually exposing Li targets and study such pure Li plasmoids in the most relevant shielding regimes.

Task 1.4.1. Literature/technical review on the possibilities for the cooling system with translation/manipulation capabilities. Active collaboration (including brainstorming sessions) with DiFFER and UIUC work team members in order to identify and select the more suitable oil and/or inert gas cooling options (water cooling is in principle not compatible with liquid lithium due to safety concerns) that will be necessary for testing liquid Li targets at LNF.

Task 1.4.2. Conceptual design, heat transfer modelling and technical works on the selected cooling system with translation capabilities. Possible endeavors on the assembly of the first components and their technical implementation.

Milestones: Progress report identifying the most suitable/optimum cooling system and accessory elements as well as setup assembly **(M4).**

Deliverables: Preparation, purchase and machining of the first main elements. If time allows the first works for their installation may be started **(D4).**

Objective 1.5 Dissemination of the generated knowledge and results.

Milestones: Publication and dissemination of the results in scientific journals and international conferences **(M5)**

Deliverables: A minimum of 3-4 publications in prestigious scientific journals and a minimum of 4-5 congress contributions will be produced **(D5)**

3.3. Work plan and schedule

The research group is formed by 4 researchers from the Plasma-Surface interaction group at CIEMAT: Alfonso de Castro Calles (AC, also the IP) E. Oyarzábal Vicente (EO), Daniel Alegre Castro (DA) and David Tafalla García (DT).

The working group is formed by Professor D. Ruzic (DR) and D. Andruczyk, director and assistant professor of the Center for Plasma Material Interactions of the University of Illinois respectively also by Dr. Thomas W. Morgan (TWM),

project leader of MAGNUM-PSI device and head of the EUROfusion specific activities in LM PFCs. These three international members are among the best world experts in LM PFCs. They will provide specialized work/know how, not available in CIEMAT, also acting as advisors in the project. The resting members of the working group are affiliated to CIEMAT: Ricardo Carrasco García (RC) and Purificación Méndez Montero (PM), persons that head the Neutral Beam Injection and electric generator systems (facilities essential to operate the OLMAT particle beam) respectively, Ana Belén Portas Ferreiro (AP) in charge of the coordination of the Data Acquisition needs during experiments and P. Fernández-Mayo (PF), current PhD student enrolled in the Plasma-Surface interaction group of CIEMAT.

Chronogram

Objective	Task	Team members	Year 1			Year 2			Year 3		
			Q1	Q2	Q3	Q1	Q2	Q3	Q1	Q2	Q3
O1.1	1.1.1	AC, EO, DA	X			X			X		
O1.1	1.1.2	AC, EO	X	X		X			X		
O1.1	1.1.3	AC, EO	X	X		X			X		
O1.2	1.2.1	AC, EO, DT, DA, PF, PM, RC, AP		X	X		X	X		X	
O1.2	1.2.2	AC, EO, DT, DA, PF, PM, RC, AP		X		X	X	X	X		
O1.2	1.2.3	AC, EO, DT, DA, TWM							X	X	X
O1.3	1.3.1	AC, DA	X	X	X		X	X	X	X	
O1.3	1.3.2	AC			X		X	X	X	X	
O1.3	1.3.3	AC, PF		X	X		X	X	X	X	
O1.4	1.4.1	AC, EO, TWM, DA, DR, DAZ	X			X			X	X	X
O1.4	1.4.2	AC, EO, TWM, DA, DR, DAZ, PF								X	X

3.4. Identification of critical points and contingency plan.

Due to its intrinsic characteristics the viability of the proposed project is highly guaranteed. The main experimental part of the project, which consist in the exposure of different targets to particle beam flux and CW laser will require about 4-6 operational days per year to be achieved. Thus, any possible contingency that may arise will be accommodated along the rest of the year in order to achieve the desired objectives. If one of these facilities suffers a major contingency, the other one will be usually available to, at least, partially continue with the research. Also, the targets can be exposed in MAGNUM-PSI whose use is already contemplated in the proposal. In the worst case, unlikely scenario, with major delays/contingencies simultaneously affecting different experimental facilities, as the project involves several independent activities, the continuation of the project is assured in case any of the experiments is strongly delayed or cannot be performed. For example, a long shutdown period (extremely unlikely) may be used to go deeper into the preparation/calibration of targets/diagnostic configurations, into the extensive analysis work of existent or previously generated data or to go ahead with conceptual designs regarding system upgrades for eventual Li target testing.

Concerning the targets to be tested, the fact that some of them are already available and that for the new ones there are several sources available to the project, through the different collaborations in which the group is involved, assures the consecution of the proposed objectives. Most likely the new targets will be provided by the company AENIUM (specialized in 3D printing, additive manufacturing) that already collaborates with the group and has provided the first elements of this type on November 2024. Apart from this, the group has several collaborations with partners from EUROfusion laboratories like Jülich Research Center in Germany, DIFFER in Netherlands, ENEA in Italy and COMPASS in Czech Republic that have previously provided targets and can do it again along the project duration.

Finally, sample characterization before and after exposure can be conducted at several other laboratories including CIEMAT, UPM-CIME, AENIUM and EUROfusion laboratories we have already collaborated with (Jülich Research Center, DIFFER, etc.).

