Scientific Proposal for a Theory Simulation Verification and Validation (TSVV) Project

Topic	Stellarator core turbulence
Principal Investigator	***José Manuel García-Regaña***
Lead Beneficiary	***CIEMAT***

Abstract

Turbulence in the core of modern stellarators such as W7-X, optimized for neoclassical transport, has become a priority research topic within the fusion community. Aspects such as access to high-performance scenarios or impurity accumulation—or lack thereof—are closely tied to the turbulence levels in the core. Improving our capability to understand, reproduce, and predict core turbulence in stellarators is a key step toward controlling the performance of present devices and informing the design of future stellarator reactors.

In this project, we propose a comprehensive series of tasks within the framework of gyrokinetic theory, to be carried out in 2026–2027, that will address open problems and questions regarding core turbulence in stellarators. These tasks, organized as a set of deliverables and milestones, are structured around a set of three main objectives, which can be summarized as follows: extending and comprehensively validating gyrokinetic turbulence codes; advancing the fundamental understanding of turbulent transport in stellarators and tokamaks with 3D perturbations; and developing and delivering reduced turbulent transport models. In addition, the proposed tasks aim to help close a number of gaps, which are also described in the proposal. The work will be conducted primarily through numerical simulations with the GENE, EUTERPE, GENE-3D, and stella codes, in close collaboration with a broad network of contributors, and complemented by analytical theory.

The project will decisively address aspects of turbulence that remain insufficiently explored, despite their importance for reactor-relevant scenarios. Such aspects include electromagnetic turbulence at moderate to high beta, the multi-species character of confined plasmas, and the domain treatment of simulations beyond the flux-tube model. Beyond these scientific aspects, the project is committed to continue developing codes and new numerical tools, optimizing them for use on HPC platforms, and working toward their dissemination and standardization.

1. Motivation and context

The helical-axis advanced stellarator (HELIAS) concept [Nührenberg-86] and the optimization of the magnetic configuration with respect to neoclassical losses [Wobig-93] are the two central theoretical ideas underlying the design of Wendelstein 7-X (W7-X), the flagship experiment of the European stellarator programme within the Fusion Roadmap [Roadmap-12]. The successful neoclassical optimization of W7-X was demonstrated [Beidler-21] during the experimental campaigns of the initial operation phase (OP1). However, the W7-X campaigns also stressed the need of understanding turbulent transport in optimized stellarators.

Observations during the first W7-X campaigns showed that limitations in plasma core performance — such as ion temperature clamping [Beurskens-21] or the shortfall of the energy confinement time with respect to the ISS04 stellarator scaling [Fuchert-18] — were associated with high levels of core turbulent transport. Reversely, high performance was found to be linked to turbulence reduction achieved through an increase of the density gradient by external means, such as pellet injection [Bozhenkov-20] or, more recently, NBI heating [Ford-24]. In addition, there was also strong indications of the key role of turbulence in preventing core particle depletion as well as impurity accumulation [Geiger-19].

In this context, where the crucial role of core turbulence was highlighted during the initial operational phase of the world's largest stellarator, turbulence modeling for stellarators was, at that time, still immature. This was, to a large extent, the motivation for proposing stellarator turbulence simulation within the scope of several TSVV projects that emerged under the auspices of the EUROfusion´s E-TASC programme. Since 2021, some of these projects have provided significant momentum to the development of stellarator turbulence codes, their cross-verification and validation. Among those projects, the ones whose scope was closest to that of TSVV-J were: TSVV-13, for core turbulence in stellarators; TSVV-12, for stellarator optimization — including turbulence optimization — toward the design of next-generation stellarators; TSVV-10, for the modeling of core turbulence in burning plasmas; and TSVV-3 and TSVV-4, for modeling fluid and gyrokinetic turbulence in the three-dimensional edge and scrape-off layer (SOL) region of tokamaks and stellarators.

In particular, the launching of TSVV-13 could not have been more timely, as it was preceded by the convergence of several factors. As already mentioned, the operation of the largest stellarator to date — optimized with respect to neoclassical transport and therefore more exposed to the turbulent transport channel — created a strong demand for validation to the modeling community. Second, the development of new codes, such as GENE-3D [Maurer-20] or stella [Barnes-19], gave rise a community of new users and developers around them. Finally, ongoing GPU upgrades of established codes such as GENE [Jenko-00] and EUTERPE [Kleiber-23], along with the growing computing power of modern HPC platforms, further reinforced the initial momentum with which TSVV-13 was launched.

Although notable stellarator turbulence studies have been conducted in past decades (see, e.g., [Jenko-02, Kornilov-04, Watanabe-06, Xanthopoulos-07]), these efforts have been scattered over time rather than forming a continuous and dense stream of results — which TSVV-13 has helped to establish. Just to mention some of its achievement, within TSVV-13, code capabilities have been extended [Wilms-21, Boetticher-24] and systematically cross-verified [González-Jerez-22, Sánchez-21, Sánchez-23], coupled to transport solvers [Bañón Navarro-23], and validated against experiments for both heat [Agapito-25, Zocco-24] and particle transport [Thienpondt-23]. Noteworthy first-of-a-kind studies addressing turbulence in multi-species plasmas [García-Regaña-24], electromagnetic turbulence in W7-X [Mulholland-23], and Alfvén–ion-Larmor scale interactions, also in W7-X plasmas [Riemann-25] have been also carried out.

