MINISTERIO DE CIENCIA E INNOVACIÓN

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AGENCIA ESTATAL DE INVESTIGACIÓN

MEMORIA CIENTÍFICO-TÉCNICA DE PROYECTOS INDIVIDUALES
Convocatoria 2021 - «Proyectos de Generación de Conocimiento»

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

1. DATOS DE LA PROPUESTA – *PROPOSAL DATA*

IP 1 (Nombre y apellidos)**:** Emilia Rodriguez-Solano Ribeiro (AKA Emilia R. Solano)

IP 2 (Nombre y apellidos)**:** Elena de la Luna Gragantilla

TÍTULO DEL PROYECTO (ACRÓNIMO): Estudio de transiciones L-H y pedestal en modo H en tokamaks (L2HPED).

TITLE OF THE PROJECT (ACRONYM): Study of L-H transitions and H-mode pedestal in tokamaks (L2HPED).

2. ANTECEDENTES, ESTADO ACTUAL Y JUSTIFICACIÓN DE LA PROPUESTA - *BACKGROUND, CURRENT STATUS AND JUSTIFICATION OF THE PROPOSAL*

Scientific Fusion Background:

Currently, research in magnetically confined plasmas in tokamaks investigates confined plasma states to be expected, or desirable, in the next tokamak fusion devices, ITER and DEMO. The challenge of any magnetic confinement scheme for fusion development is to maintain a hot (≈10 keV) and dense (≈10^{22} m^{-3}) central plasma, while preserving the integrity of the plasma facing components (PFCs). This is no easy task, the fusion programme regularly pushes the frontier of our knowledge of plasma physics, plasma-wall interactions and our technological capabilities.

Experimentally, progress is made via studying hotter, denser plasmas in larger, more fusion relevant devices. Currently the JET tokamak, a European facility sited in the United Kingdom, is where most fusion-relevant magnetic confinement plasma physics research is conducted in the world. Uniquely, JET can operate with fusion fuels Deuterium (D) and Tritium (T), as well as non-active Hydrogen (H) and Helium (He). Since 2011 JET has the same PFCs as ITER: Be walls and Tungsten (W) divertor, usually referred to as JET-ILW (ITER-like Wall). JET can achieve plasma parameters closest to those expected in next step devices. At the moment (2021) JET is carrying out a Deuterium-Tritium (DT) campaign, to be followed next year by a Tritium campaign. Both of these are expected to provide unique results. In conjunction with subsequent matching experiments in Deuterium to optimise isotope studies, the T and DT experiments are already pushing the frontiers of magnetic confinement studies and should enable a more solid grounding for planning experiments in ITER and subsequent fusion devices such as DEMO.

After JET, the next step fusion device is ITER. ITER is tokamak being built in Cadarache, France. The European Union, China, India, Japan, Korea, Russia and the United States all participate in its design and construction. ITER's purpose is "to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes". Experiments in ITER are expected to provide essential information to address the scientific and technological challenges presented by burning plasmas in fusion reactors. After ITER, EUROfusion is designing DEMO, aiming at demonstrating fusion energy production.

ITER represents the next step in the path towards developing fusion energy reactors and its success is the highest priority of the European Magnetic Confinement Fusion program. We aim to increase understanding of the L-H transition and pedestal behaviour in ITER-relevant conditions in JET, AUG and DIII-D, in order to improve predictions and extrapolations for ITER and DEMO operation. Operation of ITER will begin with a non-active phase (PFPO: Pre-Fusion Plasma Operation), likely to be at half field in Helium and/or Hydrogen, and with restricted input power. This will be followed with a Deuterium active phase and finally fusion production in Deuterium-Tritium experiments. Reliable predictions of plasma behaviour in the various ITER operating phases are highly sought after.

The L-H transition:

Building larger devices with more auxiliary heating has uncovered the existence of then unexpected plasma states. It was found in the 1970's and 80's that as external heating input increases, plasma confinement decreases. This initial regime of operation is called L-mode (L for Low confinement). It was later found that with sufficient heating power, the plasma transitions to a different state with high confinement, now called H-mode [*Wagner et al., Phys. Rev. Lett. 49 (1982) 1408*]. In H-mode particle and energy confinement improve by about a factor of 2 above the L-mode.

Characterisation of the threshold heating power and other conditions necessary to enter H-mode is one the important asks of tokamak research, since fusion devices such as ITER and eventually DEMO rely on H-mode expected confinement. The L-H transition power threshold is characterised as P_{loss}= P_{Ohm}+P_{aux}-dW/dt or as P_{sep}=P_{loss}-$P_{rad,bulk}$. Here P_{Ohm} is the ohmic heating power, P_{aux} is the auxiliary heating applied, dW/dt is the change in plasma energy due to the power ramp preceding the transition, and $P_{rad,bulk}$ is the power radiated in the plasma core.

Generally it is known that the power threshold for the L-H transition depends on electron average density (n_e), plasma species, divertor configuration, toroidal field (B_t) and sometimes on plasma current (I_p). Typically the data is grouped in "density scans", plasmas with different average target density but the same composition, divertor configuration, B_t, I_p.

For some density scans there is a given density at which the power threshold is minimum, called $n_{e,min}$. See Fig. 2.1 as an example. It illustrates a recent result of L-H transition studies in Helium and D plasmas, showing that in JET $n_{e,min}$ is considerably higher in He than in D *[ER. Solano et al., Nuclear Fusion 61 (2021) 124001]*. Above $n_{e,min}$ the L-H transition is said to occur in the high density branch, and below it is the low density branch. For D plasmas it appears that $n_{e,min}$ in JET is of order 0.4×n_{GW}, where n_{GW} is the Greenwold density, a density normalised by the plasma average toroidal current density. In contrast, L-H transition studies in AUG report little or no difference in $n_{e,min}$~0.35×n_{GW} between H, D and He, and the same P_{loss} for D and He [*F. Ryter et al., Nucl. Fusion 53 (2013) 113003; F. Ryter et al., Nucl. Fusion 49 (2009) 062003*].