3.5. Previous results of the team in the theme of the proposal

The present project is a continuation of the activities that the research group (and specially the IP candidate) has been carrying out during the last 2.5 years on LMs for their application as divertor material and specifically on the characterization of generated Sn plasmoids and their heat mitigation capabilities under the support of EUROfusion consortium. The IP candidate and the research team have acquired expertise in specific experimental research devoted to study vapor shielding dynamics and LM plasmoids by using the OLMAT (particle beam) and the high power CW laser HHF facilities. OLMAT is a scientific installation annexed to the TJ-II stellarator that was commissioned in 2021 and has been operated during three consecutive years [12,19,20,21,28,29], producing scientific results and being at present fully operative. The CW laser was commissioned in 2023 and relevant results in terms of Sn particle ejection heat flux thresholds have been already obtained [30]. During both particle beam/laser HHF operation a wide range of diagnostics have been developed in a parallel way for analyzing and monitoring atomic/plasma physics phenomena.

Concerning this characterization, it is worth to remind again the novel (world pioneering) configuration of single Langmuir probe, completely embedded on the LM (Sn) target surface (see Figure 2 left) and capable of locally diagnose the center of the created LM plasmoids continuously (ms timescales) that has been developed by the IP candidate and successfully operated under really harsh, extreme power loading environments (up to 35 MW/m^2 [19-21]). Such pioneering diagnosis combined with visible spectroscopy has enabled a deeper characterization (ms scale temporal evolution of electron temperature and density as well as ionic composition) of Sn plasmoids, their non-stationary dynamics and the first insights on the related thermal shielding regime [21]. Moreover, an associated computational analysis method for the non-usual interpretation of the complex LP signals (affected by thermionic emission and the presence of Sn in several ionized states) has been developed. In this way, research on the investigation of vapor shielding and the formation/characterization of LM plasmoids in front of the studied targets is routinely carried out.

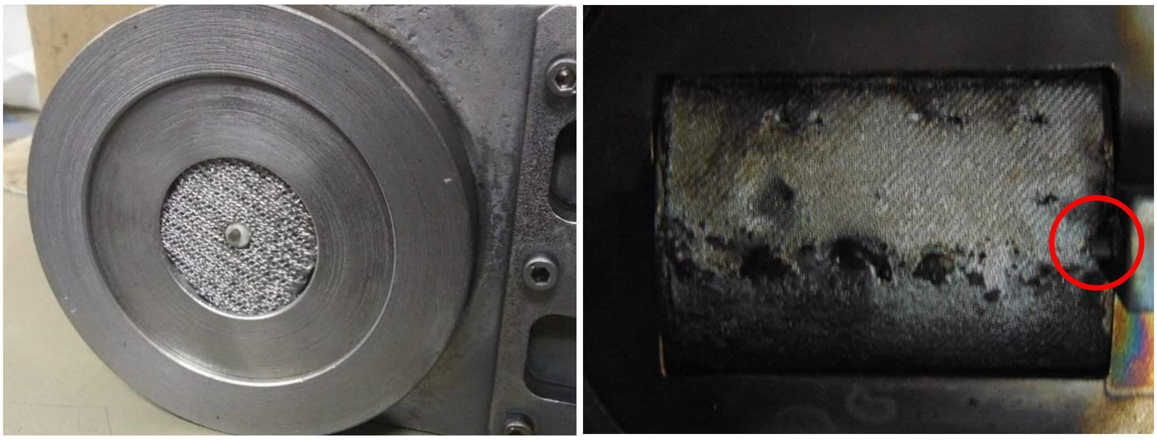


Figure 2. Left: Investigated target (circular center region) consisting on a W felt substrate covered by Sn with a LP tip embbeded at the center before exposure to particle beam heat fluxes. Right: Studied SnLi target (after its exposure to particle beam and laser heat fluxes) presenting a LP lateral configuration (tip visible within red circle)

Regarding SnLi alloys the first experiments have been also carried out in June 2024 by means of an international collaboration with the Institute of Plasma Physics-Prague (IPP Czech Republic). In them a SnLi target (previously tested in COMPASS tokamak) was exposed to 15 MW/m^2 (100 ms particle beam load) and 500 MW/m^2 (2 ms laser transient load), monitoring with a new version of LP (laterally introduced see Figure 2 right) the creation of plasmoids with variable content of Li and Sn, transiently evolving with target temperature and Sn/Li surface content. Although some technical issues were encountered with this probe configuration, proper I-V data were obtained and the LP analysis method has been generalized to more complex plasmas containing two LM species, being the complete analysis work ongoing with encouraging and novel results predicted to be obtained. This experiment with SnLi has been the foundation of an international collaboration with a group that is expected to lead the future development of LM PFCs in Europe through the commissioning of the upgrade version of COMPASS Tokamak, device that will investigate these innovative PFC concepts with a full LM divertor [31]. Globally, the successful employment of this novel diagnosis in both Sn and SnLi targets has supposed an important experimental milestone that has opened a new and original research line centered in the characterization and understanding of LM plasmoids and their power exhaust capabilities questions prone to be incorporated in future fusion devices.

Additionally, the personal initiative of the candidate has allowed to start another collaboration with the research group Teoría para Colisiones Atómicas-Moleculares (TCAM Universidad Autónoma de Madrid), that performs theoretical studies about collisional processes between high energy hydrogenic species and Sn atoms/ions, attempting to experimentally validate TCAM results and theoretically understand the experimental observations at CIEMAT. These collaborative actions have already started including some preliminary calculations on the cross sections for Sn ionization by protons as well as the first qualitative assessment of global collisional processes involving eV range electrons and keV high energy hydrogen neutrals/protons.

All these works are aligned with the proposal topic and have been performed during the last 2.5 years, globally leading to the publication of 3 articles [28,29,30] (being other two under review), and 10 conferences contributions at PSI-24, PSI 2025, ISLA 2022, ISLA 2024, USA-Japan LM workshop 2023, 65th APS-DPP 2023, EPS 2024, 29th IAEA fusion conference 2023 and 1st MIT workshop on additive manufacturing 2024 (1 invited, 6 contributed oral, 3 poster, for more details on the conference acronyms see section 4.3).