The present proposal for the "*TSVV-J: Core Stellarator Turbulence*" project builds upon the efforts carried out within TSVV-13, and its current momentum as the initial driving force. Priorities include continued cross-code verification, code standardization, and applications addressing key challenges in stellarator core turbulence, using both high-fidelity and reduced models. While W7-X will serve as the primary configuration advanced stellarator designs and 3D-perturbed tokamaks will also be considered.

2. Scientific objectives and impact

The scientific objectives of TSVV-J are a natural continuation of those of TSVV-13, from which TSVV-J itself will benefit. However, these objectives will be pursued with greater degree of sophistication and specificity within the TSVV-J than within the TSVV-13. This evolution is a consequence of the more advanced state of the stellarator core turbulence modeling tools, compared to their situation at the launch of the E-TASC/TSVV programme in 2021, and the accumulated experimental evidence and knowledge through the exploitation of W7-X over the period 2020-2025, spanning four experimental campaigns from OP1.2 to OP2.3. In the following, we enumerate these objectives, outline the methodology, and discuss the innovative potential of the proposal to achieve them, highlighting its expected impact.

The three objectives of the TSVV-J project are as follows:

Objective 1 (O1) – Achieve comprehensive validation of **gyrokinetic turbulence codes in 3D magnetic configurations** against stellarators, prioritizing W7-X, and, whenever possible, tokamaks with broken axisymmetry, going beyond the flux-tube approximation and self-consistently treating multiple particle species.

Objective 2 (O2) – Advance the **fundamental understanding of turbulent transport** in the core region of stellarators under a wide range of plasma conditions through state-of-the-art gyrokinetic simulations.

Objective 3 (O3) – Develop and **deliver reduced turbulent transport models** suitable for integration into stellarator optimization frameworks.

Methodology

The core methodology of the project relies on the **systematic and coordinated exploitation of European state-of-the-art gyrokinetic codes for the simulation of gyrokinetic microturbulence in 3D geometry**, enabling the pursuit of a series of **milestones** and **deliverables** that address identified **gaps** and naturally contribute to the accomplishment of the objectives listed above. In contrast to the work carried out in TSVV-13, where code verification and development to tackle new physical problems occupied a substantial part of the project during its initial years, in the two-year span of TSVV-J (2026–2027), this activity will take a secondary role, though it will not be discontinued.

The set of gyrokinetic codes that will be exploited, optimized, and further developed throughout the course of the Project are: **GENE** [Jenko-00], **EUTERPE** [Kleiber-23], **GENE-3D** [Maurer-20], and **stella** [Barnes-19]. Using these codes, the project aims to carry out most of the **validation against experiment** (**O1**), as well as **fundamental studies** of turbulence in stellarators and in tokamaks with three-dimensional perturbations (**O2**). The resulting high-fidelity simulations, and additional ad-hoc ones, will provide the basis for assessing the capability of **reduced models** to predict turbulent transport losses at lower computational cost (**O3**). As novel elements, the **GX** code [Mandell-24] will also be incorporated to occasionally support specific verification and validation activities. In addition, for a refined assessment of the importance of turbulence on core transport—particularly to quantify the relative importance of turbulence with respect to neoclassical transport on a routine basis, and, eventually, to continue investigating the interplay between core microturbulence and neoclassical ingredients—two neoclassical codes will be employed: **KNOSOS** [Velasco-20] and **SFINCS** [Landreman-14]. **Running all these tools will require a substantial amount of computing time**. To give a scale the CPU budget we estimate necessary, in previous years the TSVV-13 team has consumed between 60 and 90 million CPU hours per year at CINECA/Marconi to achieve the its objectives. In the TSVV-J, we will certainly need considerably more, because **the computational weight of radially global or full-flux-surface simulations will be much higher**. Finally, **the primary device** on which the project will mainly focus is **W7-X**. Nevertheless, the assessment of **advanced aspects of turbulence in newly designed configurations** within the TSVV-J, **as well as ITER**—particularly in the presence of three-dimensional perturbations of its equilibrium—will be included in the body of results of the project.

