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

Topic	TSVV-A: H-Mode and Small/No-ELM Pedestals
Principal Investigator	***Tobias Görler***
Lead Beneficiary	***MPG***

Abstract

This proposal addresses one of the most pressing issues in fusion research: characterising the plasma edge transport for the optimisation of future devices, and developing the ability to model and predict the L-H transition and its various characteristics. These deliverables are suggested to be met in the context of a multi-fidelity approach, ranging from gyrokinetic (GK) models to real-time capable reduced models. Building on experience gained in the 2021–2025 phase, we will apply the findings to new, challenging GK edge and pedestal characterisation studies, albeit with a more focused target of small-ELM/no-ELM regimes and their transfer to future devices in mind. Particular emphasis will be given to the interplay with electromagnetic modes and cross-scale coupling with fine-scale electron temperature gradient (ETG) turbulence and resonant-magnetic-perturbations, for instance.

In close collaboration with TSVV-C and, to a certain extent, TSVV-B, several turbulence studies will extend beyond the separatrix. Based on the current state of the art, L-H transition-type behaviour is expected when varying the input power in corresponding flux-driven setups. During the project, these studies will be refined using new physics capabilities, such as improved neutral and sheath models, as well as considering parallel magnetic fluctuations and sub-ion-scale effects.

Despite the high-fidelity simulation campaigns, a multifaceted work plan has been developed to address the community's need for faster, reduced models for reactor design and optimisation. Based on active discussions with TSVV-11 (TSVV-H in future), we will use recently developed IMAS interfaces to routinely perform GENE/TGLF comparisons for the scenarios in question, thereby assisting TSVV-H with assessments of one of their main reduced turbulence models. We will also aim for studying and refining L-H transition-type behaviour with reduced models. Another effort will focus on developing or extending specific reduced models for ETG and electromagnetic modes, which were confirmed as relevant edge modes in the previous project phase, for which the team has comprehensive experience. Finally, the fluid component will be used to develop scalings for easier access to and comparison with experimental results, which is considerably faster than full GK modelling, and could be used for point-wise comparison and assessment. The proposal takes advantage of including groups from across Europe that are known for their leading role in GK, fluid, and reduced modelling for all of these activities. A detailed work plan, team description and risk assessment are provided in the full proposal.

Motivation and context

Ever since the discovery of the High Confinement Mode (H-mode) at the ASDEX tokamak in 1982 and follow-up reproduction in other devices, this plasma operation mode has been considered one of the most promising for a fusion power plant. However, despite experimental progress, the exact physics of the transition from low-to-high (L-H) confinement remained elusive for decades. Although several mechanisms had been proposed over time, self-consistent high-fidelity simulations reproducing such transitions had not been reported, except for one US code result [Chang17]. As many scientific questions were left open, substantial effort had been invested foremost in the preceding TSVVs 1/4 (2021-2025) and the pilot project phase (2019-2020) to develop a corresponding European capability from high to lower fidelity models. Five key objectives had been addressed before. Firstly, a larger number of local and global gyrokinetic (GK) simulations had been undertaken to characterize pedestal turbulence in AUG L-, H-, I- and EDA H-modes, as well as JET hybrid H-modes, see, e.g., Refs. [Stimmel21/22,Leppin23/25] contributing to the understanding of the complex multiscale mixture of turbulent transport channels in the various radial pedestal domains. The impact of low magnetic shear regions, as found in the presence of large bootstrap currents, has been studied in detail in the plasma core (for simplicity), and a corresponding barrier formation has been observed in both gradient- and flux-driven GENE[Jenko00,Goerler11] and ORB5[Lanti20] simulations [Volcokas23,Giannatale25]. Acknowledging that the edge radial electric field E_r is considered a key factor in transitioning from low- to high-confinement regimes, several dedicated studies were conducted as part of a second objective to explore the associated sensitivities. Initial focus on steady-state ion-orbit-loss (IOL) calculations coupled to SOLPS indicated only modest reduction of the E_r associated with IOL, while poloidal asymmetries remain weak[Brzozowski12]. Simulations using the full-f GK code GYSELA[Grandgirard16] studied the impact of the magnetic ripple on plasma flows and hence E_r[Varennes22], as well as the impact of the safety factor which could be validated qualitatively against WEST and Tore Supra measurements [Varennes24]. The third objective was to integrate core, pedestal and SOL physics, based particularly on the latest GK developments made available by TSVV-4. These new capabilities enabled qualitative studies of the plasma profile response to input power increases similarly to experimental L-H transitions in limited and diverted conditions, achieving such fidelity for the first time in Europe. Alongside the fourth objective, which focused on interpretative and predictive capability for the L/H transition, a comparison has been established for the first time of a multi-fidelity hierarchy of models from ASTRA-TGLF studies[Bonanomi22] to highly encouraging flux-driven fluid results, e.g., in Ref. [Zholobenko25] and GK codes such as GENE-X[Michels21,Ulbl24] at the high fidelity end. This enables detailed assessments of the status quo and the addition of physics refinement at various stages. Furthermore, large-scale, fluid-code-based parameter scans, e.g., Ref. [Giacomin22], have been conducted with the GBS[Ricci12] code to establish a theoretical power-threshold scaling that closely resembles the ITPA one. The final objective was to validate and develop reduced-transport models. Here, a high-dimensional GK database was, e.g., used to benchmark quasilinear tools and local GK codes [Snoep25]. Additionally, a reduced micro-tearing mode (MTM) model was refined and validated and MTM saturation mechanisms studied[Hamed23]. Finally, a heuristic pedestal transport model [Luda23] was tuned and validated to establish improved boundary conditions for integrated modelling. Details regarding TSVV-1 and associated publications can be found at https://wiki.euro-fusion.org/wiki/TSVV-01.