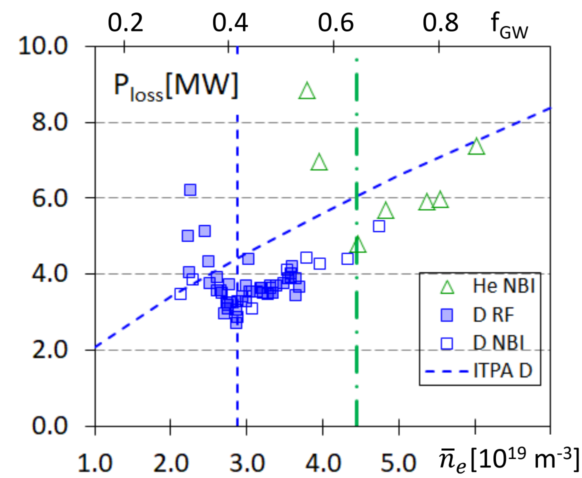


Fig. 2.1: P_{loss} as a function of average electron density (lower horizontal axis) and Greenwald density fraction (upper horizontal axis) for Deuterium plasmas and Helium plasmas, with B_t=2.4 T, I_p=2 MA, in Horizontal Target divertor configuration. Both Ion Cyclotron Radio Frequency (RF) and Neutral Bean Injection (NBI) heating were applied in D, while Deuterium-NBI was used in these He plasmas.

Phenomenological models of the value of $n_{e,min}$ in AUG have been proposed, and are typically used to elaborate predictions for ITER [*F. Ryter et al., Nucl. Fusion 53 (2013) 113003, R. Bilato et al., Nucl.*

Fusion 60 (2020) 124003, *ITER Research Plan within Staged Approach, ITER-Report 18-003 (2018) 351*]. They postulate that a sufficient ion heat flux across the separatrix would be necessary to create the radial electric field (or ion pressure gradient) necessary to trigger the transition.

ITPA inter-machine studies of the L-H transition power threshold in Hydrogenic plasmas has found that in the high density branch the power threshold for L-H transition scales with plasma surface area, toroidal field (B_t), average electron density (n_{e20}, expressed in units of 10^{20} e/m^3) and ion species mass (M) as P_{LH}= 0.0488±0.006) $n_{e20}^{0.717\pm0.035}\, B_T^{0.803\pm0.032}\, S^{0.941\pm0.019}$(2/M). We have shown at JET that plasma shape can introduce a factor of 2 multiplier in vertical target or corner configurations [*CF Maggi et al., Nucl. Fusion 54 (2014) 023007*, *E Delabie et al., Proc. of the 25th IAEA Fusion Energy Conference, Saint Petersburg, Russia, EX/P5 (2014)].* It must be noted that studies in JET confirmed that the wall material affects the L-H power thresholds. The JET-ITER-Like-Wall (JET-ILW) was installed in 2011. It has the same Plasma Facing Components (PFCs) as ITER, making the results from JET particularly relevant for ITER. Because JET is uniquely capable of operating with Tritium and DT plasmas, L-H transition isotope studies have high priority in the on-going T and DT campaigns.

From the basic physics side, the present paradigm [*K. Burrell et al., Plasma Phys. Control. Fusion 44 (2002) A253*] is that the H-mode occurs when sufficient E×B shear stabilises fluctuations at the plasma edge. At JET, recent Doppler reflectometry measurements of fluctuation velocities at and before the L-H transition in D and Helium plasmas finds no evidence of critical velocity shear values before the transition, nor evidence of evolution of such shear along heating power ramps [*C. Silva et al., Nucl. Fusion 61 (2021) 126006*]. We find that the trigger for the transition is therefore unlikely to be related to a critical E×B shear. Nevertheless, the transition itself can build higher E_r shear profiles that would contribute to pedestal steepening.

In slow L-H transition studies at JET we have identified a coherent n=0, m=1, up/down MHD mode which appears as soon as the plasma enters H-mode *[ER. Solano et al., Nucl. Fusion 57 (2016) 022021]*, the M-mode, because it is very noticeable in the MHD Mirnov signals, and it has Medium confinement, between L and H. It is localised in the pedestal region. The M-mode is observed in many pedestal and SOL measurements: density, temperature, heat flux to outer target, Dα. Its frequency appears to scale with the poloidal Alfven frequency, but is much smaller than it. There is no theory of the M-mode.

The understanding of the physics governing the transition from L- to H-mode confinement regimes is essential to optimize ITER operations with different gases and to design DEMO plasma scenarios. From the installation of the ITER-like wall in JET, several experimental campaigns investigated the physics of L-H transition, with Helium and different hydrogen isotope plasmas. This project can contribute to further our understanding of and predictions for the L-H transition in future devices, with data from the JET-ILW.

The H-mode pedestal:

In the **H-mode** the plasma density, temperature and rotation profiles develop the so-called **pedestal**: at the plasma edge the profiles become much steeper, and the radial electric field, Er, develops a well structure. The steep gradient region of the pedestal is also called an edge transport barrier (ETB), since (assumed) diffusive transport coefficients at the plasma edge are much lower in H-mode than in L-mode. Although the H-mode ETB can be quite narrow (~1% of the plasma minor radius), the characteristics of this layer have a large impact on overall plasma confinement, as a strong link is usually observed between the pedestal height and the core confinement in H-mode plasmas.

Typically the pressure gradients in the pedestal region collapse periodically due to **Edge Localised Modes** (ELMs). Large ELMs, usually described as Type I ELMs , periodically relax the steep pressure gradient developed in the transport barrier formed at the plasma edge of the H-mode plasmas, leading to short bursts (ms) of energy and particles towards the wall, but also help to maintain steady plasma conditions. Large Type I ELMs are generally present in H-mode plasmas with high energy confinement. Experimentally it *was found that the ELM size increases with decreasing pedestal collisionality (~n_e/T_e^2)* [*A. Loarte et al., Plasma Phys. Control. Fusion 45 (2003) 1549*]. Predictions for ITER [*A. Loarte et al.,* *Phys. Scripta T128 (2007) 222*], at low collisionality, show that if ELMs are left unmitigated, they may result in severe damage to the plasma facing components. This is particularly important for DEMO, which may require operation without ELMs. This has motivated the exploration of H-mode regimes that maintain good energy confinement with small or no ELMs. In addition to the need to mitigate or eliminate the ELMs, an effective impurity control capable of maintaining the W impurity concentration as low as possible in the core region (in the range of 10^{-5}) is another essential requirement for achieving ITER and DEMO goals. Therefore, the investigation of H-mode scenarios with no or small ELMs, capable of maintaining good H-mode performance with stable conditions for density and radiation, is of great importance to the tokamak fusion community.