3.6. Human, material and equipment resources available for the execution of the Project.

The research team members have participated in experiments at world leading tokamak (JET, EAST) and stellarator (TJ-II, HIDRA) devices as well as many HHF facilities (OLMAT, PISCES A/B, PILOT and Nano PSI). The team includes members with strong backgrounds/expertise in: plasma material interactions, plasma physics and associated diagnostics (optics, spectroscopy, Langmuir Probes, IR pyrometry), material science/engineering and LM PFCs, data analysis and interpretation, operation of high power particle as well as plasma/laser sources, surface analysis techniques and basic laboratory experimentation. The international work team members have a well-recognized world class reputation in the fields of fusion energy and plasma material interactions and have been leading the related research in LM PFCs and associated physics/technology topics during the last 10-20 years both in Europe and USA. The rest of the members of the work team (excluding the PhD student) have demonstrated their expertise during the last 20-30 years within the tasks of operating and maintaining the particle beam, power generator as well as the data acquisition systems necessary for the experimentation.

This project will be executed at the Laboratorio Nacional de Fusión (LNF), (included in the Spanish map of Unique Science and Technology Infrastructures –ICTS-). Some, already-existing infrastructures and devices that allow for the routine operation of the TJ-II stellarator are available, including particle beam and laser sources, power supplies, vacuum and data acquisition systems, diagnostics and mechanical workshops. The OLMAT particle beam, the high-energy CW laser as well as their available diagnostics will be the main experimental facilities to be used in this project.

In OLMAT one of the two neutral beam injectors (NBI) of the TJ-II stellarator is used to irradiate targets in a separate diagnosed chamber under high vacuum conditions. Fusion-relevant (for steady state ITER-DEMO divertor operation) heat fluxes (up to 45 MW/m^2) in pulses of up to 150 ms are achieved with high energy (20-33 keV, H^0/H^0-H^+ particle fluxes (10^{22} $m^{-2}s^{-1}$). The OLMAT beam has a circular cross section with 20 cm diameter size and the delivered power density presents a spatial Gaussian distribution that has been recently characterized with high accuracy by calorimetry.

Additionally, the high-energy CW laser is a singular addition that no other laboratory in the world has for HHF studies. It allows the simulation of continuous heat fluxes of 10 MW/m^2 in a tens mm^2 area, (steady state ITER, DEMO divertor fluxes). At the same time, in ms pulsed mode, it can perfectly simulate fast, powerful transients like disruptions and ELMs of 1 GW/m^2 in a few mm^2 area. It can also simulate fast, mild transients like mitigated ELMs (tens MW/m^2 of up to 2 kHz frequency) in areas around hundreds mm^2.

The complete set of diagnostics comprises IR pyrometers (OPTRIS, CTlaser 3MH1 with 1 ms time resolution) and IR thermography for measuring the thermal response of the targets, spectroscopic sensors (monochromatic and UV-visible range detectors) to characterize the composition of the plasmoid that forms in front of the targets and fast-frame cameras to observe their evolution in shape and size. The more original and novel diagnosis method for the proposed experiments is the specifically developed embedded Langmuir probe configuration presented previously. Surface science techniques such as SEM, EDX, SIMS available at the Fusion Technology Division of CIEMAT can be also very useful to analyze in a complementary way questions as: the damage in target surfaces and LP parts produced during the experimentation as well as the LM surface wetting/coverage in pre and post HHF exposure phases. All these capabilities make OLMAT a unique HHF installation in the world that may combine the investigation of physical phenomena such as vapor shielding, thermal sputtering and the formation/characterization of the LM plasmoids with material/technological LM PFC research.

As stated in the description of Objective 1.4, some of the targets and diagnostic configurations may be tested at the linear plasma facility MAGNUM-PSI, where a cascaded arc plasma source produces a hot, dense plasma which is guided to the target by a superconducting magnet. Plasma parameters relevant to high performance detached divertor operation in ITER are reached in this way: electron density n_e ~10^{19}–10^{21} $m^{-3,}$ electron temperature T_e ~0.1–10 eV, particle fluxes of ~10^{23}-10^{25} m^{-2} s^{-1}, heat fluxes above 10 MW/m^2 and strong magnetic field up to 2.5 T. A multitude of diagnostics are employed to analyze the plasma and the wall material during and after exposure. The target can be retracted under vacuum into the Target Exchange and Analysis Chamber (TEAC) by a long bellow system. After exposure and retraction, targets can be analyzed in the TEAC with surface analysis equipment and powerful Ion Beam Analysis techniques like RBS, NRA, etc.