As such advanced modelling capabilities are extremely rare worldwide, the activities can be considered among those spearheading the community, and further advancements, as proposed below, will be crucial to ultimately model L-H transitions and pedestal turbulence with high realism.

Scientific objectives and impact

The main TSVV-A scientific objectives are quite concisely given by the call. In the following, we provide the necessary details regarding our interpretation of these objectives, outline the methodologies and concepts and discuss the anticipated impact.

A) Develop the ability to perform self-consistent, robust and validated gyrokinetic simulations of L-H transitions, enabling accurate H-mode pedestal profile predictions

Given the dynamic nature of L-H transitions, corresponding numerical treatments must be based on flux-driven approaches that capture the evolution of flux-surface-averaged profiles in a self-consistent manner, on an equal footing with fluctuating quantities. As the latter can reach high amplitudes in the plasma edge, full-f approaches are typically required as well. Finally, integrating the Scrape-Off-Layer (SOL) into the simulation domain is essential for ensuring realistic boundary conditions, e.g. for developing radial electric field shear layers in the steep-gradient regime near the separatrix. To address this primary objective of plasma theory research in Europe and worldwide, we plan to utilise the GENE-X and GYSELA(-X) gyrokinetic (GK) plasma turbulence codes, which are flagship full-f codes developed in the preceding TSVV-LH (2019–2020) and TSVV-1&4 (2021–2025) projects, as well as the gyrokinetic extension of the nonlinear MHD JOREK code [Huysmans07] (see TSVV 8/9). Using three codes is advantageous due to their different specialisations. While GENE-X is a Eulerian full-f code that adopts a flux-coordinate-independent (FCI) approach, the semi-Lagrangian code GYSELA offers a different numerical approach with sophisticated immersed boundary conditions. Finally, the gyrokinetic particle-in-cell (PIC) code JOREK-GK enables and targets studies with Resonant-Magnetic-Perturbation (RMP) induced transitions. Based on encouraging findings from the 2021–2025 phase, in which L-H transition-type behaviour (i.e. profile steepening and radial electric field E_r formation in response to input power scans) could be observed in a hierarchy of models ranging from ASTRA+TGLF to fluid and fully GK simulations qualitatively, we are now taking the next step of reproducing, and ultimately predicting, the L-H transition in a realistic manner using self-consistent, high-fidelity modelling. In this context, scans of the input power sources will be (re-)launched, making use of the latest developments incorporated into the codes from TSVV-4/C. Over the next two years, we will assess the impact of neutrals (models, respectively), parallel magnetic fluctuations ($B_{||}$), and plasma-wall interactions (i.e. advanced sheath boundary conditions), as well as the inclusion of sub-ion-scale effects (directly or via coupling to reduced ETG models or GENE). However, resolving the full transition on energy and particle confinement time-scales will be extremely computationally costly, so the extent of such scans will need to vary. In any case, any sign of transitions will be scrutinised in the simulations launched with different source magnitudes and/or different initial density and temperature profiles.

B) Carry out gyrokinetic analyses of natural or controlled small/no-ELM regimes and assess their transferability to future fusion devices, including ITER

Given the enormous computational effort associated with dynamic profile evolution studies (A), which only permit limited investigation of physical effects such as the potential character of multi-scale plasma turbulence, 'stationary' analyses of experimental no/small ELM scenarios are a second key topic. Although a number of GK pedestal simulations have emerged in the last five years, the overall database remains limited. Due to the large number of possible physical factors at play, dedicated efforts are highly relevant. In this context, we propose considering

- Small/no-ELM JET, TCV, further WPTE H-modes; focus on KBM/MTM in view of (C),
- Edge-Localized-Coherent-Edge (QCE) and EDA H-mode discharges,
- RMP-induced small-ELM / ELM-suppressed scenarios, and
- Negative-triangularity (NT) and I-mode-like pedestals,

to provide ample coverage of a large variety of possible regimes. A main workhorse for the first two targets will be the GK δf code GENE [Jenko00, Goerler11], which will be used to explore the impact of impurities and electromagnetic (EM) fluctuations, and to assess fine-scale electron temperature gradient-driven turbulence in the presence of ion gyroradius scale turbulence. The gained experience will allow to identify possible needs for refinements for studies performed in (A), e.g. if cross-scale interaction turns out to be important, and naturally feeds into reduced model development (C). Taking advantage of the narrower focus of the call, and addressing a particular weakness of the 2021–2025 campaign, more staff are being allocated to these simulation campaigns facing experimental scenarios directly. Participants from IPP, SPC, DIFFER and ENEA-CNR will perform dedicated nonlinear analyses, mostly by means of gradient-driven, radially global simulations, of WPTE or scenarios already identified in the respective domestic programmes. For example, DIFFER intends to address scenarios involving potential MTM/KBM proximity in view of (C); SPC aims to compare the L-mode edge with the standard H-mode and small ELM, as well as negative triangularity pedestals, in TCV; and IPP plans to carry out detailed and up to multi-scale characterisation of AUG QCE/EDA-H modes and JET no-ELM pedestals.