Innovative potential and impact along objectives O1, O2 and O3

The cost of simulations in stellarators has traditionally been higher than in tokamaks due to their more complex geometry, which is computationally more expensive to resolve, even in the simplest flux-tube model, which does not fully cover a surface geometry. As a result, flux-tube (FT) simulations were not presented in large numbers—tens or even hundreds per study—until this decade. **It is now relatively common to see stellarator core turbulence investigations including flux-tube simulations in large number**, albeit in the electrostatic approximation, for instance in extensive parametric studies [Thienpondt-25], evaluations of turbulence in optimized configurations [García-Regaña-24], coupled to transport solvers and in comparisons with turbulence diagnostics [Agapito-25, Bañón-Navarro-23, González-Jerez-25]. **We can consider that, although still computationally expensive, electrostatic flux-tube simulations in stellarators are performed on a routine basis nowadays.**

Beyond flux-tube simulations, there have also been advances with full-flux-surface (FFS) or radially global (RG) versions of the afore-mentioned codes. For example, see [Willms-23, Sánchez-21] for studies on the effect of domain choice on stability and turbulence or [Riemann-25] for studies of radially global turbulence in the transition between Alfvénic to ion scales. Nevertheless, FFS or RG simulations cannot yet be regarded as routine. **The innovative nature and impact of the present proposal are substantially based on promoting FFS and RG simulation to a level where it becomes standard practice for validation purposes** (O1).

Flux-tube simulations will remain one of the workhorses of the project, with reorientations that we outline here. First, they will continue to be essential for addressing fundamental physics studies (O2), as previously done in [Zocco-22, Podavini-24] for an investigation of turbulence near marginality in W7-X, role of impurities of bulk turbulence in [García-Regaña-24] or for validating reduced models, as in [Mulholland-25] for linear KBM instabilities (O2). Second, fast day-to-day experimental interpretation and planning will continue to rely heavily on flux-tube simulations, with their results refined by dedicated FFS or RG simulations whenever necessary (O1). Finally, we believe that bringing FT simulation outputs into a database could provide an excellent tool for, again, benchmarking reduced models and equipping the experimental community with resources for rapid analysis of experimental data. Therefore**, flux-tube simulations are expected to retain a high impact, motivated by their role as a bridge to reduced models and analytical theory, as well as by their low computational cost and, consequently, their ability to densely cover broad regions of parameter space.**

Lastly, and no less importantly, the TSVV-J will strive to have a **significant impact** in its field of action by **anticipating experiments, scenarios, and specific decision points through predictions**. This stands in contrast to the usual approach, in which turbulence simulations typically arrive to interpret or post-dict experimental results. In this way, the aim is to achieve **stronger feedback throughout the decision-making process** for experimental campaigns, to inform key choices in the development of the stellarator program, and to mitigate risks.

3. Project description and implementation (up to N pages)

3.1 Project description and alignment of its tasks with its objectives

This TSVV-J proposal is organized around a series of **milestones** and **deliverables**. Milestones are conceived as major contributions to code development and the formulation of analytical models, opening the door to addressing high-relevance open questions. On the other hand, deliverables can be seen as specific studies of particular problems and concrete questions. For a summarized list of both, see the table "Milestones" in the Work Plan section and the "Scientific Deliverables" section. The following paragraphs provide a concise description of the work addressed by these milestones and deliverables, classified by objective, taking into account the objective to which each contributes most significantly.

Objective 1 (O1) – Achieve comprehensive validation of gyrokinetic turbulence codes

An **extensive characterization of turbulent transport in the electrostatic regime** will be performed in gradient space for a wide range of W7-X configurations with the code stella, as well as for other devices for comparison. The aim is to conduct a **broad validation exercise** that will also serve as the basis for a database enabling rapid interpolation given a set of profiles and configurations (**D.FAST-TURBTRANSP**). Beyond its translation into IMAS and storage at the Gateway, which will require dedicated ACH support, the database will be coupled to a fast python-based interpolation tool for use by the experimental staff (**M.IMAS-TURB-DB**), analogously to NEOTRANSP in the W7-X context, which is used on a daily basis for a fast access to neoclassical transport quantities given a set of input configuration and kinetic profiles.

Regarding the **extension of the validation to particle and impurity transport**, impurity and particle transport will be quantified through simulations with GENE and the GENE-KNOSOS-TANGO suite in different W7-X scenarios (**D.W7X-PART-TRANS3**). In addition, a comprehensive study of tungsten transport will be carried out with the stella code in reactor-relevant W7-X scenarios, stellarator reactor candidates from TSVV-I, and ITER with 3D perturbations, via gyrokinetic (stella) and neoclassical (KNOSOS, SFINCS) simulations. This part is particularly important for informing operational decisions on tungsten walls in W7-X, future stellarators and for operation scenarios at ITER. Reduced models to assess the impacto of impurities on ITG stability will also be developed and compared against nonlinear simulations (**M-RM.ITG.WITH.Z**).

Regarding the **promotion of radially global and full-flux-surface** (or full-annulus) simulations, electromagnetic turbulence simulations will be carried out with EUTERPE, focusing on specific discharges from W7-X and TJ-II, thereby expanding configuration and scenario coverage (**D-EM.GLOBAL.TURB**). It is worth noting that this part presents a clear synergy with the TSVV-G line of work, with which TSVV-J will maintain close communication. Additionally, also using EUTERPE, nonlocal neoclassical effects (considering a NEOTRANSP-based nonlocal E_r model as input) will be studied on global turbulence in W7-X and other optimized configurations (**D.NEOTURB-GLOBAL**).