4. EXPECTED IMPACT OF THE RESULTS.

4.1. Expected impact on the generation of scientific-technical knowledge in the thematic area of the proposal.

As mentioned in section 2 there is still no armor concept able to withstand, in a feasible and economically viable way, the demanding power handling conditions of EU-DEMO or other public/private future nuclear fusion reactors. This project, thanks to the unique experimental and diagnosis capabilities of their HHF facilities can contribute to solve this important issue. The research outputs and generated knowledge will answer questions related to the conditions in which such plasmoids can be generated and at what degree they can ultimately contribute to the power exhaust challenge and the crucial resilience/protection of LM PFCs to transient loading in fusion devices (question that is mandatory and completely necessary regardless of the PFC solution adopted). We will intend to show how the operation with LM PFCs and the generation of LM local plasmoids can be harnessed within the tremendous power exhaust challenge. As stated previously, the research and work team include scientists with solid backgrounds in experimental plasma physics/plasma material interactions, related data analysis and material science/engineering. With the international, long and broad experience of its members in the field of plasma-material interactions for fusion energy we hope to contribute in advancing the understanding of new power exhaust scenarios driven by the development of LM PFCs. The comprehension of key physics questions regarding LM vapor/plasma clouds that are generated in front of them under fusion relevant HHF exposition and utterly their armor protection capabilities is also of paramount importance and, so far, is not so well studied/investigated. The present proposal will fill this gap in the knowledge, harnessing the collaborative endeavour of a research and work team group with strong and multidisciplinary skills and know-how prone to be integrated. More specifically, the scientific activities here proposed can provide very valuable data such as: mitigated power fractions depending on the surface temperature, plasma density and composition of Sn and/or Li local plasmoids; radiative cooling rates (L_z coefficients depending on electron density); and possibly thermal sputtering yields (surface temperature dependent). Crucial comprehension of the main atomic/plasma processes behind the creation of the LM plasmoids as well as about the electrostatic characteristics of such systems is also envisioned to be obtained. The results may be also used to validate existent atomic physics data on the interaction of Sn and Li species with hydrogenic ones as well as regarding their radiative characteristics. Globally, throughout the proposed actions, key scientific/technical knowledge for bringing to maturity more resilient LM PFC concepts and more affordable power exhaust solutions for long-pulse, future fusion reactor prototypes can be gained. Such objectives are totally aligned within the international efforts focused on demonstrating that thermonuclear fusion can be developed as a safe, clean, efficient, abundant, reliable and non-intermittent source of energy for the second half of this century.

Last but not least, it is important to mention that, despite the complexity of LM PFCs implementation when compared to W solutions, due to their higher resilience capabilities, public institution devices as NSTX, EAST, COMPASS and WEST as well as private companies as General Fusion, Tokamak Energy and Helical Fusion have already presented their plans and are carrying out projects for transitioning to them as the serious concerns found with solid W PFCs are being amplified and widely recognized. At this regard, the IP applicant has previous experience working with some of the mentioned private companies and public research partners so the works proposed herein can very valuable for such institutions and can open further interesting collaborations as well as economic return.

4.2. Social and economic impact of the expected results.

Although a commercial fusion reactor is still away and the full impact of fusion research has yet to be reached, society has already benefited from fusion research and will continue to do so. Basic fusion research has allowed the generation of new knowledge and concepts in fundamental atomic/plasma physics, material sciences and related machining methods, computation & IT, as well as new materials and specific plasma deposition/etching technologies that are reflected in many other fields as electronics, additive manufacturing, coating technologies, materials for extreme environments as well as artificial intelligence among others. Recently, the social and economic impact of nuclear fusion has been reviewed [32]. The most likely scenarios for the full fusion energy deployment (most likely driven by private-public collaboration) range for the first commercial fusion plants between 2040's-2070's. At the same time, the large funding achieved by private companies (an estimated total of 4000-5000 Million €) in the last years suggests that the realization of commercially-available nuclear fusion reactors is finally nearer, as many private investors are finally confident on it.

Within this context, both public and private sectors recognize the PFC solutions and power exhaust scenarios among the main critical issues. Much effort will be put in both public and private companies in solving such actual problems. This positions the group at a privileged situation to investigate and testing, at reactor-relevant conditions, LM PFCs and related power exhaust mechanisms. The research endeavors proposed herein can provide a fundamental contribution to these questions through the advance in the understanding of the creation and nature of LM plasma shields able to mitigate fusion relevant power loads. This will be specially demanding if EU-DEMO construction, as seems likely, is moved forward. As this happens and reactors become viable, industry will respond to the need for designing and building such devices. They will require trained persons such as engineers, physicists, technicians as well as consultants with appropriate knowledge. In this scenario, countries with active fusion experimental programs (and with experimental facilities as the ones described in this proposal) will have an important advantage given that there exists a pool of available knowledge and know-how. At this point is worth mentioning that nuclear fusion has allowed an industrial return in Spain of 1,391 M€ between 2008-2021 (source CDTI), hence the possible future economic impact of fusion research in the country can be visualized. Such tentative impact in the Spanish economy will be totally dependent on the preliminary basic research in fusion sciences (as the proposed herein) that will be able to position the fusion scientific/technological ecosystem at the necessary place.

Likewise, our proposal intends to strengthen the international collaborations with DiFFER, UIUC and IPP-Prague, consolidate relations with private, industrial partners (like the one we have established with the company AENIUM for 3D printing manufacturing of PFC substrates) and to seek new ones. Such efforts appear fundamental to apply the generated knowledge to industrial application, involving efforts from both the scientific and technology communities and to utterly generate economical return. Moreover, these results may be also applied in a synergetic way within other fields, where the experimental capacities of the project may open an active area of collaboration with private industries and partners. One of them is the development of micro-structured targets that may enhance the thrust in plasma propulsion devices by means of a reduction in the secondary electron emission and the related diminution of energy losses through the electron channel of the device. Two members of the research team (A. de Castro and E. Oyarzábal) have decisively contributed to this innovative and synergetic investigation. Other examples can be the use of liquid metals for carbon dioxide capture, related catalysis, or potential hydrogen storage or batteries (lithium). Likewise, the HHF facilities to be used in this project result interesting for other communities investigating the development of materials to be used in extreme heat load environments, for example aerospace or solar concentration energy industries and there are plans within the research team to propose LM shielding solutions for specific research/testing regarding hypersonic or spacecraft device applications (such as ablative ceramic/carbon tiles impregnated with liquid metal). Due to its unique HHF testing capacities with cutting edge research on LMs, the group is singularly well placed to establish potential collaborations with these kind of scientific and industrial partners.