The characterisation of the QCE and EDA H-mode regimes will be complemented by full-f ion-scale GENE-X simulations extending into the SOL region. GENE-X is particularly well-suited for this task due to its geometric flexibility wrt. complex diverted geometries, and its inclusion of EM and collisional effects. QCE discharges are typically characterised by a strong shaping, often approaching a double-null configuration. The presumed EM nature of the quasi-coherent mode (QCM) which appears to extend into the SOL inaccessible to GENE, and the high collisionality of these scenarios pose significant challenges for the plasma model. To address these challenges, we will investigate the effect of parallel magnetic fluctuations and explore the impact of advanced

collision models developed within TSVV-4/C.
For studying resonant magnetic perturbation (RMP)-induced small ELM regimes we plan to utilize the advanced respective modelling capabilities offered by the electrostatic gyrokinetic code JOREK-GK. Here, the 3D magnetic equilibrium modified by RMPs, including the MHD plasma response [Becoulet22], is computed first. ITG/TEM turbulence is then simulated in this perturbed geometry, specifically addressing the density pump-out phenomenon observed during RMPs.
Finally, small/no-ELM regimes will be addressed by means of negative triangularity (NT) and I-mode-like scenarios. From an operational point of view, the aim is to achieve a cold and dense plasma in the divertor, indicating the presence of an edge transport barrier with respect to temperature but not density. Distinct edge density and temperature profiles have been reported experimentally in both NT and I-mode regimes, making them particularly appealing for use in a power plant. Concerning experimentally reported NT confinement improvements, TSVV-2 identified that a large fraction originates outside ρ=0.9 [Balestri24], a region inaccessible to standard GK codes. Fortunately, this region can be modelled with the GYSELA, JOREK-GK and GENE-X codes of TSVV-A/C. This – in the sense that the NT geometry is most relevant compared to other physics - "simplest" of the no-ELM regimes [Austin19] is thus taken as proof-of-principle cross-code benchmark. Naturally, comparisons with experimental data are targeted, including recent TCV measurements in matched NT/PT discharges which show that the near-separatrix E_r well has an NT depth intermediate between those in L- and H-mode PT plasmas. Furthermore, predictions for NT-based reactor scenarios will be informed by ρ*-scaling studies.

C) Develop first-principles-based and fast reduced models of turbulent transport in the pedestal region of future fusion devices

We understand that one of the main customers for the activities requested in this context is TSVV-11/TSVV-H. Corresponding consultations have hence contributed to the following objectives:
With respect to reduced turbulence models, a major focus of TSVV-11 is currently on TGLF. In line with corresponding requests, TSVV-A will aim for routinely comparing GENE flux-tube simulations, e.g. performed as an intermediate step towards the radially global simulations, with TGLF by taking advantage of the IMAS interfaces for translating to TGLF, which have recently been implemented in TSVV-1. TSVV-H will provide the necessary TGLF settings. The assessment and refinement of a reduced modelling of the L-H transition will be addressed in a dedicated subtask. Finally, we acknowledge that scalings are another important factor in estimating the performance of future power plants. Therefore, the previously initiated activity of developing/refining predictive scalings based on large-scale parameter scans performed using the GBS fluid code will be continued.

Given the pioneering nature of the endeavours summarised above, their innovative potential is high. Any results achieved in (A) and (B) will contribute significantly to our understanding of and ability to predict fusion plasmas in the context of future power plants, while (C) is highly significant in terms of developing tool chains for engineering these future devices.

Project description and implementation

The project will be organized around the main three objectives outlined by the call. Details how these and sub-tasks shall be addressed in 2026-2027 are given below, including statements regarding reduced model development.

A) Towards self-consistent, robust and validated gyrokinetic simulations of L-H transitions, enabling accurate H-mode pedestal profile predictions

As mentioned above, we take advantage of the unique capabilities offered through three entirely different numerical approaches (Semi-Lagrangian, PIC, Eulerian):

A.1) Flux-driven Semi-Lagrangian GYSELA simulations - *P. Donnel, G. Dif-Pradalier, Y. Sarazin, X. Garbet (0PM):* The structure of the flux-surface averaged radial electric field Er is believed to be key in triggering and sustaining edge transport barriers. However, a self-consistent computation, however, requires advanced core-edge-SOL modelling covering many of the physical mechanisms at play: ion orbit losses, radial force balance and neoclassical physics, turbulent drives (Reynolds stresses) and plasma-wall interaction physics. Capitalising on corresponding capabilities added in TSVV-LH and TSVV-1/4 – some further developed in TSVV-C – the Semi-Lagrangian full-f GK code GYSELA will be employed to capture the self-consistent evolution of the flux-surface averaged profiles including Er, on an equal footing with the fluctuating quantities, while solving the GK evolution of ions and trapped electrons. Resolving the full transition will likely require too many numerical resources, since it occurs on energy and particle confinement times and necessitates properly accounting for EM effects with increasing pressure. Yet, any signs of such transitions will be scrutinised in simulations launched with different initial density and temperature profiles. The aim is to diagnose the ability of turbulence - via the two components of the Reynolds stress [Sarazin21] – in these regimes (different grad(n), grad(Ti), grad(Te) and collisionality) to reinforce the edge E_r well. This will extend the seminal work performed in ITG-dominated turbulence with adiabatic electrons and a poloidally-uniform scrape-off layer [Dif-Pradalier22] to regimes featuring ITG and TEM (requiring kinetic electrons) and an advanced treatment of plasma-wall interaction in the SOL.The latter point is tied to a T0+9month milestone in TSVV-C.