Delving into simulations beyond the flux-tube and electrostatic approximations, the role of Microtearing Modes (MTMs) during high-performance operational phases in W7-X will be investigated, both with local simulations using GENE and with global simulations using GENE-3D, in order to validate or refute the local results and quantify MTM-driven transport against experimental heat and particle fluxes. Additionally, the delivered simulation output, through appropriate synthetic diagnostics, will help identify MTM signatures in experiments (**D.W7X-MTM**).

Objective 2 (O2) – Advance the fundamental understanding of turbulent transport in the core region of stellarators under a wide range of plasma conditions through state-of-the-art gyrokinetic simulations.

The plasma β that can be achieved in optimised stellarators before the emergence of strong electromagnetic turbulence is an open question. We aim to use the gyrokinetic code stella in both flux tube and flux annulus modes to explore **the microstability and turbulent transport of finite beta stellarator plasmas** (**D-BETA.LIMITS**), with emphasis on W7-X, where recent works report indications of KBM activity in moderate-to-high-β discharges from last campaigns [Aleynikova-25]. This will require numerical implementation of electromagnetic fluctuations for flux annulus simulations and will likely involve implementation of improved numerical algorithms for magnetic fluctuations in the flux tube version (**M-EM.FFS.STELLA**). Meanwhile, with the current electrostatic flux-annulus version of stella will be employed to study zonal flow dynamics in stellarators in light of recent work on the toroidal secondary mode in tokamaks, in order to characterize field-line-coupling effects for W7-X plasmas and to investigate under which conditions they become important (**D.ADVANCED-ZF).**

We will also initiate a systematic investigation to identify the **conditions under which multi-scale effects become important in stellarators** (**D-GK.MULTISCALE**). Understanding the role of multi-scale interactions in stellarator turbulence is essential, since the commonly used scale-separated approach—simulating ion and electron scales independently—assumes no significant coupling between them. While this assumption has enabled tractable gyrokinetic simulations, studies in tokamaks have already shown that **cross-scale interactions can occur and suppress turbulent transport** [Maeyama-17, Pueschel-2020, Maeyama-22].

This part of the work will be addressed using GENE and stella, with ACH support required for the performance optimization of the latter.

Finally, stellarators such as W7-AS [Brakel-02] and, more recently, W7-X [Andreeva-22, Chaudhary-24] have shown **improved confinement at rational values of the rotational transform**, attributable to turbulent self-interaction along magnetic field lines. Gyrokinetic simulations suggest that this mechanism strongly stabilizes turbulence and drives $E \times B$ in tokamaks [Ball-25]. This part of the project aims to assess the strength of parallel self-interaction in low-shear stellarators and, in collaboration with TSVV-I, assess what W7-X equilibria optimize this effect. The results will also clarify the role of turbulent self-interaction in non-axisymmetric sawtooth oscillations in tokamaks (**D-TURB.SELFINTER**).

Objective 3 (O3) – Develop and deliver reduced turbulent transport models suitable for integration into stellarator optimization frameworks.

Turbulence optimization in stellarators is largely based on the electrostatic approximation. However, reactors will operate at moderate to high β. We propose to advance in this field by developing electron kinetic reduced models which provide analytical insight, are numerically affordable and easy to implement in optimization loops. The analytical work will feature a velocity-space spectral representation of the electron distribution function, allowing us to predict key features of instabilities never studied before in the stellarator context such as electromagnetic trapped electron modes [Zocco_subm_JPP], and microtearing modes [Zocco_in_prep_2025a, Zocco_in_prep_2025b]. Thus we will further extend previous work on kinetic ballooning instabilities [Mulholland_subm_2025, Wilms_rep_2025], and guide numerical modelling of advanced scenarios in W7-X (**D-RM.ELECTRONS**).

Additionally, the formulation of a fast, geometry-sensitive dispersion relation solver for ITG and TEM leveraging model reduction (**M.RM-DISP-REL**) will be carried out, along with a model for fluxes using quasilinear weights computed from the dispersion solver combined with saturation rules (**M.RM-QL-FLUXES**). These two milestones will support a study of electrostatic turbulence in arbitrary 3D magnetic geometries, providing quantitative predictions for linear eigenmode spectra and nonlinear heat fluxes in agreement with high-fidelity simulations, by adapting and refining existing saturation rules from tokamak models (TGLF, QuaLiKiz) to stellarator-specific cases (**D-RM.ESTURB**). Secondly, an analysis of nonlinear flux-tube simulations in multiple stellarator geometries (W7-X, HSX, NCSX) will be conducted at varying collisionality and pressure-gradient compositions, comparing results with reduced-model predictions from milestones M.RM-DISP-REL and M.RM-QL-FLUXES, while keeping the total pressure gradient fixed and scanning the density/temperature gradient ratio to assess the interplay between stability, geometry, and collisionality (**D.RM-VS-NONLINEAR**).