4.3. Plan for scientific communication and internationalization of the results (indicate the forecast of open access publications).

The results obtained during this project will be presented (as oral or poster presentations) at international conferences and workshops as for example:

-International Symposium of Liquid Metal Applications for fusion-ISLA

-International Conference on Plasma Surface Interactions for fusion devices (PSI)

-European Physical Society Conference on Plasma Physics (EPS)

-American Physical Society Conference on Plasma Physics (APS)

-International Conference on Plasma Facing Materials and Components (PFMC)

-Symposium on Fusion Technology (SOFT)

The most relevant results will be published, in open access, in one or more of the following international journals with high impact factors in the areas of nuclear fusion, plasma material interactions and/or plasma physics: Nuclear Fusion, Physics of Plasmas, Nuclear Materials and Energy, Fusion Engineering and Design, Review of Scientific Instruments.

A number of 3-4 open-access articles is planned to be published, but more can be expected due to the novelty of this research. The results will be communicated inside the EUROfusion community but also in international scientific conferences. Presence of at least one research member in the most important ones related to nuclear fusion materials and plasma surface interactions is planned as for example:

[redacted]		
1-2 members at ISLA/APS or	1-2 members at SOFT/PFMC or	1-2 members at ISLA/APS or
1-2 members at PSI/EPS	1-2 members at EPS/APS	1-2 members at PSI/EPS

4.4 Plan for dissemination of the results to the most relevant groups for the theme of the project and to society in general.

CIEMAT is part of EUROfusion and is present in the Work Programs more relevant to the design of the EU-DEMO prototype (Plasma-Surface Interactions and Power Exhaust, Materials, Divertor, etc.). The results of this project will be shared with other EUROfusion laboratories within specific task force meetings, and hence, they will be considered for the final decision on the PFCs for EU-DEMO. Moreover, as explained in the previous point, the results of this project will also be shown in many international conferences, so other public and private companies will also benefit from them.

Regarding dissemination to the general public, CIEMAT, and particularly LNF (including the members of this project), participate in many outreach activities. The team's dissemination program for society will include new activities that are currently underway such as; Science

Week, European Researchers' Night and International Day for Women and Girls in Science. The IP candidate is very active in dissemination activities for young students. As example, he has recently started its participation in "Ciclo de Seminarios El CIEMAT en tu instituto" opening an agreement with IES San Juan Bosco (Jaén) that, additionally, is placed in a least developed Spanish province. The first seminar on fusion energy research was given by the candidate to 2º Bachillerato pupils on last 8th November 2024. All team members working at CIEMAT act as guides for public tours to the LNF facilities, leading 10 or more tours per year. All these dissemination endeavors oriented to the general public will continue during this project with the specific goal of creating a future talent pool and motivating new students and young generations towards the research fields related to nuclear fusion and plasma material interactions.

4.5. Transfer plan and valorization of results

The existent and future generated know-how in terms of LM PFCs, their necessary technologies and physics of LM containing plasmas will be susceptible to be transferred (two-way transference) between CIEMAT and the two main international institutions collaborating within the project (DiFFER and University of Illinois). As we will gain a very valuable knowledge and experience regarding the generation and understanding of LM plasmoids for power exhaust/handling in fusion devices, such results can be the foundation of further and more complex collaborations whose actions may consequently open the door to the private sector in terms of fabrication of advanced LM PFC solutions for EU-DEMO and other public or private nuclear fusion devices. Thus in the future the results of the research like the proposed herein can position interested private companies in great advantage to participate in the public calls for the fabrication of EU-DEMO components. These contracts will likely range within tens of millions of Euros as extrapolated from actual ITER contracts. Active collaboration with a 3D printing, additive manufacturing company has been already started by the group, being the first testing of some prototypes fabricated by such company carried out in November 2024. Such actions will be continued within the framework of this proposal.

4.6. Summary´s management plan of the planned data

The data generated in this protect will be archived at the CIEMAT data management department: http://documenta.ciemat.es/handle/123456789/3. Articles, conference talks, reports, and raw data following the FAIR principles (Findable, Accessible, Interoperable, and Reusable) will be archived there. For example, the raw data derived from the experimental operation is kept at ASCII or Excel worksheets suitable to be exported with all parameters and results well defined to ease the reproducibility and data interpretation by other EUROfusion groups we have already shared data with. Generally, access to the data is provided upon request for its comparison or further analysis to interested parties (registered users, students, visiting researchers, collaborators…). Publications, master/PhD theses, etc. can be accessed by the general public via http://www.fusion.ciemat.es/inicio/recursos/. Moreover, we are also sharing with the scientific community the published articles and conference talks in Researchgate website.

4.7. Effects of gender inclusion in the content of the proposal

The activities developed by team members will comply and follow the guidelines laid out in CIEMAT's II Gender Equality Plan (2021-2025). The plan includes measures to expand training and awareness based on equality between women and men in accordance with the legal provisions of Article 51.c, Article 60 and Article 61 of Organic Law 3/2007, of 22 March, for effective equality between women and men. The yearly evaluation and monitoring of the Gender Equality Plan is supervised by the Equality Unit, organically dependent on Secretary-General and its function is the development of actions related to the principle of equality between women and men. In the work and research groups of this project, women are a minority (28.5% and 25% respectively) as the technical field is unfortunately lacking in them. With regard to the low numbers of women in STEM related disciplines, which is lower in physics and extraordinarily low in plasma material interactions, all team members have a firm commitment to promoting active participation of women in this project, considering the diversity of gender perspectives in decision-making and will adjust strategies if necessary to address any identified disparities.