A.2) Flux-driven PIC simulations with JOREK-GK - *M. Bécoulet, G. Huijsmans (0PM)***:** The full nonlinear GK PIC version of the JOREK code, called JOREK-GK, solves for GK ions and guiding centre electrons. It is therefore designed to model plasma turbulence driven by ion temperature gradient (ITG) and trapped electron modes (TEM) from first principles. All plasma quantities are represented via a PIC approach and initialised with Maxwellian distributions based on magnetohydrodynamic (MHD) equilibrium profiles. Ion dynamics include parallel streaming and gyrocentre drift motions, with the electrostatic potential obtained by solving the quasi-neutrality condition in its weak form. The current version of JOREK-GK is electrostatic and assumes a fixed magnetic field configuration; however, fully 3D magnetic perturbations—such as resonant magnetic perturbations (RMPs) or tearing modes—can be incorporated. A key scientific objective of JOREK-GK is to investigate the spontaneous L–H transition and the associated formation of the edge transport barrier, or 'pedestal'. Capturing this transition accurately and self-consistently remains a major challenge for all current GK simulations. One of JOREK-GK's major strengths compared to GYSELA-X is its realistic treatment of tokamak geometry, including the X-point and SOL, thus enabling complementary studies in diverted scenarios.

A.3) Input power scans with the Eulerian code GENE-X - *P. Ulbl, F. Sheffield***:** We aim to improve upon previous studies with GENE-X, which revealed a rapid change in turbulent dynamics when ramping the input power in diverted geometries [Ulbl24]. However, these studies were limited by the absence of neutral particle sources, resulting in unrealistically low separatrix density. Recent fluid results have strengthened the possibility of capturing fast phase transitions with injected power [Zholobenko25]. To address the previous limitations, we will conduct revised power scans utilizing new developments from TSVV4/C. Specifically, **(A.3a)** will utilize new particle sources to provide accurate experimental density profiles, **(A.3b)** will incorporate a self-consistent neutrals model, and **(A.3c)** will include sub-ion scale physics effects by coupling to a reduced ETG model or incorporating GENE fluxtube results. In all cases, the relevance of parallel magnetic perturbations ($B_{||}$) will be studied. The overall power-ramp will be refined by utilizing the new flux-driven mode.

B) GK analyses of natural or controlled small/no-ELM regimes and their transferability to future fusion devices, including ITER

B.1) Multiple scale small/no-ELM pedestal characterisation with the Eulerian δf-code GENE
The main workhorse to study the impact of (also larger numbers of) impurities and EM fluctuations, as well to assess fine-scale electron-temperature-gradient driven turbulence in the presence of ion-gyroradius scale turbulence will be the GK δf code GENE. The gained experience will allow to identify possible need full-f modelling refinements, see (A), e.g., if cross-scale interactions turn out to be important, and naturally feeds into reduced model development (C). The following sub-tasks are considered:
B1a) Focus on likely electromagnetic mode dominated WPTE scenarios - MJ Pueschel, T. Jitsuk: Based on dedicated exchange with experimental groups, H-mode experiments will be selected for modelling where indications exist that kinetic ballooning modes (KBMs) or microtearing (MT) modes are active in the pedestal region. If confirmed by linear GK simulations, nonlinear simulations will be performed with a dual purpose: to facilitate comparison with the experiment with the aim for multi-channel (e.g., fluctuation data and flux) validation; and to provide a realistic scenario based on WPTE devices for testing of the reduced models treated in (C).
B.1b) TCV based pedestal simulations with extensions to negative triangularity plasmas - A. Balestri, H. Zhang: In particular, small-ELM TCV experiments [Labit2019] will be considered. Simulations will benefit from already available experimental data for the validation of results. Local and global simulations will focus on electron and ion-scales.

B.1c) Multi-scale characterisation of AUG QCE/EDA-H mode and JET no-/small-ELM pedestals - M. Dicorato, A. Mariani, F. Sheffield, T. Görler: Based on a set of already available experimental data, we plan to refine the characterisation, particularly by radially global ion-scale and flux-tube electron-scales simulations before running a few selected high resolution simulations for cross-scale coupling assessment. We will also address the impact of impurities and explore under which circumstances dilution models can be employed compared to the more expensive active species treatment. The outcome will be shared with EF modellers outside TSVV-A as soon as available.

B.2) Full-f, ion-scale, cross-separatrix simulations

While fine-scale resolved activities remain beyond the scope of full-f simulations due to the enormous computational costs, the latter offer another possible key player inaccessible to field-aligned code such as GENE - the interaction with the SOL. Three activities are foreseen:

B.2a) I-mode and negative triangularity studies with GYSELA - P. Donnel, G. Dif-Pradalier, Y. Sarazin, X. Garbet (0PM): I-mode-like regimes are characterised by the absence of ELMs and edge density (resp. temperature) profiles reminiscent of L-(resp. H-)mode plasmas [Hubbard16]. As such, they are interesting operational scenarios for a power plant. They also exhibit a significant Geodesic Acoustic Mode (GAM) activity accompanied by a weakly coherent mode (WCM) [Cziegler13], echoing the reported signature of TEMs [Arnichand15]. One of the key issues is the decoupling of heat and particle (both main ions and impurity) transport. In this context, turbulence and transport will be studied in mixed ITG-TEM regimes, the latter being driven either by density or temperature gradient. Indeed, TEM turbulence saturation is not equally sensitive to zonal flows in these two regimes [Ernst09]. Additionally, recent GYSELA upgrades permit non-circular magnetic flux-surface cross-sections, as described in [Connor85]. They will be exploited to compare NT/PT configurations (scanning collisionality and density/temperature gradients) with particular focus on the level and generation of zonal flows which contribute significantly to ion-scale turbulence saturation. Another key issue is the existence and shape of a near-separatrix E_r-well. Recent experimental measurements on matched NT/PT TCV discharges reveal that NT E_r-well depths lie between those in L- and H-mode PT plasmas [Rienäcker25].