Finally, stellarator optimization usually neglects the presence of non-bulk species, such as impurities. We will formulate a dispersion relation for the toroidal ITG mode including impurities in arbitrary geometry, along with the development of a Python-based tool for the rapid evaluation of impurity effects on ITG, with potential for coupling to optimization codes (**M-RM.ITG.Z**). In parallel, we will conduct a dedicated study of ultra-low-frequency, large-amplitude zonal flows, such as those reported for optimized configurations like CIEMAT-QI4 [García-Regaña-25], with the aim of identifying the linear-simulation quantities that maximize them and can serve as suitable proxies for stellarator optimization (**D-RM.ZFLOWS**).

3.2 Expanding code capabilities and exploitation to close identified knowledge gaps

Apart from the contribution of the various deliverables and milestones towards addressing the Project's objectives, to a large extent**, the motivation for the work to be undertaken within the TSVV-J project rests on the existence of certain gaps closely related to the project's scope**. The identification and discussion of these gaps were recently addressed in the *exercise Assessment of Key Physics Uncertainties and Research Needs for Stellarator DEMO Development*, initiated by Work Package W7-X (WPW7X) with the participation of numerous experts (see presentations in [Gaps_2025]).

Structured into six thematic areas, one of which is *Core Transport and Confinement*, this area reveals a strong presence of gaps whose resolution critically depends on the simulation of core microturbulence in stellarators. These gaps, together with a brief rationale, are listed below. The list of milestones and deliverables that will make significant contributions toward closing these gaps is also provided.

Gap 1: Validation of the dependence of turbulent transport on magnetic configuration: Our understanding of the relationship between configuration and transport appears incomplete and insufficiently validated, with most simulations carried out so far in the numerical modeling context focusing on only a very limited set of configurations. On the experimental side, this relationship has recently been characterized in considerable detail for W7-X [Wappl_25] and calls for a proper validation. Relevant contributions will come from: **D.FAST-TURBTRANSP , D.RM-VS-NONLINEAR , D-RM.ESTURB, M.IMAS-TURB-DB**

Gap 2: Multi-species and multi-channel impurity transport: There is strong evidence of the trade-off between reduced turbulence and favorable impurity transport is to be characterized. Completing our picture of the total transport, neoclassical + turbulent + sources, is critical for the prevention of heavy impurity accumulation. Relevant contributions will come from: **D.HEAVY-Z-TRANSP , M.ITG-WITH-Z**.

Gap 3: Advanced core turbulence simulation: Our understanding of turbulent transport relies on approximations that are often adopted with limited justification, potentially overlooking important corrections and compromising the accuracy of the picture of turbulence in our reactor candidates. Relevant contributions will come from: **D-GK.MULTISCALE, D-RM.ZFLOWS, D-RM.EM.ELEC, D.ADVANCED-ZF, D-TURB.SELFINTER, M-FFS.EM.STELLA.**

Gap 4: Profile predictive modeling: The cost of iterating and simulating across the full radius comes in the form of: a reduction in model completeness (no multi-species plasma composition or electromagnetic effects at high β) and critical dependence on edge boundary conditions, which is subject to large uncertainties (in this regard, communication with TSVV-B and TSVV-C will be key to constraining these uncertainties). Relevant contributions will come from: **D.W7X-PART-TRANSP , D.W7X-MTMs.**

Gap 5: Experimental reproduction of reactor-relevant parameters: As W7-X heating power is expanded during the forthcoming campaigns, experimental increase of β values must continue until reactor relevant values. MHD activity and EM turbulence must be monitored and eventually dealt with. Relevant contributions to the validation of these scenarios will come from: **D.NEOTURB-GLOB, D.BETALIMITS , M.RM-DISP-REL, D-RM.ESTURB, M.RM-QL-FLUXES, M.RM-W7XEXP.**

3.3 Other aspects to consider

The gyrokinetic codes to be employed in TSVV-J are EUTERPE, GENE, GENE-3D, and stella, whose main development and exploitation nodes are at the institutions represented in TSVV-J. The developer and user (stellarator) community is compact, well connected and closely involved in the W7-X experimental campaigns. The demand for training in these codes is not excessive and can be easily managed through traditional communication channels combined with visits of trainees to experienced users via resources for missions. However, there are plans to disseminate the work performed with these codes, particularly regarding the characterization of turbulence in tokamaks with 3D perturbations, to encourage the much larger tokamak community to adopt them as well. Contacts have already been established between the *ITPA Transport and Confinement Topical Group* and the TSVV-13 project, which will continue, under TSVV-J.

Among the codes mentioned above, GENE-3D and stella have undergone the most intensive development in recent years. For example, several advancements implemented in stella—such as its full-annulus version, its electromagnetic extension, and the implementation of the collision operator—have been carried out partly in the framework of TSVV-13, between 2020 and 2025. For this reason, an important component of the project will be, in the case of stella, the integration and harmonization of these developments into a clean and debugged version, with revised source code documentation for enhanced readability and to facilitate future development or improvements. This task, which aligns with best practices in software engineering, has been defined as a specific milestone (**M-STELLA.RELEASE**). Beyond this task, both GENE-3D and stella are already at an reasonably advanced stage of commitment to the EUROfusion standard software, which will continue evolving during 2026-2027 [see E-TASC-25].