At this respect, it is worth to highlight that the head of the Plasma-Surface Interaction group as well as responsible of OLMAT and laser facilities is a woman (Dr. Eider Oyarzábal, identified as EO within the research team of the proposal). Additionally, the research group has been active in promoting the scientific career of young women (mentorship of them as master students in the last years). Especially important appears the case of M. Reji (see section 6.2) that also came from an emergent country (India). After her completion of the Master thesis at CIEMAT, the IP applicant was strongly involved in actions pursuing the continuation of her career, first within a research internship at IPP-Prague (collaborators with SnLi HHF testing) and utterly through her consecution of a PhD position at the University of Illinois (former postdoctoral institution of the IP applicant). At present two members of the research team (E. Oyárzabal and D. Alegre) are also mentoring a new women Master thesis candidate (S. Shick).

Likewise, the proposal has been redacted in a neutral language, and avoiding any gender-bias. It has also been redacted following CIEMAT “II Gender Equality Plan 2021-2025” http://igualdad.ciemat.es/-/ii-gender-equality-plan-2021-2025. Inclusive language will be also used in all articles and talks related to the Project.

5. JUSTIFICATION OF THE REQUESTED BUDGET

The total budget requested for this project is **70.800 €**: It is divided and detailed as follows:

A) Travels, allowances and visits: 15,800 €

1. Attendance of research team at national and international conferences mentioned in section 4.3. A maximum number of 6 congresses in total with average cost of 1,800€ per congress (Europe and outside Europe) including registration fees is estimated: 10800 €
2. International visits to DIFFER for testing targets and samples at MAGNUM-PSI: 2 visits (about 2 weeks each) during the project at 120-150 €/day and 400-500 € per travel: 5,000 €

B) Publication costs: 12,000 €. Publication of articles in open access (ideally including large discounts, for example at conferences or through institutional agreements like CIEMAT-Elsevier), up to a maximum of 6 articles in total with average cost of 1500-2000 € each: 12000 €

C) Equipment purchase: 38,000 €

1. Heated viewports to avoid metallization during Sn and Li evaporation (10,000 €). During experiments at the highest power, the strong erosion of Sn and Li species erosion covers (metallization) the viewing ports thus diminishing their visibility and the correct experimental diagnosis (spectroscopy, pyrometry). This can be avoided/ameliorated by using such heated viewports
2. Elements for the target cooling system with translation capabilities (20,000 €) for eventual testing of lithium-based liquid metal targets. We will need a system working with oil/inert gas cooling to control lithium evaporation while maintaining a safe operation (lithium is reactive towards water).
3. Other necessary small equipment purchases that can be necessary for monitoring and upgrading experimental facilities and diagnostics such as: vacuum gauges, pumps, valves, OES sensors, and/or power/electronic sources that may be necessary (8000 €).

D) Consumables, services and similar: 5,000 €

During the project several modifications to the targets holder, manipulators and chamber may be necessary for the exposition of the desired targets. For such purpose, raw materials needed for the fabrication in LNF workshop may be included in this item. Moreover, any consumable (mainly usual optical viewports that can get metallized, optical lenses, ceramic isolators) or documents (like specific books for literature review) required for the research activities are included here.

6. TRAINING CAPACITY

6.1 Training program planned in the context of the requested project

Although we do not ask for a PhD student as a part of this proposal, it is important to mention the demonstrated teaching capacities of the IP candidate. He got a positive evaluation by ANECA to teach as "Profesor Ayudante Doctor" and has participated in teaching activities at Universidad Complutense de Madrid within the European Master of Science in Nuclear Fusion and Engineering Physics (Plasma-Wall Interactions in Fusion Plasmas, 3 ECTS). The master program is coordinated by the University of Aix-Marseille (France), developed in collaboration with several European Universities and 15 EU and non-EU associated institutions, including CIEMAT hence providing an international and multidisciplinary academic framework.

6.2. Thesis completed or in progress within the scope of the research team (last 10 years).

PhD Theses

1. P. Fernández-Mayo, "Experimentos y simulaciones termo-hidráulicas de muestras de metales líquidos en estructuras porosas y muestras sólidas expuestas a pulsos de altas cargas térmicas en el dispositivo OLMAT, Dir: E. Oyarzábal and I. Fernandez-Berceruelo. To be defended in 2027-2028
2. A. de Castro, "Hydrogenic and impurity retention studies on liquid lithium and tungsten as materials for a nuclear fusion reactor by glow discharge and laser techniques", Dir. F. L. Tabarés, Universidad Complutense de Madrid, Defended on 12/01/2018

Master Theses

1. S. Shick, "Analysis of damage of DEMO-relevant materials using a high-power laser and the high-heat-flux facility OLMAT", Erasmus Mundus Joint Master in Fusion Engineering and Physics. To be defended in July 2025 Dir: E. Oyarzábal and D. Alegre
2. M. Reji, "Thermal Studies and Spectroscopic Analysis of Liquid Tin Capillary Porous Systems at the OLMAT High Heat Flux Facility", Erasmus Mundus Joint Master in Fusion Engineering and Physics, Defended on 10/07/2024. Dir: A. de Castro
3. J. Daniel Vallejo Bernal, "Thermal response and wettability assessment of liquid tin surfaces supported in tungsten capillary porous structures for their exposure to the OLMAT High Heat Flux Facility", Erasmus Mundus Joint Master Fusion Engineering and Physics, July 2023. Dir: A. de Castro and E. Oyarzábal
4. A. Devitre, "Boron synergies in lithium film performance", Erasmus Mundus Joint Master Fusion Engineering and Physics, July 2019, Dir: F. L. Tabarés and E. Oyarzábal
5. S. Puebla, "H_2 solubility studies in liquid lithium by electrical resistivity measurements", Universidad Autónoma de Madrid. 25/06/2018. Dir: F. L. Tabarés and A. de Castro