In this project we will focus in two H-mode regimes with small or no ELMs: an H-mode regime in the so-called baseline ITER scenario (with q_{95}=3, H_{98}=1 and β_N=2) with small ELMs recently found in JET and the Quiescent H-mode (QH-mode). Here β_N is the normalized plasma pressure and H_{98} is the normalized confinement time

Small ELMs regimen in JET

Operational experience in AUG [*R. Neu et al., Nucl. Fusion* 45 (2005) 209] and JET-ILW [*R. Neu et al., Phys. Plasmas 20 (2013) 056111*] has shown that stationary H-mode operation in the presence of Tungsen (W) typically requires the use of D_2 gas puff to achieve sufficiently high ELM frequency to efficiently flush out impurities from the pedestal region, thus avoiding the development of core W accumulation, with the associated risk of radiative collapses and plasma disruptions. Since the use of high gas injection typically leads to plasma confinement deterioration, the level of gas injection applied is always an optimization parameter in the development of the H-mode regimes in metal wall devices.

Recent experiments in JET-ILW have demonstrated that it is possible to obtain H-modes in the baseline scenario, in steady state conditions, good confinement, high neutron emission rate (D-D) and impurity accumulation and small ELMs [*J. Mailloux et al., 28th IAEA Fusion Energy Conference (Oral), May 2021 (Virtual)*]. Access to these new operating regimes has been made possible by using high heating power (P_{NBI}>24 MW) in plasmas at high current (3-3.5 MA) and optimizing the injected gas to reduce the density in the pedestal, which allows access to high temperature, for electrons and ions, both in the pedestal region and in the plasma centre.

To date, two modes of operation have been identified that facilitate access to small ELMs in JET: a) combining injected gas and pellets [*J. García et al., 28th IAEA Fusion Energy Conference (Oral), May 2021 (Virtual)*] and b) removing the external gas injection ('no-gas' case) [*E. de la Luna et al., 28th IAEA Fusion Energy Conference (Oral), May 2021 (Virtual)],* which is challenging in JET-ILW due to the need to control the W influx from the edge. It is worth mentioning that operation with low gas and pellets has resulted in the best results obtained in JET-ILW in D plasmas so far and a similar scenario is included in the ongoing DT campaign. The integration of divertor detachment, which is one of the key requirements for ITER, remains an open question for this new operating regime

It is important to highlight that these new H-mode regimes with small ELMs in JET have been obtained at low pedestal collisionality (~0.1-0.4), which clearly distinguishes them from previous results obtained in other devices, where small ELMs had typically ben obtained at high collisionality or in plasma configurations that are not compatible with ITER operation [*E. Viezzer et al., Nucl. Fusion* 58 *(2018) 115002*].

The new small ELMs H-mode regimes found in JET have generated a lot of interest in the fusion community. A proof of the interest aroused by these results is that the ITPA Edge Plasma and Pedestal Physics Topical Group (ITPA-PEP) has decided to propose a new coordinated experiment in 2022 to study plasmas with small ELMs in different devices, in which the PI2 has been nominated as JET representative.

Quiescent H-modes

The Quiescent H-mode (QH-mode) is a naturally ELM-less H-mode with steady-state edge gradients and good confinement. It was originally discovered at DIII-D [*KH. Burrell et al., Phys. Plasmas 8 (2001)*

2153] and later also observed on ASDEX Upgrade with a carbon (C) wall [*W. Suttrop et al., Plasma Phys. Control. Fusion 45 (2003) 1399*], JET-C [*ER. Solano et al., 2010 Phys. Rev. Lett. 104 (2010) 185003*] and JT-60U [Y. Sakamoto *et al., Plasma Phys. Control. Fusion* 46 (2004) A299].

In QH-modes pedestal MHD such as the Edge Harmonic Oscillation (EHO) appears to provide enough transport across the pedestal to avoid excessive pressure gradient build-ups and ELMs. A JET EHO observed in JET-C has been characterized as a toroidally spinning current ribbon, located in the flat-top of the pressure pedestal. We have found many similarities between the DIII-D and JET-C EHOs *[ER Solano, KH Burrell, EJ Strait, "Using rotating current ribbons to model MHD: the EHO", 45th EPS Conference on Plasma Physics, 2 - 6 July 2018, Prague, Czech Republic, Poster P4.1044]*. It has not been possible to prove that in DIII-D the EHO is located in the pedestal flat-top, as JET-C data indicated. But there are tantalizing hints that we would like to pursue. For now the conventional understanding of the EHO is that it is a saturated kink-peeling mode, driven unstable by large edge current densities *[F. Liu et al., Nucl. Fusion 55 (2015) 113002]*, localising the current perturbation in the steep gradient region. An alternate view is that it is an external mode *[D. Brunetti et al., Phys. Rev. Lett. 122 (2019) 155003]*, associated with a flattening of the q profile in the edge region.

With the JET-ILW there has been no dedicated research on QH-mode and EHOs, but transient EHOs have been observed in hybrid plasmas in D, T and DT. There is an experimental effort to develop QH-modes in the Eurofusion WPTE, in medium-size tokamaks. Transient EHOs have also been observed in AUG, *[E Viezzer, J Hobirk, P Cano-Megias, E Solano, et al., "Progress towards a quiescent, high confinement regime for the all-metal ASDEX Upgrade tokamak", 47th EPS Conference on Plasma Physics, June 2021 (Virtual), Poster P1.1054]*.

In DIII-D QH-mode studies have now evolved to studying wide-barrier QH modes, in which broadband magnetic turbulence appears to regulate the pedestal height even in the absence of EHOs [*K.H. Burrell et al., Nucl. Fusion, 60 (2020) 086005; Xi Chen et al,. Nucl. Fusion 60 (2020) 092006*].

A successful demonstration of QH-mode at the JET scale and with the ITER-like Wall has the potential to provide key input to the physics basis towards application in ITER and DEMO. The possibility of carrying out such studies in JET in the next few years is being discussed in Dec 2021-February 2022.

Connection with earlier projects:

This project is an extension of FIS2017-85252-R, which was largely based on JET experiments. From the work planned then we were able to execute L-H transition experiments in Helium at JET *[ER Solano et al, Nucl. Fusion 61 (2021) 124001, C Silva et al., Nucl. Fusion* 61 *(2021)126006]* and progressed with Deuterium, Tritium *[ER Solano et al., 28th IAEA Fusion Energy Conference, EX/2-3 (oral), May 2021 (Virtual); ER Solano et al., 47th EPS Conference on Plasma Physics (invited), June 2021 (Virtual)]* and DT L-H experiments. We attempted to study L-H transitions in H, H+He, H+T and T, but technical limitations beyond our control (failure of various elements of the Ion Cyclotron Heating phase plant) meant that all of this work will need to be repeated in 2022 (H+T and T), and/or even in a later hypothetical Hydrogen campaign. In this project we will continue investigating L-H transitions in JET.