3.4 Risk mitigation

Risk	Proba-bility (1-5)	Impact (1-5)	Risk index (1-25)	Mitigation	Risk index after mitigation
Some milestone related to code development is delayed.	2	1	10	Regular reporting and review of milestones progress in order to anticipate the realization of some deliverable, or parts of it.	5
Insufficient allocated CPU hours on CINECA/ Pitagora or system incidents preventing its use.	3	5	25	Application for computing time to instances other that EUROfusion, e.g. the Spanish HPC Network (RES, Spain) and equivalent national agencies, PRACE, etc.	15
Some team member leaves the TSVV.	2	3	20	Recruitment of a possible substituting member with similar competencies and expertise in the work developed by the member leaving. Communication to the PMU for modification of the TAs, if necessary. This situation has been handled satisfactorily before, in the course of the TSVV-13 project	5
Next W7-X campaings, OP2.4 and OP2.5 campaigns suffer delays	1	3	20	Mitigation measures for this risk fall outside the scope of the TSVV, but other activities could be reinforced to support the deliverables most exposed to it, such as further validation and modeling of past W7-X campaigns, participation in other experiments such as TJ-II, etc.	10

4. Team members and project management

Team structure

The proposed Principal Investigator (PI) is José M. García-Regaña, who will be supported by a team that includes leading experts in gyrokinetic theory, as well as developers and users of the gyrokinetic codes employed within the project (see Table 1 for their names, level of commitment, and initials, which are later used to indicate their involvement in each deliverable and milestone). The team has already established a track record of collaboration and smooth communication since 2020 in the context of TSVV-13, with many of its members continuing their participation in TSVV-J.

The PI will be responsible for organizing monthly remote meetings to present partial progress and rehearse papers for journals and conferences. Subgroups working on specific deliverables or milestones will meet more frequently. The PI will also coordinate and submit responses to annual calls for computing time on Cineca/Pitagora, international missions, and other relevant calls, as well as compile and merge annual reports from each subgroup.

At least once a year, an in-person meeting with the widest possible participation shall be held to accelerate progress on specific tasks and overcome delays. Sufficient budget for domestic and international missions is essential to enable these meetings and necessary face-to-face discussions.

All team members will be required to upload their work to the EUROfusion Pinboard under the corresponding WPs, including WPSTELL, to ensure smooth communication. Progress will also be reported to the W7-X team through its regular or topical group meetings.

Member	***Beneficiary***	***Period***	***Commitment (PM/year)***
José M. García-Regaña (JGR)	*CIEMAT*	*2026-2027*	*10*
Hanne Thienpondt (HT)	*CIEMAT*	*2026-2027*	*6*
Edilberto Sánchez (HS)	*CIEMAT*	*2026-2027*	*6*
José Luis Velasco (JLV)	*CIEMAT*	*2026-2027*	*2*
Claudia Salcuni (CS)	*CIEMAT*	*2026-2027*	*3*
Alejandro Bañón Navarro (ABN)	*MPG (IPP-Garching)*	*2026-2027*	*6*
Alessandro Zocco (AZ)	*MPG (IPP-Greifswald)*	*2026-2027*	*4.7*
Jörg Riemann (JR)	*MPG (IPP-Greifswald)*	*2026-2027*	*4.8*
Georgia Acton (JA)	*MPG (IPP-Greifswald)*	*2026-2027*	*3*
Linda Podavini (LP)	*MPG (IPP-Greifswald)*	*2026-2027*	*2*
Ksenia Aleynikova (KA)	*MPG (IPP-Greifswald)*	*2026-2027*	*2*
Michael Barnes (MB)	*UKAEA (Uni. Oxford)*	*2026-2027*	*6*
M. J. Pueschel (MJ)	*DIFFER*	*2026-2027*	*4*
Maikel Morren (MM)	*DIFFER (TU/e)*	*2026-2027*	*3.5*
Justin Ball (JB)	*EPFL*	*2026-2027*	*3*
Total resources			*66*

Table 1: List of members of the TSVV-J and distribution of resources, which in total amount to 6 full-time equivalents. In addition, several external experts with strong interest and competencies in stellarator turbulence will be included at zero PM.

Apart from the funded members listed in Table 1, numerous external experts with 0 PM will contribute to the progress of the project. Among them are, Iván Calvo (IC, CIEMAT), Don Fernando (DF) and Hugo Cu Castillo (HCC) from IPP-Garching, Ralf Kleiber (RK), and Josefine Proll (JP) from IPP-Greifswald, Richard Nies (RN, U. Oxford), Daniel Kennedy (DK, UKAEA), Oraz Anuaruly (OA) and Chris Smiet (CS) from EPFL. They will be invited to attend the TSVV-J regular meetings and to present their own work.