7. SPECIFIC CONDITIONS FOR THE EXECUTION OF CERTAIN PROJECTS

Not applicable

References (The participants in the research and work teams are marked in bold letter)

[1] C. Luo, L. Xu , L. Zong et al., "Research status of tungsten-based plasma-facing materials: A review", Fusion Eng. Des. 190 (2023) 113487

[2] J.H. You et al. "Divertor of the European DEMO: Engineering and technologies for power exhaust", Fusion Eng. Des. 175 (2022) 113010

[3] J. Linke, J. Du, T. Loewenhoff et al., "Challenges for plasma-facing components in nuclear fusion", Matter Radiat. Extrem. 4 (2019) 056201.

[4] G. Federici, W. Biel, M.R. Gilbert, R. Kemp, N. Taylor and R. Wenninger "European DEMO design strategy and consequences for materials" Nucl. Fusion 57 (2017) 092002

[5] H. Reimerdes, R. Ambrosino, P. Innocente et al., "Assessment of alternative divertor configurations as an exhaust solution for DEMO", Nucl. Fusion 60 (2020) 066030

[6] S. I. Krasheninnikov “Divertor plasma detachment”, Phys. Plasmas 23 (2016) 055602

[7] R. E. Nygren and F. L. Tabares, “Liquid surfaces for fusion plasma facing components - A critical review. Part I: Physics and PSI”, Nucl. Mater. Energy 9 (2016) 6.

[8] J. Gilligan, D. Hahn and R. Mohanti, “Vapor shielding of surfaces subjected to high heat fluxes during a plasma disruption”, J. Nucl. Mater 162-164 (1989) 957.

[9] P. Rindt, J.L. van den Eijnden, **T.W. Morgan** and N.J. Lopes Cardozo, “Conceptual design of a liquid-metal divertor for the European DEMO”, Fusion Eng. Des. 173 (2021) 112812

[10] S. Entler, J. Horacek et al,,“Approximation of the economy of fusion energy”, Energy 152 (2017) 489-497

[11] A. Durif, et al., “Leading edge cracking observed in WEST”, Phys. Scr. 97 (2022) 074004.

[12] F.L. Tabarés, **E. Oyarzábal, D. Alegre, D. Tafalla.**…, **A. de Castro** el al, “Commissioning and first results of the OLMAT facility”, Fus. Eng. Des. 187 (2023) 113373

[13] V. A. Evtikhin, A. V. Vertkov, V.I. Pistunovich et al., “Technological aspects of lithium capillary-pore systems application in tokamak device”, Fus. Eng. Des. 56-57 (2001) 363

14] F. L. Tabarés, **E. Oyarzábal**, A. B. Martín-Rojo, **D. Tafalla, A. de Castro** et al., “Reactor plasma facing component designs based on liquid metal concepts supported in porous systems”. Nucl. Fusion 57 016029, 2017

[15] G. G. van Eden, **T. W. Morgan**, D. U. B. Aussems et al., “Self-regulated plasma heat flux mitigation due to liquid Sn vapor shielding”, Phys. Rev. Lett. 116 (2016) 135002

[16] G. G. van Eden **T. W. Morgan** et al., “Oscillatory vapour shielding of liquid metal walls in nuclear fusion devices”, Nat. Commun. 8 (2017) 192

[17] P. Rindt, **T. W. Morgan** et al., “Power handling and vapor shielding of pre-filled lithium divertor targets in Magnum-PSI”, Nucl. Fusion 59 (2019) 056003

[18] C. Guillemaut, et al., “Experimental estimation of tungsten impurity sputtering due to Type I ELMs in JET-ITER-like wall using pedestal electron cyclotron emission and target Langmuir probe measurements”, Phys. Scr. T167 (2016) 014005

[19] **A. de Castro, D. Tafalla, D. Alegre, E. Oyarzábal** et al., “Plasma characterization of tin-enriched clouds generated during the exposure of a liquid tin Capillary Porous System target at the OLMAT High Heat Flux facility”, 65th APS-DPP, Denver-Colorado, October 30-November 3, 2023, Oral Contribution

[20] **A. de Castro**, et al., “Radiative Tin plasma clouds generated using intra-ELM energy range H^0/H^+ beams at the OLMAT High Heat Flux Facility”, 50th EPS Conference on Plasma Physics, 8th-12th July 2024, Oral Contribution

[21] **A. de Castro**, M. Reji, **D. Tafalla** et al., “Dynamics of tin plasmoids and vapor shielding onset from a liquid metal CPS target using ITER intra-ELM energy-range H^0/H^+ beams”, Nucl. Fusion (under review)

[22] F. Torreti, J. Sheil, R. Schupp et al., “Prominent radiative contributions from multiply-excited states in laser-produced tin plasma for nanolithography. Nat Commun 11, 2334 (2020).