B.2b) JOREK Gyrokinetic Modelling of RMP-Controlled regimes and NT plasmas **-** *M. Bécoulet, G. Huijsmans (0PM)***:** JOREK-GK is also suited for gyrokinetic studies of naturally occurring or externally controlled small or ELM-free regimes, in two specific contexts. In scenarios where edge-localized modes (ELMs) are suppressed via resonant magnetic perturbations (RMPs), the modified magnetic topology, including the plasma response, can be obtained from nonlinear resistive MHD simulations using the standard JOREK code. Particles can then be initialized on this 3D equilibrium in JOREK-GK enabling studies of the RMP effects on ITM/TEM turbulence, such as density pump-out. The possible scenarios involve COMPASS, AUG, HL2A where the RMP spectra with MHD plasma response were modelled already. Additionally, finite-size ρ^*-scaling studies are foreseen with JOREK-GK to provide predictions for future NT reactors. JOREK-GK will treat realistic experimental pulses using TCV, DIII-D, WEST experimental data simulating ITG/TEM turbulence dynamics including zonal flows, ion orbits losses, neoclassical physics, collisions, SOL and divertor physics. A GENE-X and JOREK-GK benchmark on selected NT scenarios is foreseen.

B.2c) GENE-X characterization of AUG QCE discharges **–** *P. Ulbl, F. Sheffield:* Complementary and comparative study to B.1c) assessing the impact and relevance of cross-separatrix physics. For instance, the Quasi-Coherent-Mode is found to penetrate into the SOL but it remains unclear whether this part needs to be modelled to capture the pedestal transport level in QCE discharges.

C) First-principles-based and fast reduced model development of turbulent transport in the pedestal region of future fusion devices

C.1) Assess quasi-linear nature of edge turbulence, spectral comparisons with TGLF - *M. Dicorato, T. Görler, M.J. Pueschel***:** TSVV-11/H identified further assessments of (a) the quasi-linear (QL) nature of plasma edge/pedestal turbulence to inform corresponding integrated modelling activities regarding ranges of validity and (b) comparisons between linear and multi-scale nonlinear GK spectra and one of their main tools TGLF as highly relevant. Obviously, this task relies on (B1) studies. They shall be accompanied by linear simulations to assess the QL level by observables such as the transport relevant cross-phases and/or mode frequencies. Extending a recent implementations of a GK IDS (IMAS) interface, we intent to establish quick linear and multi-scale spectra TGLF comparisons (limited to comparisons of flux-tube simulations, e.g., in regions of strongest drive, for now). We will also consider TSVV-11/H input regarding refinements of sensitivity scans, e.g., the impact of collisionality on the fluxes for parameters as used in the power scan (A3).

C.2) Assessing and extending reduced models for the L-H transition - *G. Lo-Cascio, C. Angioni (0 PM)*: Within the scope of obtaining a description of the L-H transition that can be applied to discharge scenario transport modelling, a companion activity based on applying transport codes up to the separatrix using the TGLF-SAT2 transport model is also being considered. TGLF-SAT2 has been shown to be capable of providing realistic levels of transport for L-mode edge turbulence. Other key elements for describing an L-H transition from a transport modelling standpoint include the ability to realistically predict the E_r profile, particularly when approaching the separatrix, and the effect of ExB rotational shear on transport levels for edge parameters. Regarding the latter, it has already been found that turbulence reduction was weaker in TGLF than in flux-tube GENE simulations. To predict the radial electric field profile, examining the main terms that determine the consistent evolution of the radial electric field in GK edge turbulence codes, see (A), can guide the development of reduced models. This should also include the effects of a turbulent drive on poloidal rotation and have an appropriate connection to the SOL as a boundary condition.

C.3) Reduced models for electromagnetic modes - *MJ. Pueschel, T. Jitsuk:*
C.3a) Refinement of the Micro-Tearing Mode model: As TSVV-1 based analyses have indicated, a major improvement of the MT reduced model Solve_AP [Hamed19/22] can be expected when including dependencies along the magnetic field lines, thus in particular capturing changes in curvature. These shall be implemented, verified against GK simulations and - in the framework of (B1a) - validated against experiments. In this context, the Solve_AP model will be used in QL frameworks such as the one described in [Xie20].
C.3b) Assessments of the KEY code – a reduced model for Kinetic Ballooning modes (KBM): Recent developments in KBM theory [Mulholland25] have enabled the creation of a new tool, the KEY (KBM Eigenvalue Yielder) code, a fast dispersion solver capturing substantial kinetic effects of linear KBM physics and predicting growth rates in stellarator scenarios. Initial tests have confirmed that this tool is applicable to pedestal-like situations, as well. We will build on these tests and conduct further verification of the model under realistic circumstances, such as the parameters from (B1a) or cases from a pedestal database maintained by collaborators at IFS.
C.3c) JAX implementation of Solve_AP and KEY and saturation rule assessment: If and when steps (C3a) and (C3b) demonstrate conclusively that the models can be used reliably for integrated modelling, they will be re-written in Python/JAX. This refers to a framework designed for GPU accelerators in the context of high-performance computing and large-scale machine learning. Once complete, these new versions will be made available to users such as TSVV-H or other EUROfusion (EF) groups that focus on machine learning with pedestal applications.