5. Work plan

Milestones (The superindex “*” denotes the responsible person(s) of each milestone)

No	Title	Description	Expected date
1	M.STELLA-RELEASE	Integration of the different versions of the code into a single one, along with documentation of the source code and its diagnostics and data management suite (GA*, HT*, MB)	June. 26
2	M.FFS-EM-STELLA	Numerical implementation of electromagnetic fluctuations for flux annulus simulations in stella (MB*, DK, GA, HT).	Dec. 26
3	M.IMAS-TURB-DB	Stellarator core turbulence database for W7-X with flux-tube simulations (HT*, JGR*, CS, ACH Support).	Dec. 26
4	M.ITG-WITH-Z	Model and tool for the fast evaluation of the effect or impurities on toroidal ITG stability for arbitrary geometry (HT*, IC, JGR).	Dec. 26
5	M.RM-DISP-REL	Fast geometry-sensitive dispersion relation solver for ITG and TEM leveraging model reduction (MJ*, MM, JP).	Dec. 26

6	M.RM-W7XEXP	Reduced models and scaling laws for heat and particle fluxes in W7-X using existing validated databases validated against experiments (ABN*, DF, HCC).	Dec. 26
7	M.RM-QL-FLUXES	Model for fluxes with quasilinear weights computed from dispersion solver combined with saturation rules (MJ*, MM).	June. 27

6. Scientific deliverables

Description of deliverables

To by accomplised in 2026

D.FAST-TURBTRANSP Rapid turbulence diagnostic tool based on an initial electrostatic turbulent transport database (see related milestone M.IMAS-TURB-DB). Part: JGR*, HT, CS, ES, ACH support staff, W7-X team.

D.RM-ZFLOWS Derive linear-simulation quantities that maximize ultra-low-frequency, large-amplitude zonal oscillations in optimized stellarators by correlating nonlinear and linear spectra across configurations from TSVV-I/TSVV. Participants: CS*, JGR, ES, HT.

D.EM-GLOBALTURB Study of electromagnetic turbulence through global simulations with EUTERPE for specific discharges and experimental profiles from W7-X and TJ-II. Participants: ES*, JGR, JLV, HT, CS, JR, RK.

D.RM-EM-ELEC Development of reduced electromagnetic electron models to accelerate turbulence optimization by formulating velocity-space spectral representations of the electron distribution function to predict key instabilities—electromagnetic trapped-electron modes and microtearing modes. Participants: AZ*, KA, GA, LP.

D.W7X-MTM Investigation of the role of Microtearing Modes (MTMs) during high-performance operational phases in W7-X (M) validate or refute the local approximation by comparing local GENE and global GENE-3D simulations. Participants: ABN*, DF, HCC.

D.W7X-PART-TRANSP Quantify impurity and main ion transport during high-performance phases in W7-X GENE simulations alone and with GENE-KNOSOS-Tango framework. Participants: ABN*, HCC, DF.

D.RM-ESTURB Study of electrostatic turbulence in arbitrary 3D magnetic geometry by means of reduced models (see milestones M.RM-DISP-REL and M.RM-QL-FLUXES Participants: MM, MJ, AZ, JP.

To by accomplised in 2027

D.BETALIMITS Assessment of β limits in stellarators via high-resolution *stella* simulations in flux-tube and flux-annulus geometries. Participants: MB, GA, DK, MJ.

D.HEAVY-Z-TRANSP Comprehensive study of tungsten transport in reactor-relevant W7-X scenarios, stellarator reactor candidates from TSVV-I, and ITER with 3D perturbations. Part: JGR*, JLV, ES, HT, CS.

D.NEOTURB-GLOB Study of nonlocal neoclassical effects on the radial electric field (Er) and, in turn, the effect of this on global turbulence using EUTERPE for W7-X and other optimized configurations. Participants: JR*, RK.

D.GK-MULTISCALE Investigation of multi-scale effects in stellarator turbulence. Participants: ABN*, HT, JGR, ACH support staff.

D.ADVANCED-ZF Study zonal flow dynamics in W7-X in light of recent work on the toroidal secondary mode in tokamaks. Participants: MB*, RN, GA.

D.RM-VS-NONLINEAR Analysis of nonlinear flux-tube simulations in multiple stellarator geometries (W7-X, HSX, NCSX) at varying collisionality and pressure-gradient compositions comparing results with reduced-model predictions from milestones. Participants: MJ, MM.

D.TURB-SELFINTER Study of turbulence in low-shear stellarators near rational flux surfaces determining the strength of parallel self-interaction and its potential to enhance performance. Participants: JB, OA, CS (from TSVV-I).