[23] X. Sun, X Wang, J. Liu “Liquid Metal Extreme Materials”, Prog. Mater. Sci. 145 (2024) 101298

[24] J. D. Vallejo Bernal, “Thermal response and wettability assessment of liquid tin surfaces supported in tungsten capillary porous structures for their exposure to the OLMAT High Heat Flux Facility”, Master Thesis, July 2023

[25] **A. de Castro**, C. Moynihan,…, **D. Andruzcyk and D. Ruzic**. “Exploration of $Sn_{70}Li_{30}$ tin lithium alloy as possible material for flowing liquid metal plasma facing components” Nucl. Mater. Energy 25 100829 2020

[26] **A. de Castro**, C. Moynihan, S. Stemmley, M. Szott and **D. Ruzic**. “Lithium, a path to make fusion energy affordable”, Phys. Plasmas 28 050901 2021

[27] M. Szott, S. Stemmley, C. Moynihan, **A. de Castro** and **D. Ruzic**, “Structured large-pore foams improve thermal performance of LiMIT-style liquid lithium PFC”, Nucl. Fusion 62 (2022) 016018

[28] **E. Oyarzábal** et al. “Comparative study of different Sn wetted W CPSs exposed to NBI fluxes in the OLMAT facility”, Fus. Eng. Des. 190 (2023) 113711

[29] **A. De Castro**, et al. “Physics and technology research for liquid-metal divertor development, focused on a tin-Capillary Porous System solution, at the OLMAT high heat-flux facility”, J. Fus. Ener., 42 (2023) 45

[30] **E. Oyarzábal, A. de Castro, D. Alegre** et al., “Exposure of Sn-wetted W CPS targets to simultaneous NBI beam and high-power CW laser pulses at the OLMAT high-heat flux facility” J. Fus. Ener. 44 (2025) 3

[31] J. Horacek et al., “Plans for Liquid Metal Divertor in Tokamak Compass”, Plasma Phys. Rep. 44, (2018) 652–656

[32] Trinomics, “Foresight Study on the Worldwide Developments in Advancing Fusion Energy, Including the Private Initiatives”, Study for the European Commission.

Other documentation: In the resting pages of this narrative a support letter for the proposal, written by Professors David Ruzic and Daniel Andruzcyk, CPMI-University of Illinois at Urbana-Champaign-USA, is attached.

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

THE GRAINGER COLLEGE OF ENGINEERING
Department of Nuclear, Plasma, and Radiological Engineering
Suite 100 Talbot Laboratory, MC-234
104 S. Wright Street
Urbana, IL 61801, USA

January 13, 2025

To whom it may concern

I have been informed of the intention of Dr. Alfonso de Castro from Laboratorio Nacional de Fusión at Ciemat to apply for a research grant to support their project titled " *LIMPLASH LIquid Metal Plasma Shields for power exhaust in magnetic fusion* from the Spanish Ministry for Science, Innovation and Universities within their programme titled “Proyectos de Generación de Conocimiento 2024”, in the framework of Plan Estatal de Investigación Científica y Técnica y de Innovación 2024-2027".

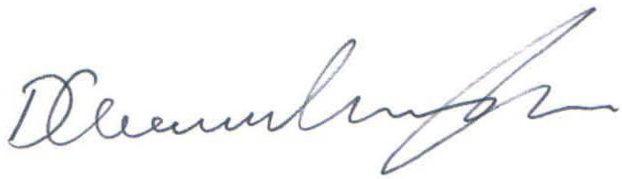
At the Center of Plasma Material Interactions (CPMI, University of Illinois at Urbana-Champaign-USA, https://cpmi.illinois.edu/about-cpmi/), we enthusiastically support these efforts and will look forward to the results from this project. CPMI is a world class scientific institution conducting basic and applied research that leads the efforts to bring liquid lithium Plasma Facing Components (PFCs) to maturity, thus offering more resilient solutions to be used at reactor relevant scale in future fusion devices.

Dr. Alfonso de Castro has invited myself, Professor Daniel Andruczyk, and Professor David Ruzic, to be members of the work team for this project. It is foreseen that we will collaborate with scientific/technical advice and mutual experimental collaboration on the preparation of CIEMAT facilities for the eventual, fusion-relevant heat flux testing of liquid lithium PFCs. These actions will be oriented to the final goal of studying, characterizing and understanding the generation and dynamics of lithium vapor/plasma clouds envisioned for heat flux mitigation in fusion relevant power exhaust scenarios (i.e. vapor shielding).

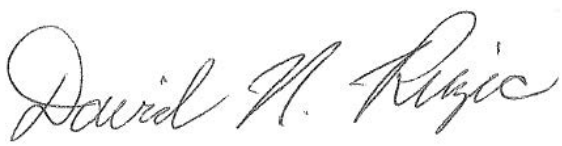
In my opinion this initiative will be an important contribution to the critical issues of mandatory power handling in magnetic fusion devices. I understand that, if successful, the activities proposed in their application will be funded by a Grant from the Spanish Ministry for Science, Innovation and Universities. This document supports the proposal, confirms our interest in the projected endeavors and anticipates valuable new results from it.

If you have any questions regarding the information provided, please don’t hesitate to contact me at andruczy@illinois.edu.

Sincerely,



Research Associate Professor
Dr. Daniel Andruczyk
Director Master of Engineering in Plasma Engineering (MEngPE)
Head of Hybrid Illinois Device for Research and Applications (HIDRA)
Center for Plasma Material Interactions (CPMI)
Dept. Nuclear, Plasma and Radiological Engineering (NPRE)
University of Illinois Urbana-Champaign (UIUC)



David N. Ruzic
Professor Emeritus
Department of Nuclear, Plasma and Radiological Engineering, Grainger College of Engineering
Emeritus Professor of Medicine; Carle-Illinois College of Medicine
Director, Center for Plasma Material Interactions   http://cpmi.illinois.edu
Director, Illinois Plasma Institute http://ipi.illinois.edu
work: (217) 333-0332, cell: (217) 840-3282; email: druzic@illinois.edu