A second topic in the previous project focused on the use of ELM control methods (gas, pellets and vertical kicks) for W control during different phases of the JET pulse, highlighted the importance of ELMs in reducing the influx of W from the edge into the confined plasma [*E. de la Luna et al., 27th IAEA Fusion Energy Conference, EX/2-1 (oral) May 2018 (Gandhinagar, India*]. This is why the discovery of the new H-mode regime in JET-ILW, obtained with almost zero gas injection, that exhibits good confinement, no impurity accumulation and very small ELMs was an unexpected result in JET-ILW *[E. de la Luna et al., 28th IAEA Fusion Energy Conference, EX/3-2 (oral) May 2021 (remote)]*. The investigation of the small ELMs H-mode regimes in JET will be one of the main research topics in this project.

On QH-mode studies we were able to compare data on EHO between JET and DIII-D [*ER Solano et al., 45_{th} EPS Conference on Plasma Physics, July 2018, Prague, Czech Republic*], finding many similarities, and we have joined the AUG QH-mode studies, lead by E. Viezzer (Universidad de Sevilla). Recent results are described in *[E Viezzer, J Hobirk, P Cano-Megias, E Solano, et al, "Progress towards a quiescent, high confinement regime for the all-metal ASDEX Upgrade tokamak", 47th EPS Conference on Plasma Physics, June 2021 (Virtual), Poster P1.1054]*. We have identified various transient EHOs in AUG, and are endeavouring to prolong their duration.

THE TEAM

The present project would be carried out by 2 senior fusion plasmas scientists from the Fusion Nacional Laboratory in CIEMAT (CIEMAT-LNF) with complementary expertise, and a team of external collaborators, including many leading figures of the field.

Principal Investigator 1 (PI1): Emilia R. Solano (CIEMAT-LNF) has been working on pedestal physics since the mid 1990´s, both as a theorist and data interpreter. Her strength is in developing insight from first principle models, and then contrasting such models with experimental observations. She is presently leading L-H transition studies in JET's DT and T campaigns. She will lead the parts of this project related to L-H transitions and Quiescent H-modes.

Principal Investigator 2 (PI12): Elena de la Luna (CIEMAT-LNF) is an expert in H-mode, pedestal physics, ELMs and active ELM control. She has been a JET Task Force Leader since 2019. She will lead the part of the project on Small ELM scenarios in JET.

Work team, Spain:

Dr. Nerea Panadero Alvarez (CIEMAT, Madrid, Spain): Expert in pellet injection, both in experimental analysis and modelling, with emphasis on pellet ablation and the effects on pellet material deposition.

Work Team, international:

Dr. Carlos Silva (Instituto de Plasmas e Fusão Nuclear, Lisbon, Portugal) is an expert in edge, scrape-off layer and divertor physics studies, including multi-scale turbulent transport and diagnostic development in fusion devices. Recent work includes the study of the edge radial electric field when approaching the L-H transition, with different ion species and heating methods.

Dr. Jon Hillesheim (UKAEA, Abingdon, United Kingdom): expertise in turbulence and transport, pedestal, and L-H transition, including experiments, comparison to theory, and model validation studies at JET and MAST-U. He is responsible for the upgrade of the JET reflectometer that now enables routine Doppler reflectometry measurements at JET. He has been a JET Task Force Leader since 2017.

Dr. Paulo Rodrigues (Instituto de Plasmas e Fusão Nuclear, Lisbon, Portugal) is a specialist in MHD theory (equilibrium, plasma waves and instabilities). He has both analytical and computational skills (MHD codes like CASTOR or MISHKA). Previously worked mainly on the interaction between Alfvén waves and energetic particles, but the challenges of the M-mode phenomenology have recently attracted much of his interest and attention.

Dr. David Zarzoso (Centre National de la Recherche Scientifique, Marseille, France) is an expert on the interplay between energetic particle modes, MHD instabilities and turbulence in tokamaks.

Dr. Pietro Vincenzi (Consorzio RFX, Padova, Italy) is an expert on transport modelling, especially on the interaction of Neutral Beam heating with the plasma. Aside from L-H transition transport studies at JET, he works on integrated optimization of the DEMO NBI system design.

Dr. Jerónimo García (CEA, Cadarache, France) is an expert in various aspects of plasma modelling, interpretive and predictive: gyrokinetic theory, transport barriers, transport bifurcation and criticality, plasma heating and integrated modelling. He has been JET Deputy TFL since 2019.

Dr. Yann Camenen (CNRS/Aix-Marseille University, Marseille, France) is an expert on the transport modelling in tokamaks and gyrokinetic simulations.

Mattia Dicorato (PhD student, CNRS/Aix-Marseille University, Marseille, France), as part of his PhD work, is studying the pedestal stability of JET plasmas, including the small ELMs H-mode regime, using the gyrokinetic code GKW, with a focus on the role of impurities and on electron heat transport from micro-tearing modes. His PhD just started and will end in September 2024. Two of the supervisors of his PhD, Y. Camenen and J. García, are also collaborating in this project.

Dr. Keith Burrell (DIII-D, General Atomics, San Diego, USA) is a leader in QH-mode research on DIII-D since its discovery in 1999 and an EHO expert. He is also a world-recognised expert CX diagnostics, pedestal physics and L-H transitions.

Dr. Xi Chen (DIII-D, General Atomics, San Diego, USA) is the co-discoverer, with Dr. Burrell, of the wide-pedestal QH-mode. She is an expert on EHOs in wide pedestal QH-modes, and on equilibrium reconstruction of QH-mode.

The team has 4 female scientists and 9 male.