References

[Agapito-25] D. L. C. Agapito et al. Phys. Plasmas 32, 073904 (2025).
[Aleynikova-25] K. Aleynikova et al. *Indications of kinetic ballooning mode activity in Wendelstein 7-X plasmas*, submitted (2025).
[Andreeva-22] T. Andreeva et al. Nucl. Fusion 62 026032 (2022).
[Ball-25] J. Ball et al. arXiv:2503.08793 (2025).
[Barnes-19] M. Barnes et al. J. Comp. Phys. 391, 365 (2019).
[Beidler-21] C. D. Beidler et al. Nature 596, 221 (2021).
[Beurskens-21] M.N.A. Beurskens et al. Nucl. Fusion 61 116072 (2021).
[Bozhenkov-20] S.A. Bozhenkov et al. Nucl. Fusion 60 066011 (2020).
[Brakel-02] R. Brakel et al. Nucl. Fusion 42 903 (2002).
[Bañón Navarro-23] A. Bañón Navarro et al Nucl. Fusion 63 054003 (2023).
[Boetticher-24] A. von Boetticher et al . Plasma Phys. Control. Fusion 66 105016 (2024).
[Brakel-02] R. Brakel et al. Nucl. Fusion 42 903 (2002).
[Chaudhary-24] N. Chaudhary et al. Nucl Fusion 64 106038 (2024).
[E-TASC-24] J. M. García-Regaña et al. *TSVV13: Stellarator Turbulence Simulation: Progress, status and plans,* at EUROfusion E-TASC General Meeting (2024).
[Ford-24] O.P. Ford et al. Nucl. Fusion 64 086067 (2024).
[Fuchert-18] G. Fuchert et al. Nucl. Fusion 58 106029 (2018).
[Gaps_2025] https://indxico.euro-fusion.org/event/3535/
[García-Regaña-24] J. M. García-Regaña et al. Phys. Rev. Lett. 133, 105101 (2024).
[García-Regaña-25] J.M. García-Regaña et al. Nucl. Fusion 65 016036 (2025).
[Geiger-19] B. Geiger et al. Nucl. Fusion 59 046009 (2019)
[González-Jerez-22] A. González-Jerez et al. J. Plasma Phys. 88(3) 905880310 (2022).
[González-Jerez-24] A. González-Jerez et al. Nucl. Fusion 64 076029 (2024).
[Jenko-00] F. Jenko et al. Physics of Plasmas 7, 1904 (2000).
[Jenko-02] F. Jenko and A. Kendl. New J. Phys. 4 35 (2002).
[Kleiber-23] R. Kleiber et al. Comp. Phys. Comm. 295 109013 (2024).
[Kornilov-04] V. Kornilov et al. Phys. Plasmas 11 (6) 3196–3202 (2004).
[Landreman-14] M. Landreman et al. Phys. Plasmas 21, 042503 (2014).
[Maeyama-17] S. Maeyama et al. Physical Review Letters, 119 195002 (2017).
[Maeyama-22] S. Maeyama et al. Nature Communications, 13, 3166 (2022).
[Mandell-24] N. R. Mandell et al. J. Plasma Phys. 90 (4) 905900402 (2024).
[Maurer-20] M. Maurer et al. J. Comp. Phys. 109694 (2020).
[Mulholland-23] P. Mulholland et al. Phys. Rev. Lett. 131, 185101 (2023).
[Mulholland-25] Mulholland Zocco et al. Resonant theory of kinetic ballooning modes in general toroidal geometry, JPP (2025), under review
[Nührenberg-86] J. Nührenberg and R. Zille, Phys. Lett. A 114 129 (1986).
[Podavini-24] L. Podavini et al. J. Plasma Phys. 90(4) 905900414 (2024).
[Pueschel-2020] M.J. Pueschel et al. Nucl. Fusion 60 124005 (2020).
[Riemann-25] J. Riemann et al. Phys. Rev. Lett. 134, 025103 (2025).
[Roadmap-12] "Fusion Electricity: A Roadmap to the Realisation of Fusion Energy" (EFDA, 2012)
[Sánchez-21] E. Sánchez et al. Nucl. Fusion 61 116074 (2021).
[Sánchez-23] E. Sánchez et al. Nucl. Fusion 63 046013 (2023).
[Thienpondt-23] H. Thienpondt et al. Phys. Rev. Research 5, L022053 (2023).
[Thienpondt-25] H. Thienpondt et al. Nucl. Fusion 65 016062 (2025).
[Velasco-20] J. L. Velasco et al. J. Comp. Phys. 418, 109512 (2020).
[Wappl_25] M Wappl et al. Plasma Phys. Control. Fusion 67 075025 (2025).
[Watanabe-06] T.-H. Watanabe and H. Sugama Nucl. Fusion 46 24 (2006).
[Wilms-21] F. Wilms et al. J. Plasma Phys. 87(6) 905870604 (2021).
[Wilms_rep_2025] Wilms Zocco et al. An eigenvalue solver for kinetic ballooning mode optimization. Proxima Fusion internal report. (2025)
[Wobig-93] H. Wobig, Plasma Phys. Control. Fusion 35, 903 (1993).
[Xanthopoulos-07] P. Xanthopoulos et al. Physical Review Letters 99(3), 035002 (2007).
[Zocco-22] A. Zocco et al. Phys. Rev. E 106, L013202 (2022).
[Zocco-subm-25a] A. Zocco et al. Journal of Plasma Physics under review (2025).
[Zocco-prep-25a] A. Zocco et al. The drive of the collisionless microtearing mode in general geometry, In preparation (2025).
[Zocco-prep-25b] Zocco, Finite β microinstabilities in tokamaks and stellarators, in preparation (2025).