C.4) Assess reduced ETG models and implementations into GENE-X - *F. Sheffield, T. Görler, M. Dicorato, A. Mariani*: Based on the ETG simulations performed in (B1), we will compare with available reduced ETG models such as [Hatch24] or [Farcas25] and consider possible refinements. Adjusted rules will feed into (A3). We will also test for ITER cases the model of [Saarelma23,Saarelma24], which was successfully tested against JET ILW, MAST U and AUG H-mode experiments, confronting it with dedicated GK simulations.

C.5) L-H/H-L regimes transition scaling laws based on large GBS based parameter scans - *B. De Lucca*: The corresponding analysis of the turbulent regimes in the tokamak edge and SOL performed in TSVV-1, by using two fluid models, shall be refined and completed, extending the work of [Giacomin22]. The physics behind the regime transition from a low to a high confinement mode, revealed by the simulations will be analysed, thanks to linear and nonlinear theory. Predictive scalings for the back and forth transition will then be obtained and compared with empirical scalings, ultimately to support ITER operation.

EUROfusion Standard Software (ESS) - *T. Görler:* TSVV-A ensures that the aforementioned reduced models will be made available to the EF community with appropriate documentation and IMAS-compatible interfaces once validated. Regarding larger code packages involved in TSVV-A, most of them are actively developed by other TSVV tasks (e.g., GENE-X, GYSELA(-X) within TSVV-C) which are hence likely designated code coordinators. The main software tool left is the GENE code which had also been coordinated by TSVV-1. As one of the main developers of the GENE code, the PI confirms that GENE has reached comparatively high levels wrt. to the ESS Criteria which are regularly monitored by E-TASC. Nevertheless, further activities, e.g., verification & validation are foreseen for new features such as an improved ExB shear model. For 2026, user training events for both GENE and GENE-X are envisioned covering the most relevant not yet addressed ESS activity.

Team members and project management

Team: The team members selected according to above objectives are all established experts or PhD students specializing in the respective fields from five different beneficiaries (CEA, DIFFER, ENEA-CNR, EPFL-SPC, MPG). This way a large fraction of the European expertise regarding edge GK and corresponding reduced modelling efforts can be utilized. In detail, the following researchers are considered **besides the PI T. Görler (6 PM/y)**:

Name	Beneficiary	PM/y	Role
Bécoulet, Marina	CEA	4	Senior scientist
Dif-Pradalier, Guilhem	CEA	4	Senior scientist
Donnel, Peter	CEA	4	Senior scientist
Sarazin, Yanick	CEA	2	Senior scientist
CEA Consultants *(0 PM): J. Assaad, X. Garbet, V. Grandgirard, G. Huijsmans, K. Obrejan*			
Jitsuk, Taweesak	DIFFER	3	PostDoc
Pueschel, MJ	DIFFER	5	Senior scientist
Mariani, Alberto	ENEA	4	Senior scientist
Balestri, Alessandro	EPFL-SPC	3	PhD student
De Lucca, Brenno	EPFL-SPC	3	PhD student
Zhang, Haoran	EPFL-SPC	5	PhD student
EPFL Consultants *(0 PM): J.R. Ball, S. Brunner, O. Krutkin, P. Ricci*			
Dicorato, Mattia	MPG	4	PostDoc
LoCascio, Guillaume	MPG	3	PostDoc
Sheffield-Heit, Facundo	MPG	4	PhD student/PostDoc
Ulbl, Philipp	MPG	6	Senior scientist
MPG Consultants *(0 PM): C. Angioni, B. Frei, F. Jenko, G. Merlo, W. Zholobenko*			
UKAEA Consultants *(0 PM): H. Dudding, B.F. McMillan*			

In addition to the core team (CVs attached), the term 'consultants' refers to experts and/or supervisors who are available for regular consultation and exchange but free of charge.

Management and communication: As in the previous project phase, we expect full team stand-up **meetings at least once a month** and **at least one in-person meeting/workshop per year** (project monitoring/review), *depending on the availability of funding for travel*. The team suggests that the travel budget should also cover at least some of the consultants' travel costs. In addition, subgroup meetings and joint events with TSVVs with topical overlaps will be considered on a case-by-case basis (like the TSVV-01-11 meetings in the past; now with TSVV B/C/H). We will actively maintain communication channels such as a EUROfusion wiki and Indico page, a dedicated mailing list and, if a need for day-to-day communication evolves, a messenger service. TSVV-A will aim to facilitate regular communication, e.g., by inviting other EF edge modelling researchers to the annual workshops. Scientific exchange is also often well established, as several key developers (GENE/GENE-X/GYSELA) involved in TSVV-A stay in touch with their code user communities.

Personnel-related risks: Given the project period of only two years, personnel-related risks should be lower than in previous project phases. However, all participating labs assure us that they have sufficient manpower to replace individual team members if necessary. In some cases (IPP), replacements could be drawn from the pool of consultants. Subject to the outcome of an alternative funding application, e.g., P. Ulbl could be replaced by B. Frei or another GENE-X PhD student.