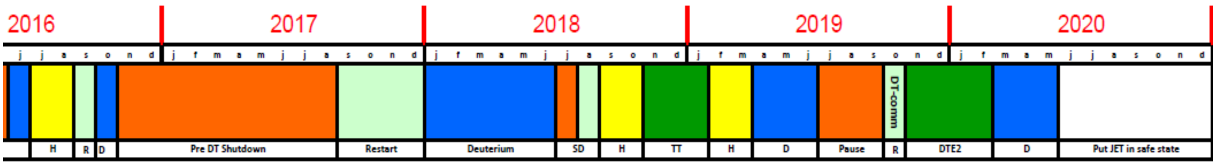
Interdisciplinary aspects

The team includes experiment leaders, diagnostics analysis experts, interpreters, theorists and modellers, to bring together many different points of view to address a strongly interrelated set of problems. L-H transition and pedestal physics are well known to be complicated by the overlap of multiple time and space scales: the pedestal width can be comparable to ion banana orbit widths and to micro-structures such as turbulent eddies; the inter-ELM transport time scale is comparable to the current density evolution and local resistive times, etc… In the past, different aspects of the problem have been studied with different approximations and it is quite a challenge for MHD experts and transport experts to combine all available information in a single model. We would start within our respective areas of expertise, and learn from each other.

Eurofusion and JET Management background: past and future

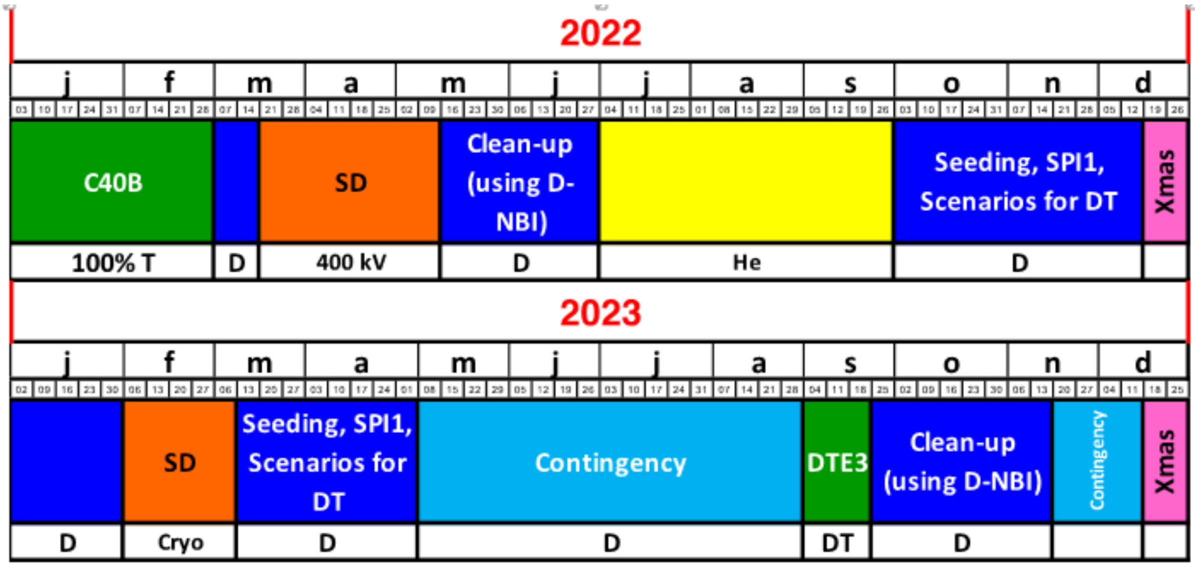
The planned JET experimental schedule known in 2017 had various campaigns, illustrated below: Deuterium, Hydrogen, Tritium, Hydrogen, Deuterium, the Deuterium-Tritium campaign (DT), and a final Deuterium campaign ending in early 2020.

JET Schedule until 2020, with DTE2 in 2019



Much has changed since then. Numerous technical challenges resulted in the cancellation of the 2019 Hydrogen campaign, delay and loss of programme in the pre-DT Deuterium campaign, the consequent delay of DT from late 2019 to late 2021, and even the scheduling of a new T campaign in early 2022, after DT, in order to finish Tritium experiments already planned but not executed in 2020 due to technical issues, lack of time and Tritium budgets.

The longer term plans for JET are unclear, partly due to Brexit. The management and funding arrangements of JET experiments for 2022 have not been finalized yet. From the latest documents released (Oct 2021) the future JET Timeline is as follows: Tritium and Deuterium campaigns in the first half of 2022, Helium and Deuterium campaigns in the second half of and early 2023, short additional DT campaign in 2023, Deuterium again.



From 2022 JET work will be integrated within Eurofusion's Work Package Tokamak Exploitation (WPTE), it is expected experiments will be organised by topic, across various European tokamaks. Additionally the international collaboration with DIII-D (USA) is expected to continue. Eurofusion work is part of Horizon Europe, funding is planned to cover 2021-2027.

3. OBJETIVOS, METODOLOGÍA Y PLAN DE TRABAJO - *OBJECTIVES, METHODOLOGY AND WORK PLAN*

The project naturally articulates itself around the following 2 topics:

Topic 1: L-H transition studies and associated MHD at JET

- Experimental studies of the L-H transition
- Theory of M-mode

Topic 2: H-mode pedestal studies

- Small ELM regimes
- QH-mode studies

The team intends to participate in future JET experiments in 2023-2024 (the present horizon for the device), and during the time periods without operation, we will analyse the results available and work on theory and modelling, and/or participate in experiments in other tokamaks: DIII-D, AUG, etc…

Topic 1: L-H transition studies and associated MHD at JET

As described in the introduction, the L-H transition is an important research topic within the fusion community. Here we describe the 2 L-H transition objectives of this project:

<u>Objective 1: Experimental studies of L-H transition in JET</u>

In He and D plasmas, Doppler reflectometer measurements of perpendicular velocity (related to the radial electric field profile) in the plasma edge indicate that there is no critical value of the radial electric field value or the shear of the v_{ExB} rotation before the transition. More importantly, during the L-mode phase, while the input power is being increased up to the L-H power threshold, there is no evidence of evolution of the E_r profile towards the transition time. Instead, it appears that the pressure gradient does increase along the ramp. These novel results deserve more careful investigation with different L-H transition datasets, in particular those from Tritium (expected in 2023) and DT (already available).

Overall, we would like to establish if critical values of E_r or grad(p) or grad(p_i) play a role establishing sufficient conditions for the L-H transition to take place. We also need to assess the validity of the assumption that $n_{e,min}$ is associated with electron-ion heat exchange.

In summary, the objective is to characterise and understand L-H transition thresholds and their relation to local plasma profiles, with special emphasis on unique JET experiments in H, D, T, DT, He.

This objective and its tasks are led by E R Solano.