Resource-related risks: Given its computationally extremely challenging mission, TSVV-A strongly relies on corresponding computational budgets. It will be important to ensure that a substantial allocation of the EF HPC Pitagora machine is dedicated to this project. Furthermore, the team has or will aim to secure additional resources via domestic or other European Calls. In the worst case, some of the most expensive activities (full-f power scans or multi-scale delta-f) will need to rely on mitigation efforts such as employed reduced mass ratios etc.

Work plan

Timeline: The work plan closely follows above project description and considers the lists of milestones/deliverables described below which support the project monitoring as shown in Fig. 1.

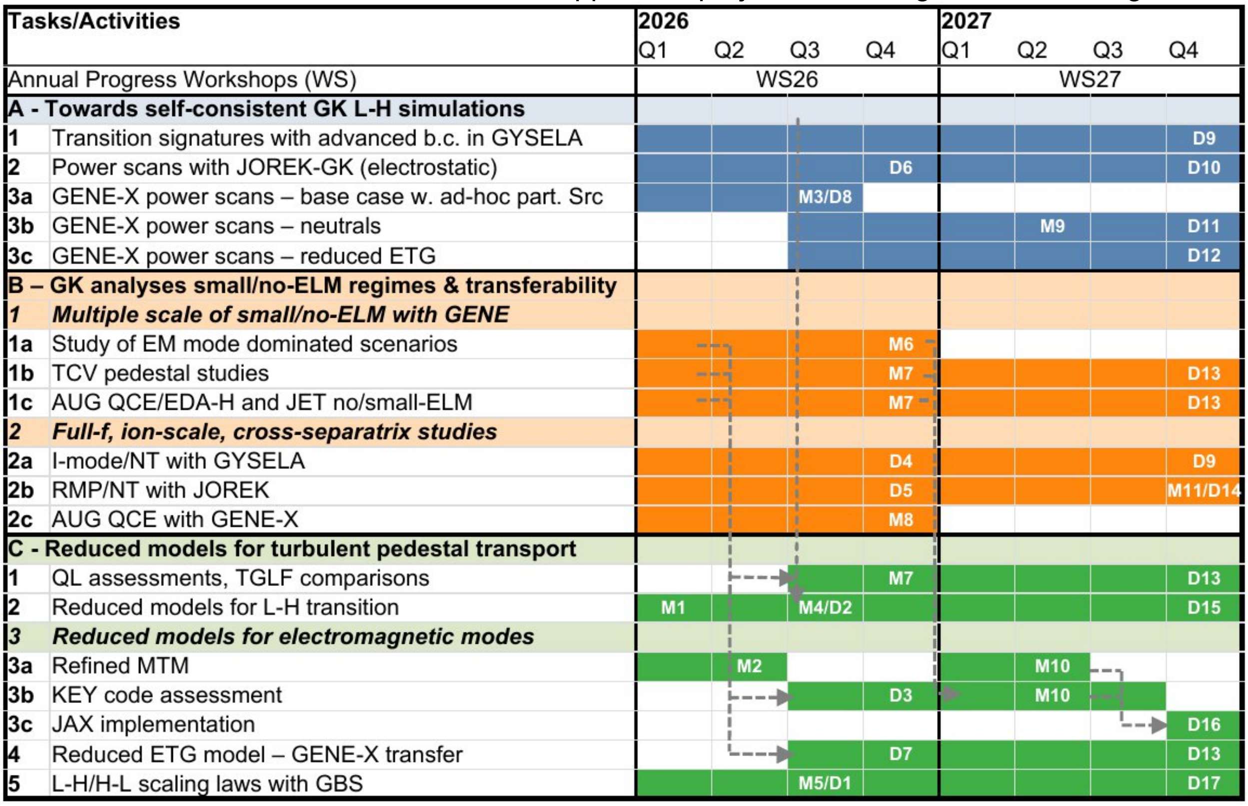

Fig. 1: Timeline of the project with milestones and deliverables. The annual progress workshops (WS) are indicated as well while monthly and other meetings are not shown for simplicity.

Milestones

No	Title - Description; <u>*Participants*</u> *- related task*	Exp. date
M.1	**E_r effect on turbulence in TGLF/GENE** - Characterization of E_r impact on turbulence in TGLF vs GENE-local in pre-H-mode edge; <u>*Lo-Cascio/Angioni*</u> *- C2a*	02/2026
M.2	**Reduced MTM model** - Parallel-resolved Solve_AP code for higher-fidelity curvature drive & linear pedestal tests completed; <u>*Pueschel/Jitsuk*</u> *- C3a*	04/2026
M.3	**GENE-X power ramp** with ad-hoc particle sources performed*;* <u>*Ulbl*</u> *- A3a*	08/2026
M.4	**V_{pol} turbulent ad-hoc model / ASTRA E_r modelling** - Turb. contributions to poloidal rotation (e.g. Reynolds stress) implemented in ASTRA–TGLF, guided by GK (A,B) and E_r boundary condition optimized; <u>*Lo-Cascio/Angioni*</u> *- C2b*	08/2026
M.5	**L-H/H-L regimes transitions scaling laws -** GBS power scan simulations in both un-/favourable configurations performed. First-principle L-H/H-L transition scaling laws derived & compared with experimental data*;* <u>*De Lucca*</u> *- C5*	08/2026
M.6	**EM dominated H-mode regimes** - NL pedestal GENE simulations in MT/KBM regimes (local/global) performed; KBM-MT co-occurrence regimes assessed; <u>*Pueschel/Jitsuk*</u> *- B1a*	12/2026
M.7	**GENE H-mode characterizations -** First batch of no-/small-ELM TCV/AUG and/or JET pedestals characterised - at least single-scale (global ion-scale, flux-tube electron scale); ETG and QL assessments; <u>*Dicorato/Mariani/Zhang/Balestri/Pueschel/Jitsuk/Görler*</u> *- B1,C1,C4*	12/2026
M.8	**QCE study w/ GENE-X/GENE -** GENE/GENE-X QCE simulations studying QCM nature & $B_{\|\|}$ fluctuations impact*;* <u>*Sheffield/Ulbl/Dicorato/Görler*</u> *- B1c/B2c*	12/2026
M.9	**GENE-X power ramp with neutral model** with self-consistent sources performed; <u>*Ulbl*</u> *- A3b*	06/2027
M.10	**Assess/validate EM reduced models -** SAP/KEY saturation rules tested against NL (incl. IFS provided cases) and TGLF (with TSVV-H); areas for improvement identified via e.g. triplet correlation times; <u>*Pueschel/Jitsuk*</u> *- C3b*	06/2027