<u>Contribution of work team:</u>
C Silva and J Hillesheim are reflectometry experts that will analyse the E_r profiles along the power ramps and just before the transition.
Pietro Vincenzi will carry out detailed transport analysis of the NBI heated L–H transition pulses to understand the relationship between the edge ion heat flux at the L-H transition and $\bar{n}_{e,min}$.

Work plan:

Task 1.1: study of v_{perp} and grad(p) profiles in L-H transition experiments (ER Solano, C Silva; J Hillesheim)

- Analyse DT dataset: 3T 2.5 MA Horizontal Target
- Analyse matching T dataset
- Study impact of shape on E_r and grad(p) before the transition, in D

Task 1.2: execute/propose/analyse L-H transition threshold experiments in JET (ER Solano, C Silva, J Hillesheim)

- Execute T L-H transition experiments (year 1)
- Develop/maintain L-H threshold database (years 1-4)
- Propose and execute D experiments to find matching data to T and DT data points (year 1)
- Propose experiments in He (year 1)
- Prepare and execute new L-H transition experiments in future JET campaigns: He, D, DT (year 1,2)
- For selected data sets, evaluation of local plasma profiles far and near the L-H transition.

Task 1.3: study of ion heat flux model of $n_{e,min}$ in D, DT and T plasmas (ER Solano, P Vincenzi)

Chronogram: the red x indicates the most important actor for a given task and year, the black x indicates the expected time for each person's contributions.

	Solano				De la Luna				Silva				Hillesheim				Vincenzi			
Year	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
T1.1 Er	x	x							x	x			x	x						
T1.2 L-H exp	x	x	x	x	x	x			x	x			x	x						
T1.3 q_{ion}	x	x			x					x			x	x			x	x	x	

Methodology:
For fixed plasma species, shape, toroidal field and plasma current, find L-H transition threshold with different target densities by slowly ramping up the auxiliary power. The dataset obtained is called a density scan. Additional information can be obtained by varying plasma current, heating or fuelling options, etc. The power threshold at the time of the transition (with suitable time averages), is characterised as $P_{loss}= P_{Ohm}+P_{aux}$-dW/dt or as $P_{sep}=P_{loss}-P_{rad,bulk}$. Here P_{Ohm} is the ohmic heating power, P_{aux} is the auxiliary heating applied, dW/dt is the change in plasma energy due to the power ramp preceding the transition, and $P_{rad,bulk}$ is the power radiated in the plasma core.

Plasma profiles are evaluated before the transition and along the heating power ramp, to identify possible local conditions for the L-H transition. Together with Doppler reflectometry measurements of perpendicular velocity of fluctuations it is possible to investigate/challenge conventional and novel L-H transition models.

Deliverables: 1 conference presentation and 1 journal paper per year.

Objective 2: Theoretical model of pedestal MHD near the L-H transition: M-mode

In slow L-H transition studies at JET we have identified a coherent n=0, m=1, up/down MHD mode which appears as soon as the plasma enters H-mode. We have named it the M-mode, because it is very noticeable in the MHD Mirnov signals, and it has Medium confinement, between L and H. It is localised in the pedestal region. The M-mode is observed in many pedestal and SOL measurements: density, temperature, heat flux to outer target, D_α.

In the available data from JET RF heated transition studies, the M-mode frequency appears to scale with plasma current divided by the square root of ion mass density, indicating it is possibly a poloidal Alfvén wave. Objective 2 is to develop analytical models of an interface poloidal Alfven wave, to match the empirically obtained scaling law for mode frequency.

The objective is to create and test a theoretical model of the M-mode.

This objective is led by E R Solano.

Contribution of work team:

P Rodrigues and D Zarzoso are MHD experts, much more knowledgeable than the PI1 on theoretical, mathematical and computational aspects of the relevant equations. P Rodrigues already has already scoped the problem in slab geometry, the team aims to take it further.

Work plan:

Task 2: Develop model of M-mode as poloidal Alfven wave (ER Solano, P Rodrigues, D Zarzoso), define applicability conditions

- Analytical model in slab geometry
- Analytical model in cylindrical geometry
- Numerical evaluation of model of M-mode as poloidal Alfven wave in toroidal geometry with suitable MHD code
- Compare with experimental data

	Solano				Rodrigues				Zarzoso			
Year	1	2	3	4	1	2	3	4	1	2	3	4
T2 M-mode	x	x	x	x	x	x	x	x	x	x	x	x

Methodology:
Since the M-mode is toroidally symmetric, study ideal MHD equations imposing n=0 symmetry. Find eigenmodes and eigenvectors, compare frequency scaling with experiments.
Compare results to database of M-mode measurements to investigate frequency trends.

Deliverables:
Publication of 2-3 Open Access articles in apropriate journals, as well as at least 1 conference presentation.

Topic 2: H-mode pedestal studies

As described earlier, one of the important objectives of the international fusion prohgramme is to develop scenarios with good confinement and without large ELMs that might damage the tokamak PFCs. Two different options are considered: plasmas with small ELMs and plasmas without ELMs.

Objective 3: Small ELMs scenarios in JET
The objective and the detailed list of tasks for this topic are as follows:

O.3: Characterize the transport properties and ELM dynamics of the H-mode regime with small ELMs in JET

This objective is led by E de la Luna.

<u>Contribution of work team:</u>

J. García and Y. Camenen are experts on the transport modelling in tokamaks and gyrokinetic simulations. They will contribute to the transport analysis of the small ELMs regime in JET and supervise the work of M. Dicorato, which has just started his PhD work with them. His contribution to this project is already described in the list of team members.

N. Panadero will study the impact of pellets on the edge plasma using the pellet ablation and deposition code available within the JINTRAC suite of codes in JET.