M.11	**NT full-f studies incl. benchmark** - NT studies performed with various codes; TCV base case (w/ at least) JOREK-GK/GENE-X benchmark accomplished**;** *Becoulet/Sheffield/Ulbl* - *B2b*	12/2027

Collaborations and information exchange: Several tasks will require close collaboration with **TSVV-C** (e.g., new neutrals/sheath GK edge code capabilities), **TSVV-H** (reduced models) and **TSVV-B** (fluid-based L-H transition studies). To some degree this is ensured by staff overlap but dedicated joint meetings as performed in the past will offer other means of information exchange/collaboration. Recognising that the use of advanced machine learning is a critical path for reduced model development beyond the proposal's scope & budget, we plan to collaborate with initiatives such as those proposed by **ENR "Pedestal Inference Engine (PIE)"** (CfP-FSD-AWP26-ENR-05-VTT-01) in a similar way, i.e. limited staff overlap, joint meetings and/or representation at respective workshops. Broader outreach will be provided through Wiki/Indico pages, presentations at other EF WPs (as before), representation at major conferences and journal publications.

Scientific deliverables

Year	Description; *Participants* - related task
2026	D.1 Scientific report or publication of GBS power scan simulations in un-/favourable configurations and derived first-principle scaling laws for L-H/H-L transitions compared to experimental data (08/2026); *De Lucca* – *C5* ***(*)*** D.2 Report on the validation of ad-hoc v_{pol} and E_r model at pedestal stop for LH transition with experiments (10/2026); *Lo-Cascio/Angioni* – *C2* D.3 Report on z-resolved SAP&KEY pedestal performance (12/2026); *Pueschel/Jitsuk* - *C3a* ***(*)*** D.4 Scientific report comparing turbulence characteristics and quantifying transport levels in NT/PT configurations and different collisionalities with GYSELA (12/2026); *Donnel/Dif-Pradalier/Sarazin* – *B2a* ***(*)*** D.5 JOREK-GK NT/PT simulations. Publication of the results. (12/2026); *Becoulet* – *B2b* ***(*)*** D.6 L-H transition studies with full-f, full geometry, flux driven ITG-TEM turbulence JOREK-GK simulations. Scan of relevant parameters. Conference presentation (12/2026); *G. Huijsmans* – *A2* D.7 Reduced ETG models and/or GENE flux-tube available in GENE-X (12/2026); *Sheffield, Ulbl* – *C4* D.8 Report on GENE-X power ramp studies w. ad-hoc particle source (12/206); *Ulbl* – A3a
2027	D.9 Scientific report characterizing turbulence, heat & particle transport in GYSELA simulations featuring both ITG & TEM instabilities but occupying various places in the (grad(n),grad(T_i), grad(T_e)) parameter space – qualitative comparison to I-mode regimes (12/2027); *Donnel/Dif-Pradalier/Sarazin* – A1/B2 D.10 Report on the obtained results of JOREK-GK modelling of L/H transition. Publication (12/2027); *Huijsmans* – A2 D.11 Report on the neutral model impact in GENE-X flux-driven power ramps (12/2027); *Ulbl* – A3b D.12 Report on the impact of sub-ion scale ETG transport on flux driven power ramps on GENE-X (12/2027); *Sheffield, Ulbl* – *A3c,C4* D.13 Reports/Publications on JET/TCV no/small-ELM regimes and AUG QCE/EDA-H-mode studies performed with GENE/GENE-X with assessments of ETGs, quasi-linearity and TGLF comparisons on a test basis; *Dicorato/Mariani/Zhang/Balestri/Pueschel/Jitsuk/Görler/Sheffield/Ulbl* – *B1a-c, C1, C4* ***(*)*** D.14 Conference publication on JOREK-GK ITG/TEM turbulence simulations with RMPs in different tokamaks (COMPASS, HL2A, AUG) (12/2027); *M Becoulet* – B2b ***(*)*** D.15 Report on assessment of revised ASTRA-TGLF L-H transition studies (12/2027); *Lo-Cascio/Angioni* – C2 D.16 Report on verification of SAP/KEY with saturation rules against NL GK in pedestal and - depending on outcome - release of JAX-ified SAP, KEY codes for integrated modelling (12/2027); *Jitsuk/Pueschel* – C2 ***(*)*** D.17 Report on revised GBS based L-H/H-L scalings with latest code upgrades and/or refined parameter scans (12/2027); *De Lucca* – C5 ***(*)***
(*)	***some aspects likely less detailed than originally planned due to budget restrictions but the commitment remains***

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