Work plan:

Task 3.1 Characterize the impact of pellet injection in the scenario with low and no-gas (pellet ablation, pellet fuelling and ELM triggering) (E. de la Luna and N. Panadero)

Task 3.2: Investigate ELM dynamics and associated divertor heat loads in the JET small ELMs regimes (E. de la Luna)

Task 3.3: Compare the pedestal structure and stability of type I ELMy H-mode plasmas and the newly found H-mode regime with small ELMs (E. de la Luna and J. García)

Task 3.4: Perform turbulent transport analysis using the gyrokinetic code GKW to gain insight into the good confinement properties of the small ELM regimes This includes the preparation of input data for the simulations (Y. Camenen, J. García, M. Dicorato)

Task 3.5: Investigate the impact of the isotope plasma composition in the pedestal structure and the onset conditions of the small ELMs H-mode regimes (comparing D and DT plasmas with low gas+pellets) (E. de la Luna, J. García, N. Panadero)

Task 3.6: Explore the operational space for H-mode operation with small ELMs in JET and other devices (E. de la Luna)

- Comparison of the unfuelled H-mode operation in JET-C (type I ELMs) and JET-ILW (small ELMs)
- Compare the new results from JET with existing small ELM regimes in other devices (AUG, DIII-D)
- Prepare and propose new experiments to be performed in 2022-2023 JET campaign. If proposal approved carried out the experiments in JET and include the new data in the on-going analysis
- Participate in a possible experimental proposal within the new coordinated experiment within the ITPA-PEP working group. If proposal approved participate in the experiments and include the new data in the on-going analysis

	De la Luna				Panadero				Dicorato/Camenen				García			
Year	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
T3.1	x	x			x	x										
T3.2	x		x	x												
T3.3	x	x	x										x	x		
T3.4	x	x	x	x					x	x	x		x	x	x	
T3.5	x					x							x			
T3.6	x		x	x												

Methodology

Analysis during 2021 has already started, focusing on the description of the plasma behaviour, ELM dynamics and initial turbulent and impurity transport simulations. It is proposed that the in-depth data analysis, including pedestal stability, transport modelling work and comparison with previous experiments will be carried out within the framework of this project. This is the first time that small ELMs have been obtained in good performance H-mode plasmas in JET, adding originality and innovation to the proposal. In addition, new experiments to explore the operational space for H-mode operation with small ELMs will be proposed for the 2022-2023 JET experimental campaigns.

Moreover, this project capitalizes on the fact that that the new small ELMs H-mode regimes found in JET have generated a lot of interest in the fusion science community, with a new ITPA coordinated experiment starting in 2022 to study plasmas with small ELMs in different devices. This will allow us to compare the regime found in JET-ILW with existing small ELM regimes in other devices (AUG and DIII-D have also indicated their interest to participate in the new ITPA-PEP proposal)

Deliverables:
Publication of 2-3 Open Access articles in apropriate journals, as well as at least 2 conference presentations.

Objective 4: Quiescent H-mode studies

QH-mode is a candidate operating regime for DEMO, and as such Eurofusion studies it in WPTE, including possibly in the JET 2022-2023 experimental campaigns.

Within EUROfusion WPTE-RT08 (lead by E. Viezzer, Univ. of Sevilla, Spain) is a research topic dedicated to the development of the QH-mode in medium size tokamaks. It foresees further experiments on AUG in 2022, 2024 and beyond (during 2023 AUG is in a major shutdown period). The main objective is to extend the transient QH-mode phases, found at AUG with a W wall for the first time, to stationarity. There is already a collaboration between AUG and DIII-D to promote similarity experiments.

If it is decided to develop the QH-mode at JET, the project team, together with the WPTE-RT08 AUG team, would propose experiments at JET, and possibly matching experiments in DIII-D and AUG.

As a contingency plan, even if QH-modes are not developed at JET, their intrinsic interest warrants continued participation in QH-mode studies in DIII-D and AUG. And we might analyse the existing transient EHOs found in JET hybrid experiments in more detail.

The objective is to develop and understand Quiescent H-modes in JET and AUG (metal PFCs), with a view to predict their applicability to future fusion devices.

This objective and its tasks are led by E R Solano.
Contribution of work team

KH Burrell will compile a list of suitable QH plasmas with EHOs.
Xi Chen will inform and advise on diagnostic selection and kinetic equilibrium reconstruction, and will contribute to develop proposals for comparison studies.

Work plan:

Task 4.1: QH-mode studies at JET

- Develop proposal
- If proposal approved, carry out experiments at JET
- characterise QH-mode operating conditions
- characterise EHO, compare with observations in other devices

Task 4.2: QH-mode studies in AUG

- Contribute to develop strategies to increase stationarity
- Characterise EHOs in AUG: equilibrium reconstruction with OMFIT, ion and electron profiles, impurity profiles.

Task 4.3: QH-mode studies in DIII-D

- Collect information on best diagnosed pulses with EHO in DIII-D. Select best examples to test models and theory. Focus on pre-EHO state: what conditions lead to EHO formation?

Characterise EHOs in DIII-D: equilibrium reconstruction with OMFIT, main ion profiles, electron profiles, Z_{eff} profiles.

- If QH-modes found at JET-ILW and/or AUG, develop proposals for comparison studies in DIII-D, or participate in such studies if already on-going

	Solano				Burrell				Xi			
Year	1	2	3	4	1	2	3	4	1	2	3	4
T4.1 JET	x	x										
T4.2 AUG	x	x										
T4.3 DIII-D			x	x	x	x	x			x	x	x

Methodology:
Magnetic data analysis, equilibrium reconstruction with OMFIT, including main ion T_i and rotation profiles, evaluation of mode location by attempting to match mode frequency and rotation at pedestal flat-top. If sufficient quality profiles and equilibrium reconstruction warrant it, request MHD stability study.

Deliverables:
Publication of 1-2 Open Access articles in apropriate journals, as well as at least 1 conference presentation.

Risk mitigation, contingency plans, need for additional personnel:

The uncertainty of work calendars in experimental facilities is often a cause of project delays. JET, AUG and DIII-D publish their work-plans each year, but things can change, and fusion research can be very dynamic. Further, in Europe a selection process defines who might do what work during experimental campaigns at JET and AUG. The two PIs have often been selected to lead experiments in JET. We count on this continuing to happen, but it is not guaranteed. In any case we expect to be team members of L-H transition, small ELMs and Quiescent H-mode experiments in JET and AUG.

Ideally many of the experiments we propose as part of this project will actually be executed. If that were not the case, we can re-orient the project towards analysis of data already in hand, especially from the JET Tritium and DT campaigns, although the information would be incomplete.

On the other hand, the PIs may be asked to devote time to different experiments, instead or as well. In that case the postdoctoral 3 year contract we request provides mitigation of general schedule risks due to potential unexpected conflicts between timely project execution and experiment preparation and execution by the PIs and other team members.

An additional young team member would also enable us to nurture the “ITER generation”: people with knowledge of pedestal physics in existing devices, someone who will actually conduct research in ITER H-mode plasmas. Pedestal expertise is especially valuable and scarce in the fusion community.

Aside from personnel, the funding request is dominated by travel, as is to be expected in such an international collaboration. If physical travel is restricted (COVID?), we will endeavour to work together via video-conferencing. It is not as efficient, but we are all learning to work like that.

4. IMPACTO CIENTÍFICO-TÉCNICO - *SCIENTIFIC-TECHNICAL IMPACT*

We expect to be able to test and improve models of the L-H transition. Such results can inform important decisions in ITER operation and DEMO design, potentially with global impact on fusion energy development. Before that, they may also affect the next DT campaign in JET.

The development of small and/or no ELM regimes with good H-mode confinement, no impurity accumulation and tolerable divertor loads is one of our aims, with potentially great impact on DEMO design. It is worth noticing that the onset of small ELMs in H-mode plasmas at low collisionality breaks the widely accepted paradigm that large Type I ELMs are a necessity to reach good H-mode performance in those conditions, thus challenging the physics models used for predictions. The new small ELMs H-mode regimes recently found in JET-ILW provides a valuable opportunity to study the confinement properties and ELM dynamics of high temperature plasmas with temperature and density profiles substantially different from those obtained in the conventional scenarios. Exploring the physics responsible for the onset of small ELMs and the absence of impurity accumulation under these conditions could contribute to a better understanding of the physical mechanism affecting pedestal stability, impurities and particle transport in the pedestal and core region and, as a result, contribute to increase the accuracy of extrapolations for ITER and future devices.

Results will be presented in relevant fusion conferences and workshops (EPS, IAEA, ITPA meetings), and published in high impact scientific journals with Open Access options, as advised by EUROfusion.

Besides publication in dedicated journals, results are expected to be disseminated to the general public. On one hand, JET results and ITER updates are communicated via press releases as part of the FuseCOM (the communication platform within the EUROFusion Consortium) outreach strategy. In particular, press releases of results from the D-T experiments on JET are planned to start in early 2022. These results are expected to be shown experimental breakthroughs in clarifying isotope effects, and in fusion records, thus attracting the interest not only of the scientific community, but also of the general public and the media. Since this team is deeply involved in those experiments, this will give us the chance to contact the main Spanish media and to reach the local public. These press releases are shared in the Ciemat and LNF web pages and social media platforms, as Instagram and Twitter. On the other hand, particular results related to this study will also be disseminated through these same web sites and social networks. When possible, the communication of obtained results will be integrated in the LNF strategy, *i.e.*, Science Week, European Researchers' Night, International Day for Women and Girls in Science (11 February), and seminars on research at the LNF to secondary students.

JET Data management plan

The project team participates in international fusion experiments and each device has its own policies on data management and Open Access. We do not own experimental data, even of the experiments we lead. It is owned by the various stakeholders of the experimental facilities where the experiments are carried out.

In JET data management is handled by EUROfusion. Access to the data is simple for all JET collaborators. In AUG, data management is handled by the Max Plank Society. Access to the data is simple for AUG EUROfusion collaborators, details can be provided upon request.

Since much of the data handled in this project is related to JET experiments, we describe the JET Data Management plan (DMP) here. The DMP describes the types and formats of data to be generated or collected and the data-sharing policies for re-use. The PIs acknowledge that the DMP is a living document to be updated as the implementation of the project progresses and when significant changes occur.

The types of data used in this project will be temporal series and videos files. In the case of JET, the main scientific and technical data output from the JET experiment are:

- Raw data – called JPFs (JET Pulse Files), real-time signals etc
- Processed data – called PPFs (Processed pulse files).
- Processed video files

The raw temporal series or post processed data can be retrieved in .xls, .txt or .cvs format to create specific databases used in this study. There is also metadata that includes basic information about the diagnostic, such as calibration procedures or line-of-sights. All the PPFs data have a sequence number associated, allowing the data users to trace back changes in the calibration or in the input data used for the creation of the processed file. Software tools needed to access the data are publicly available to all EUROfusion members.

All JET data is stored and shared in the repository provided and maintained by the EUROfusion consortium, restricted to the consortium members. As an initial step, only the consortium members will have access to the storage where dataset and metadata are filed. Authorized access by third parties can be granted provided the request is suitably accredited and vetted by the EUROfusion management.

Final peer-reviewed publications resulting from this project will be accompanied by a description of the dataset (pulse numbers and signal names) used at the time of publication, information on the methodology used to collect and analyse the data, definitions of variables, units of measurement, description of the modelling codes used (if any), with appropriate references, in order to facilitate the traceability of the published results.

EUROfusion consortium follows Horizon 2020 guidelines ensuring open access to peer-reviewed scientific publications: so that a machine-readable electronic copy of the published version, or the final peer-reviewed manuscript accepted for publication together with the metadata of the paper is deposited in the EUROfusion repository. The repository allows the researchers to deposit both publication and metadata, while providing tools to link them.

A long-term data sharing and preservation plan is already defined within the EUROfusion consortium to store, protect the integrity and make publicly accessible the data and publications beyond the life of the project.

DIII-D has a Data Management Plan, similar in nature to the JET one. The latest version is described in a live web page, https://fusion.gat.com/global/diii-d/dmp
A 3-page PDF file can be provided upon request.

5. IMPACTO SOCIAL Y ECONÓMICO - *SOCIAL AND ECONOMIC IMPACT*

Affordable and clean energy is essential for human wellbeing and progress, and it is a critical factor in improving the standard of living in developing countries. A large international effort is being made to develop thermonuclear fusion, based on magnetically confined plasmas, as a source of electricity. Fusion has the potential to provide Carbon-free energy, without the long-lived radioactive fuels and waste associated with the fission path to energy sustainability. Given sufficient investment, in the long term fusion can be an important component of a responsible approach to energy generation that does not contribute to climate change, contributing to the challenge of generating clean and sustainable energy. Developing fusion energy is a scientific and a technical challenge, requiring excellence in research, and sustained funding.

6. CAPACIDAD FORMATIVA - *TRAINING CAPACITY*

If granted, we plan to train one post-doctoral scientist to support the work of the PIs, and hopefully continue it in the future.

One of the team members is presently a PhD student at Marseille University, his work will be supervised by M. Muraglia, X. Garbet, Y. Camenen and J. García. It is possible that additional students may join the project as it develops, since some members of the work team often work with PhD students.

7. CONDICIONES ESPECÍFICAS PARA LA EJECUCIÓN DE DETERMINADOS PROYECTOS – *SPECIFIC CONDITIONS FOR THE EXECUTION OF CERTAIN PROJECTS*